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Automatic Synchronizing for Generation and Tie Lines

by

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INTRODUCTION

The subject of synchronizing generators to a system is becoming more critical due to:

1. the large size of modern base load plants (>400 MW)
2. the need to bring ready reserve on line quickly (peaking plants)
3. the increasing reliance on automation to synchronize unmanned plants
4. the shrinkage or disappearance of a reserve margin where the utility cannot afford an improper synchronization.

Concerns for synchronizing tie lines include synchronous and asynchronous aspects. The ability to restore synchronous ties quickly is taking on greater importance as parallel line load limits are being reached. Systems operating asynchronously (islanded generation) must be able to be restored to the bulk power grid at the earliest available moment with the minimum of disturbance to the separated systems. The ability to detect which of these conditions exist and to act accordingly has also taken on increasing importance due to the complexity of interconnected systems.

This paper addresses these concerns with the application of relaying systems involving automatic synchronizing (25A) and sync check (25) relays.

Elementary developments will be explored to address the dynamic conditions found at generating stations and transmission/sub-transmission substations. Schemes with increasing layers of security are explored for critical installations. Calculations for setting these relays are also addressed.

Speed matching methods for difficult turbine generator applications are also explored and a comparison of methods is illustrated.

SYNCHRONIZING DEFINED

Synchronizing is the act of electrically connecting two ac sources in a synchronous condition. A synchronous condition is attained with the minimization of the following parameters:

Frequency difference — the difference in frequency between the two sources, often referred to as "slip";

Voltage difference — the difference in voltage magnitudes between the two sources;

Phase angle difference — the difference in phase angle between the voltages of the two sources.

In polyphase systems, phase sequence is another important consideration. Because synchronizing is generally accomplished on three-phase systems by monitoring only one phase, the same phase from each source must be monitored. Phase sequence will not normally change from one synchronization to the next, unless the rotation is changed on one of the sources, or via switching (pumped storage hydro). Three-line diagrams depicting generator synchronizing and tie line synchronizing are shown in Figure 1. A one-cycle example of sources operating asynchronously is shown in Figure 2, where the frequency difference of the two systems, $f_2 - f_1 = \Delta f$ = slip frequency.

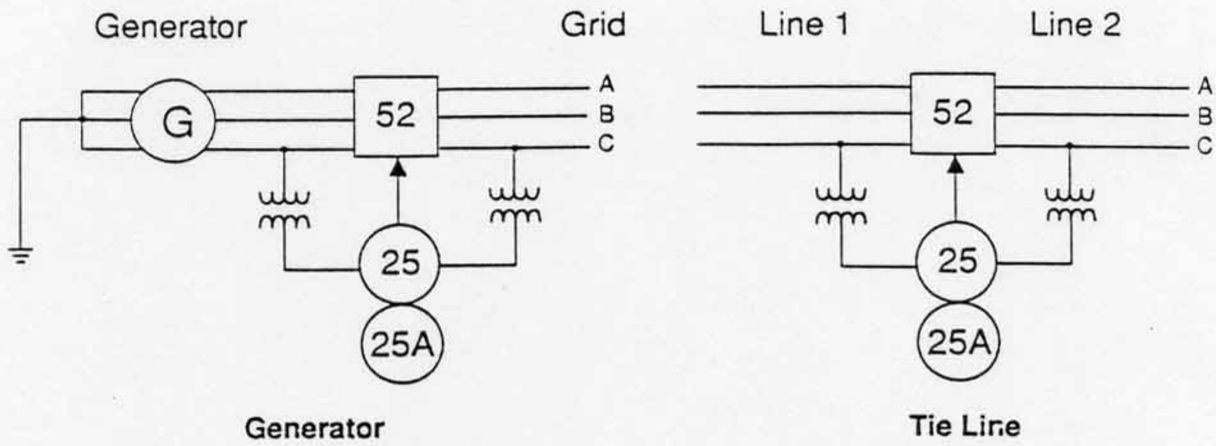


FIGURE 1 Generator and Tie Line Synchronizing

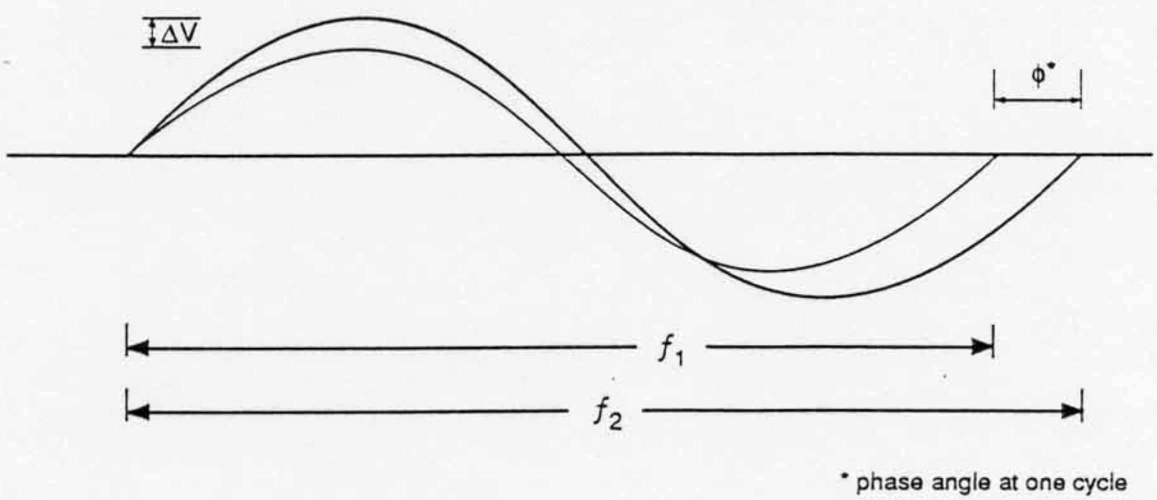


FIGURE 2 Voltage Waveform of Sources Operating Asynchronously

SYNCHRONIZING ERRORS

Numerous technical papers have been written analyzing the damage that occurs to turbine generators as a result of faulty synchronizing. The damage can be either immediate (system failure) or cumulative (loss of life).

For transmission systems, system instability can result in a continuance of the separation and the possibility of further islanding. This is known as the *in extremis* state [18].

General types of damage caused by excesses in difference of frequency, phase angle, and voltage are explored below.

EXCESSIVE FREQUENCY DIFFERENCE

Closure with excessive slip frequencies, even with a zero phase angle, causes power to flow in or out of the generator. The direction of the power flow will be out of the machine if its frequency is greater than the bus, or into the machine if its frequency is less than the bus.

The amount of power flow increases as the mismatch increases. Power flows at the moment of synchronizing are referred to as "hard loading," which can cause system stability problems. This differs from the controlled, gradual loading that takes place after normal synchronization.

Electrical effects include sudden power flows in or out of the generator and the associated unit transformer. Cumulative mechanical stresses arise from a sudden load being placed on the rotating machinery.

EXCESSIVE PHASE ANGLE

Excessive phase angle across the synchronizing breaker prior to closing tends to sharply "bump" the incoming machine. One source [20] reported that closing at a static angle as low as 15° causes a power swing that would correspond to a 0.5 Hz slip between the generator and the grid if the phase angle were 0°. This is an example of "hard loading" which is always undesirable with today's close tolerance machines.

The types of damage include, but are not limited to, shaft fatique, bearing failure, fillet and keyway failure, turbine blade root stress, and overheating due to high stator currents.

EXCESSIVE VOLTAGE DIFFERENCE

A large voltage difference between sources will cause a flow of reactive volt-amperes, with the direction of the flow depending on the relative voltage from the higher to the lower voltage source. Power swings may develop as the mismatch between mechanical power input and electrical power output oscillate as the excitation system attempts to rapidly adjust the var flow. If the mismatch is great enough, the fluctuation of the machine speed can continue to increase until synchronism is lost. Reverse power nuisance trips at generators may take place if the var flow is into the machine.

GENERATOR SYNCHRONIZING

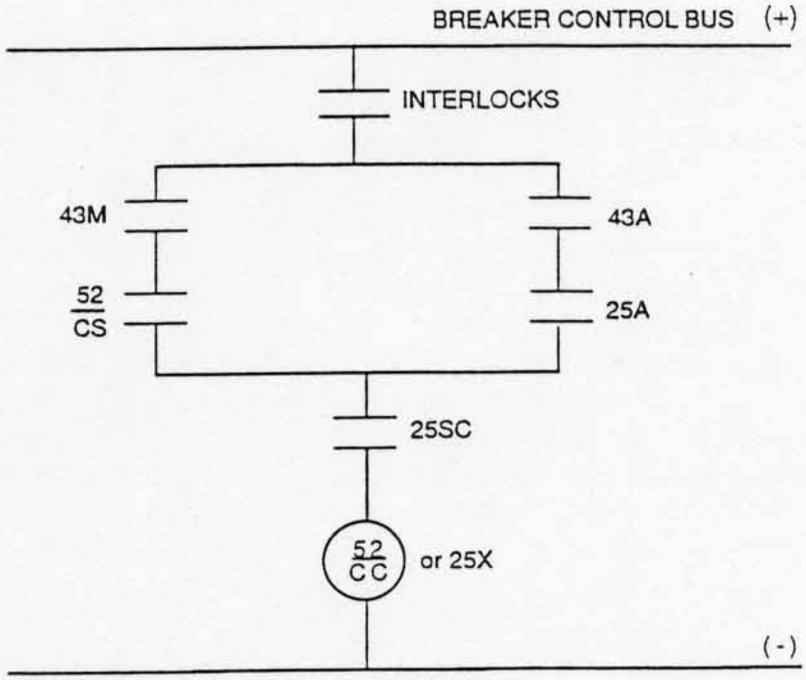
In its most simplistic application, generator synchronizing involves bringing a generator on line to the grid as shown in Figure 1. Generating plants connected to complex substation arrangements are discussed in the **TIE LINE SYNCHRONIZING** section of this paper.

ELEMENTARY DIAGRAM DEVELOPMENT

Most power plants have two power circuit breaker closing paths: manual and automatic. Both closing paths have common interlocks, such as lockout relays, disconnect switch status, and other logic interlocks as shown in Figure 3.

The manual branch of the elementary diagram begins at the auto/manual selector switch, passes through the operator's circuit breaker control switch, through a sync check relay as a backup element, and continues through to the breaker closing coil. In the manual mode, the operator is the master control element and the sync check relay is the backup element.

The automatic branch of the elementary diagram begins at the auto/manual selector switch, passes through the automatic synchronizer (autosync), through a sync check relay as a backup element, and continues through to the breaker closing coil. In the automatic mode, the autosync relay is the master control element and the sync check relay is the backup element.



Legend:

43M	Select Manual	25A	Automatic Synchronizing Relay
43A	Select Auto	25SC	Sync Check Relay
52/CS	Circuit Breaker Control Switch	52/CC	Power Circuit Breaker Closing Coil
		25X	Auxiliary Sync Relay

FIGURE 3 Elementary Diagram of Paths

Either the autosync relay will close the breaker when the electrical parameters (slip, phase angle and voltage) are within their proper limits, or the operator will close the breaker when he decides that the information on the electrical parameters, as displayed by meters and the sync scope, is acceptable.

AUTOMATIC SYNCHRONIZER APPLICATION

The autosync relay electronically calculates the proper advance angle to index the closing of the breaker. Additionally, the relay verifies that the upper and lower voltage limits, the voltage difference limit, and the slip frequency limit are within the allowable ranges. The algorithm for the calculation of the advance closure angle of the autosync relay is illustrated in Example 1.

This calculation is conducted continuously, but the signal to close the breaker will be given only when all of the criteria identified above are satisfied. Relatively slow breakers and/or high slip frequencies are conducive to larger advance closing angles.

It should be noted that certain modern, static autosync relays are capable of closing the breaker within ±0.5° of the predicted theoretical value for slips and breaker times typically found in the utility industry. An operator with a synchroscope, having the rest of the control room dynamics in front of him, would have great difficulty meeting that level of accuracy.

The operator's task is to examine the electrical parameters of voltage, frequency, and phase angle between the two sources as displayed by meters and the synchroscope. He is attempting to initiate a breaker closure on the rotating phase angle so that after the small time delay of the circuit breaker closing (typically 4–15 cycles), the phase angle will be at zero.

Attempting to perform this task, while simultaneously adjusting generator controls for voltage and frequency, is a complex task, and the opportunity for closing with a large phase angle difference is present. When larger machines are considered, the allowable margin for error decreases, and the proper closing of the breaker takes on greater significance.

Example 1:

GIVEN

Breaker Operating Time = 5 cycles: 5 cycles x $.0167 \frac{\text{sec}}{\text{cyc}}$ = 0.0835 sec

Slip Frequency = 0.1 Hz
Sync Check Relay Operation Time = 0.085 sec

CALCULATIONS

Theoretical Synchronization Advance Angle (AD):

$$AD = \left(360 \frac{\text{deg}}{\text{cyc}}\right)\left(\Delta f \frac{\text{cyc}}{\text{sec}}\right)\left(T_{CB} \frac{\text{sec}}{1}\right)$$

$$AD = 360(0.1)(0.0835)$$
$$AD = 3.01°$$

ABBREVIATIONS

AD = Theoretical Advance Angle
Δf = Slip Frequency
T_{CB} = Circuit Breaker Closing Time (available from the manufacturer)

Calculations for Autosync Relay Advance Angle Closure (1)

SYNC CHECK RELAY APPLICATION

Since the sync check relay is used for both manual and automatic schemes as a backup element, a review of its functions is in order. The sync check relay's main function is to verify that the phase angle is within the proper limits. A high quality static relay can offer permissive closing accuracy to within one degree of the setting. Another function often incorporated in the relay is voltage verification. This is the ability to verify that the voltages of the two sources are within certain gross limits. Some voltage verifiers can also substantiate that the voltage difference is within a desired amount. Figure 4 illustrates the operation of a sync check relay with voltage verification.

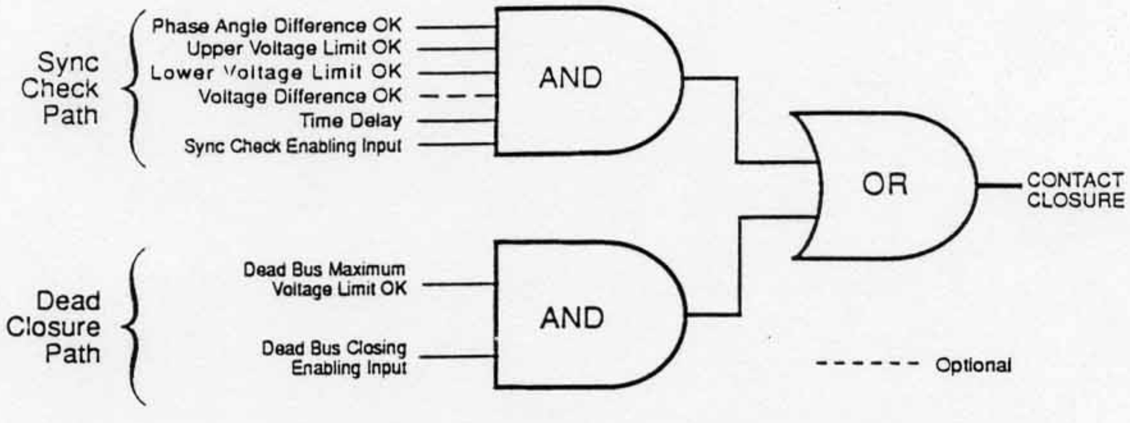


FIGURE 4 Sync Check Logic Drawing

Note that contact closure will result if all sync check or dead closure parameters are satisfied.

It should be noted that the angular setting is for both positive and negative angular values of the phase difference from 0°, and that relative slip (the generator frequency being faster or slower than the bus) is not a factor in the closure of the relay's contacts.

The setting which will establish the maximum allowable phase angle for circuit breaker closure is determined by calculating the theoretical advance angle at which the breaker should be closed with respect to the maximum allowable slip and breaker closing time. The operating time of the sync check relay should be known so that the delay caused by the relay is factored in. A safety factor of a few degrees should be added for tolerance and contact bounce. The operation is illustrated in Figure 5. Example 2 illustrates the calculations. The master control element for the synchronization will be either the autosync relay or the operator.

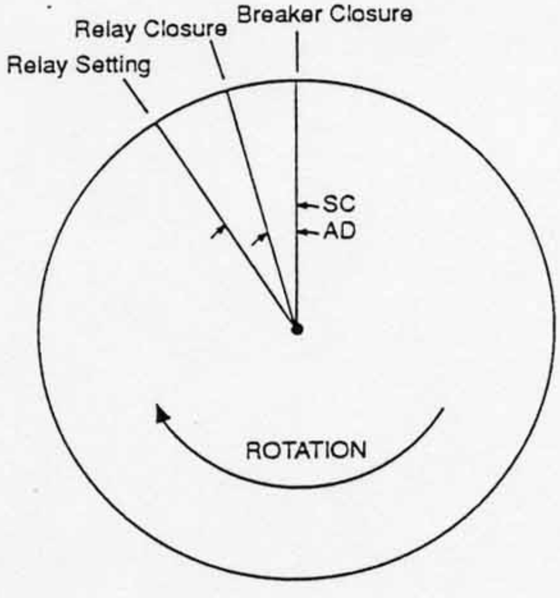


FIGURE 5 Sync Check Relay Operation with Slip Frequency Present

Example 2:

GIVEN

Autosync Theoretical Advance Angle (AD) = 3.01°

CALCULATIONS

Sync Check Backup Element Angle:

$SC = AD + [(360)(\Delta f)(T_{SCP})]$

$SC = 3.01 + [(360)(0.1)(0.085)]$

$SC = 3.01 + [3.06]$

$SC = 6.07° \cong 6°$

ABBREVIATIONS

AD = Theoretical Advance Angle

Δf = Slip Frequency

SC = Sync Check Relay Angle Setting

T_{SCP} = Sync Check Relay Propagation Time (This is inherent to the relay and varies from manufacturer to manufacturer.)

Calculations for Sync Check Relay Phase Angle Setting (2)

REDUNDANCY AND THE OPERATOR WINDOW CONCEPT

Redundancy involves the use of relays with their output contacts wired in series. This increases security against an improper closure of a circuit breaker when acceptable synchronous conditions do not exist.

The sync check relay, acting as a backup to either an autosync relay or an operator, offers two layers of redundancy to protect rotating machinery against out-of-phase closings. However, an even higher level of redundancy is available for the most critical applications. It is known as an "operator window" on autosync relays that are equipped with this feature.

With the operator window feature, the sync check relay, autosync relay, and operator are all involved in closing the breaker at the proper moment. The sync check relay and operator act as backup elements, while the autosync relay is the master control element. Operation of the sync check relay for this scheme is as previously described.

The autosync relay's enabling circuit requires a dry-contact input from the operator within a certain adjustable angle before 0° phase angle in order to execute the synchronization. The operator's control switch has an additional contact in the closing elementary diagram. If the operator does not close the contact within the acceptable angular dwell, or does not close it at all, the autosync relay is not enabled to initiate a closure. The elementary diagram is illustrated in Figure 6 and the scope angle/contact relationship in Figure 9b.

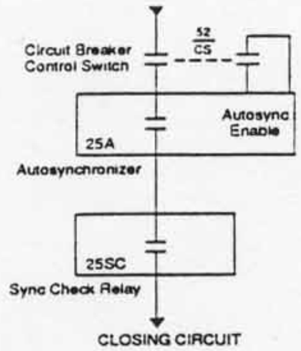


FIGURE 6 Elementary Diagram of Operator Window

Figure 7 depicts the failure analysis logic diagrams. Using the operator window feature offers a two-out-of-three-element redundancy. If any two elements fail (close improperly) due to a welded contact, relay malfunction, human error, etc., the remaining element will prevent an undesirable out-of-phase closing.

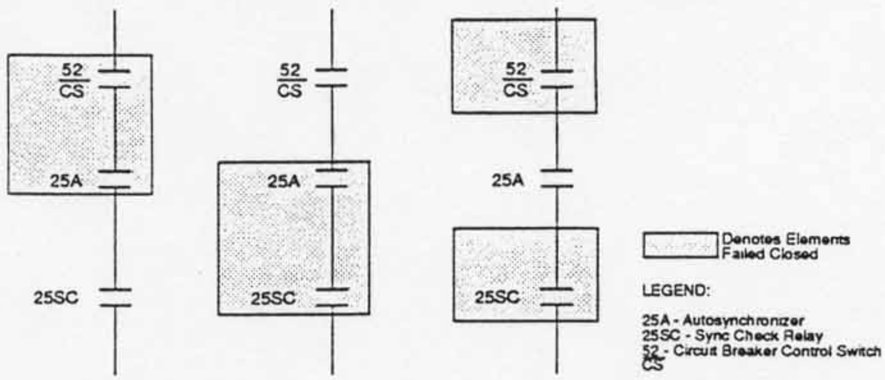


FIGURE 7 Fail-safe Analysis of Autosync/Operator/Sync Check in Series (Autosync Equipped with Operator Window Feature)

A common misunderstanding of the operator window concept is using an autosync relay not equipped with the enabling circuitry discussed above, in series with an operator contact as shown in Figure 8. The result is a timing battle between two master control elements. Both the autosync relay and the operator are independent master control elements attempting to initiate a closure of the breaker at the theoretical advance angle. This arrangement may be detrimental if the operator closes late. Autosync relays usually have a pulse output of some small finite time (500 ms) to allow seal-in relays to accomplish their task in the breaker, but the autosync relay contact will be closed and the resulting breaker closure will be late (as shown in Figure 9a). The operator window function described above (and shown in Figure 9b) would prevent the late closure by the operator from delaying the breaker closing. The operator is forced to close his contact prior to the autosync relay contact closure.

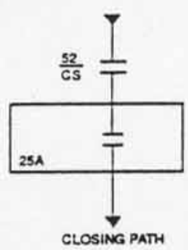
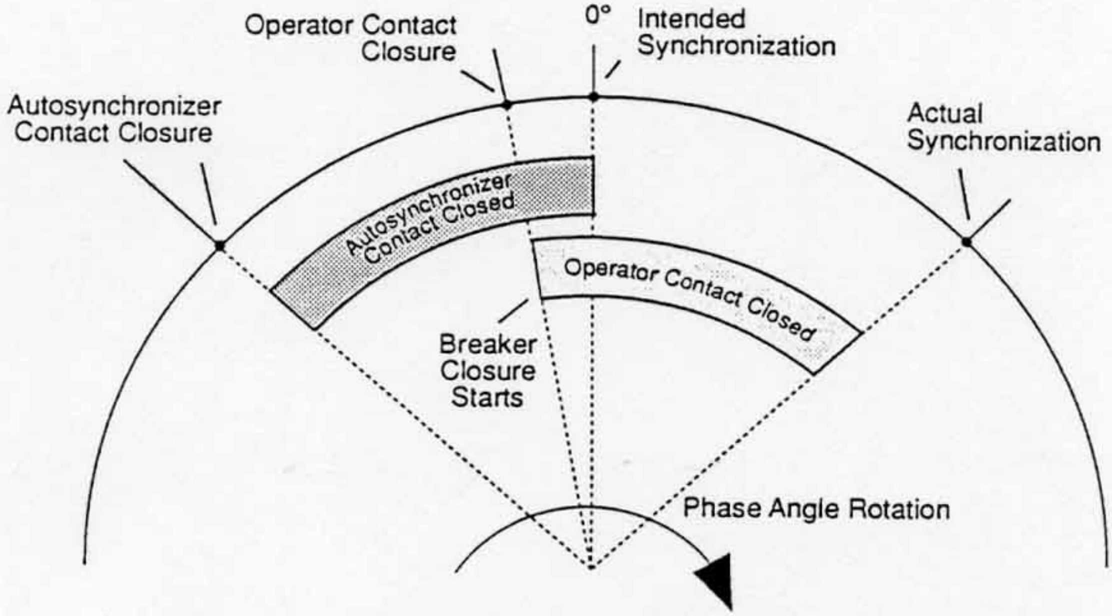
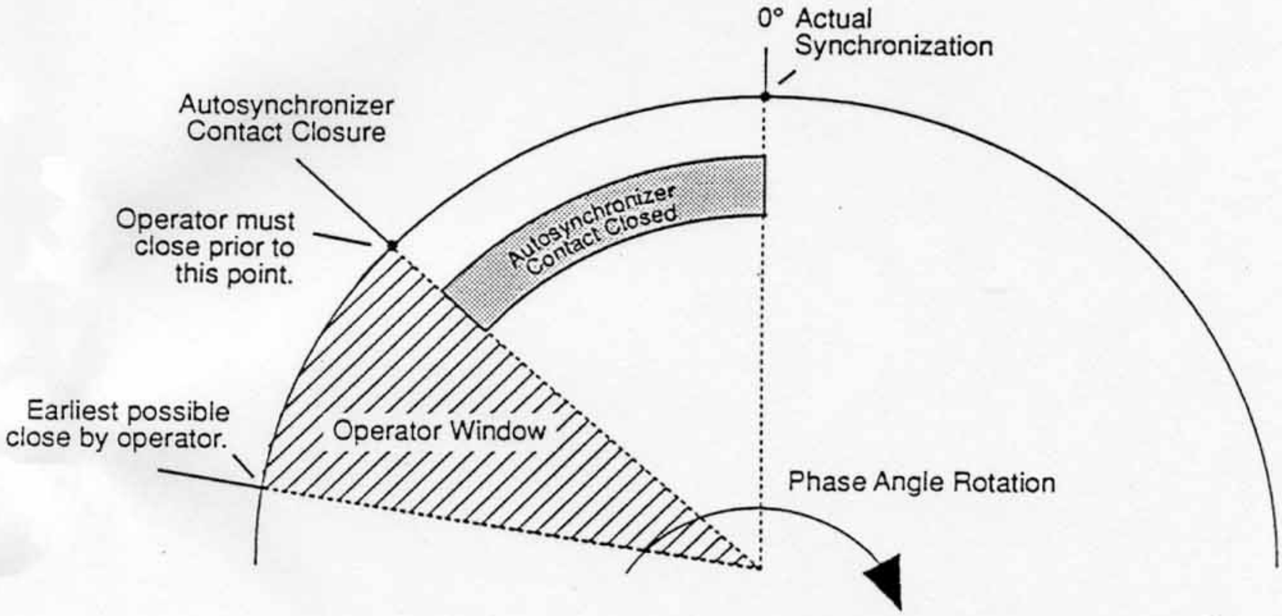


FIGURE 8 Elementary Diagram of Autosync/Operator in Series (Autosync Not Equipped with Operator Window Feature)



a. Autosync Relay in Series with Operator



b. Autosync Relay with Operator Window Feature

FIGURE 9 Scope Angle/Contact Relationships

TIE LINE SYNCHRONIZING

The restoration of separated ties can present one of three conditions: synchronous, asynchronous, or "black" (one line is energized; the other line is not).

Closure to a black source is accomplished via the hot line/dead bus feature of a sync check relay, or through the use of auxiliary undervoltage relays. This involves a simple control scheme involving interlocks and possibly SCADA permissives.

Restoration of synchronous ties involves the verification of an acceptable phase angle, which may vary due to impedance of the other ties and load on those ties. The angle is usually small for tightly tied systems but can widen considerably for long, single ties.

Asynchronous ties refer to independent systems operating at nominally the same frequency. The accurate synchronization of this system is more difficult as it must be expected that a slip will exist between the systems.

STATIC TIES

Synchronism is verified through the use of a sync check relay which examines the parameters of phase angle, time, and voltage. When a sync check relay is used for generator and tie line synchronizing, the use of phase angle limit coupled with a time duration yields an indirect measurement of a maximum slip frequency. The relationship is illustrated in Example 3 below.

Example 3:

GIVEN

Largest Allowable Static Angle = $\varnothing_{max} = 20°$
Maximum Allowable Slip Frequency = $\Delta f = 0.03$ Hz

CALCULATION

$\varnothing_{max} = 360\,\Delta f\,T$

$$T = \frac{\varnothing_{max}}{360\,\Delta f}$$

but $\varnothing_{max}$ must be multiplied by two because of plus or minus phase angle acceptance of a sync check relay, therefore

$$T = \frac{2\varnothing_{max}}{360\Delta f} \qquad T = \frac{2(20)}{360(.03)} \qquad T = 3.7 \text{ sec}$$

A phase angle of 20 degrees with a 3.7 second time delay will allow closure at a slip with a maximum slip frequency of 0.03 Hz.

Calculations for Phase Angle/Time = Slip (3)

The reason for the indirect slip measurement is to ensure the system is synchronously tied. If a tie exists, the phase angle across the open breaker will be essentially static in the time frame of interest; if a tie does not exist, the phase angle will rotate. Therefore, the sync check relay is able to determine whether the phase angle is static or rotating, and enact a breaker closure on a static phase angle.

ISLANDED SYSTEMS

When ties between two sources of generation are open, the systems operate asynchronously and are now said to be "islanded" from each other. Load will either be rejected or accepted by the individual islands based on the power interchange situation prior to the separation. Therefore, a slip frequency will develop between the islands compounding the restoration problem.

Restoration of islanded systems involves the proper indexing of the power circuit breaker closure in much the same manner as generator-to-grid synchronizing. When no ties exist between the systems, the phase angle across the open breaker will rotate.

To properly close a breaker across which the phase of the voltage is rotating, an autosync relay is used. The autosync relay will verify the slip frequency limit and voltage limits, and perform the closing of the breaker with respect to phase angle/breaker time/slip relationship so that the breaker closes at nearly 0° voltage phase angle. The calculation for the advance angle required to ensure breaker closure at 0° closing angle is illustrated in Example 4 below.

Example 4:

GIVEN

Circuit Breaker Operating Time = (4 cycles) = 0.0667 sec
Maximum Slip Frequency = 0.08 Hz

CALCULATIONS OF MAXIMUM ADVANCE ANGLE

$$AD = \left(360\frac{deg}{cyc}\right)\left(\Delta f\frac{cyc}{sec}\right)\left(T_{CB}\frac{sec}{1}\right)$$

$$AD = (360)(.08)(.0667)$$

$$AD = 1.92^\circ \text{ (maximum)}$$

where, as in Example 1, AD = Theoretical Advance Angle

Calculations for Rotating Phase Angle for Islanded Systems (4)

RESTORATION SYSTEM DEVELOPMENT

When contingencies are known for the condition(s) that can develop around an open breaker, the proper synchronizing relay types can be selected. The functions for the relays are indicated in Table 1.

RESTORATION TYPE	RELAYS
Black	Sync Check relay with voltage verifier or auxiliary undervoltage relays(s)
Synchronous tie or Black	Sync Check relay with voltage verifier
Islanded systems	Automatic Synchronizer
Islanded systems or Black	Automatic Synchronizer and Sync Check relay with voltage verifier or auxiliary undervoltage relay(s)
Synchronous tie or Islanded systems, and Black	Sync Check relay with voltage verifier and Automatic Synchronizer

TABLE 1 Types of System Restoration

For a synchronous tie or islanded system restoration, the sync check relay and autosync relay are arranged in parallel as shown in Figure 10.

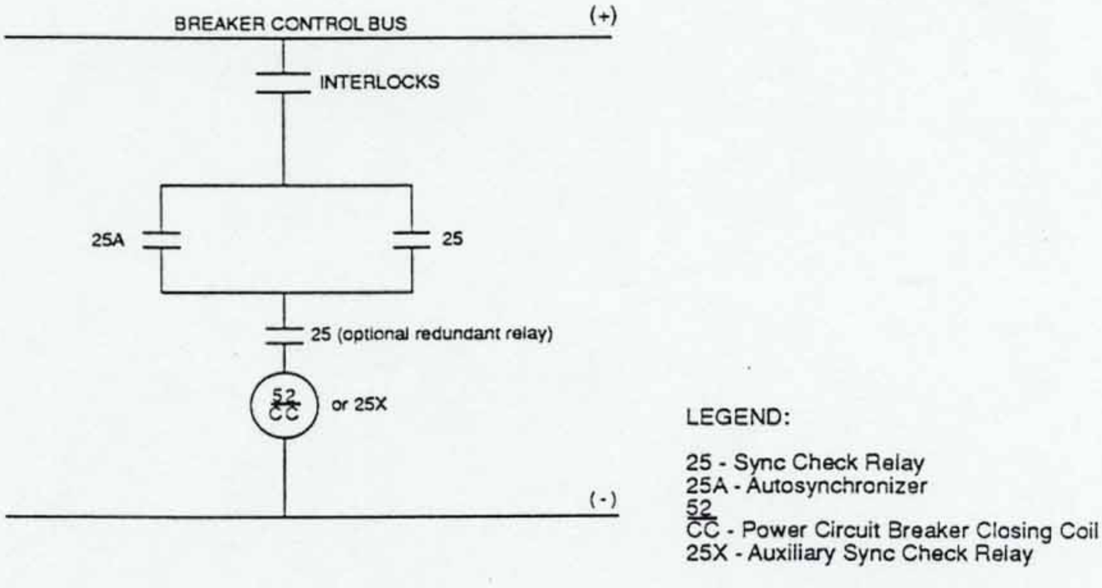


FIGURE 10 Elementary Diagram of Parallel Scheme

With this arrangement, the autosync relay will perform the breaker closing for rotating phase angle conditions (islanding) and the sync check relay will perform the closing for either synchronous conditions (tie elsewhere in the network) or black conditions.

The setting of these two relays must be coordinated so that the breaker closure process is handled by the proper relay. The required selection criteria involves the calculation of the largest expected phase angle across the breaker if the angle is static (network tie) and the highest allowable slip frequency, coupled with the breaker closing time, if a rotating phase angle exists (islanded system). From these, the largest angle is selected and set on the relay.

A high quality static autosync relay can close on slip frequencies as low as 0.0005 Hz. If a low enough slip between islanded systems is encountered, the sync check relay would close if a short time delay setting were being used.

Crossover Frequency

The slip frequency where both the sync check and autosync relays would simultaneously close is referred to as the "crossover frequency."

The crossover frequency equation compares the slip frequency/time relationship and subtracts it from the angular setting of the sync check relay, simultaneously solving the autosync relay advance angle. This relationship is shown in Example 5 below. The sync check relay portion is on the left side of the equation; the autosync relay portion is on the right.

Example 5:

GIVEN

Autosync Settings:

Circuit Breaker Operating Time = 4 cycles = 0.0667 sec
Maximum Slip Frequency = 0.08 Hz

Sync Check Settings:

Largest Allowable Static Angle = 20°
Time Setting = 3.7 sec
(This yields a maximum allowable slip of 0.03 Hz, as was illustrated in Example 3.)

CALCULATIONS

$$AD = AD$$
$$SC - (360\, \Delta f\, T_{SCP}) = 360\, \Delta f\, T_{CB}$$
$$SC = 360\, \Delta f (T_{CB} + T_{SCP})$$
$$\Delta f = \frac{SC}{360(T_{CB} + T_{SCP})}$$
$$\Delta f = \frac{20}{360(.0667 + 3.7)} = 0.0148 \text{ Hz}$$

0.0148 Hz is the crossover slip frequency where both the sync check and autosync relays would function simultaneously.

Calculations for Crossover Frequency (5)

With a slip setting on the autosync relay of 0.08 Hz, the autosync relay would have had an opportunity to close the breaker as the Automatic Generator Control (AGC) between the two systems adjusted the individual system frequencies closer. The autosync relay would close the breaker on the first available slip cycle at or below a slip frequency of 0.08 Hz. At slip frequencies below 0.0148 Hz, the sync check relay will close before the autosync relay closes.

The synchronizing system can exercise a backup sync check relay in the same manner one is used to backup a generator synchronizing scheme. The sync check relay applied as a backup element would be placed in series with the lone autosync relay, the lone sync check relay, or the parallel combination of the two relays.

The backup sync check relay would be set to reflect the greater of either the largest expected static phase angle or the calculated advance angle (based on the autosync relay calculation). The setting calculation is depicted in Example 6 below.

Example 6:

<u>GIVEN</u>

Autosync Settings:
Circuit Breaker Operating Time = 10 cycles = .1667 sec
Maximum Slip Frequency = 0.1 Hz

Static Sync Check Setting
Largest Allowable Static Angle = 15°

<u>CALCULATIONS</u>

Automatic	$AD = 360\ \Delta f\ T_{CB}$
Synchronizer	$AD = 360(0.1)(0.0167)$
	$AD = 6.0°$
Sync Check	$SC = 15°$
Backup	BU = AD or SC, whichever is greater

.Tolerances for the applied relays should be factored in, and accommodated for, in the final setting.

Calculations for Sync Check as a Backup Element (6)

SUBSTATION SYNCHRONIZING EXAMPLES

For generation plants tying into complex substations, any of the restoration types may be present — depending on the station configuration and status of the circuit breakers. Typical synchronizing arrangements and the appropriate synchronization techniques are illustrated in Table 1. Two complex bus arrangements and typical breaker closure progressions are illustrated in Figures 11 and 12.