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Relay Supervision of Manual Synchronizing

RELAY SUPERVISION OF MANUAL SYNCHRONIZING

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GENERAL

In some applications where automatic synchronizing is not required, it may be desirable to have the operator perform the synchronizing manually but still have his command to close the synchronizing breaker supervised by an automatic synchronizing device. Thus, if both the operator and the automatic device are in agreement to close, the breaker is permitted to close. On the other hand, if there is a disagreement between them no closing will take place and another "pass" must be made.

There are a number of different ways to accomplish this function and this paper covers those that are considered to be the simplest and most promising.

PRINCIPLE OF OPERATION OF SCHEME

The operating principle of the scheme is quite simple. The basic device is a GXS synchronizing relay that has a fixed angle closing characteristic. The GXS "looks" at the running and incoming voltages and if the slip (difference in frequency) between the two is less than a preset amount, the relay will produce an output at a preset fixed angle in advance of the in-phase condition, that is, regardless of the breaker closing speed and the slip (as long as the latter is less than the preset amount) the relay will produce an output at the preset fixed angle in advance of the in-phase condition.

The over-all scheme requires that the GXS operate to provide an output (contact closure), and within a short time later that the operator close his control switch. If the operator closes his control switch too soon before or too long after the GXS operates, no synchronizing will take place. The operator must then release his switch and try again the next time around. The basic schemes will function regardless of whether the machine to be synchronized is above or below synchronous speed. However, modified schemes are available which will permit synchronizing only if the machine is faster than the system or, by reconnection, slower than the system.

Complete descriptions of the schemes as well as a discussion of settings will be presented after the operating characteristics of the GXS relay are covered.

OPERATING PRINCIPLES OF GXS

The GXS relay is made up of three basic units: an instantaneous cup-type unit, a time delay disk-type unit and a telephone-type auxiliary unit. The interconnections between the contacts of these units are so arranged that a specific sequence of operation is necessary to initiate closing of the output contacts, as shown in Fig. 8.

If we consider a power system in operation with a machine being made ready for synchronizing onto the power system, the system voltages may be considered as three balanced voltage vectors rotating at speed W_s in a positive sequence direction (counterclockwise) as shown in Fig. 1. The machine voltages may be similarly assumed, except at some other speed W_m (Fig. 2).

Since these voltages are balanced, it is only necessary to compare one phase of the system voltage to the same phase of the machine voltage. Any phase-to-neutral or phase-to-phase voltage may be selected just as long as it is the same on the system as on the machine. The GXS relay measures the phase angle difference and the difference in electrical speeds between the system and the machine. Thus, since we are interested in the difference between quantities, we can assume the system vectors to be standing still and the machine vectors to be rotating relative to the "fixed" system. Assuming that the phase 1-to-neutral voltage is used, Fig. 3 illustrates that for a machine which is fast compared to the system, the incoming machine vector V_i rotates in a counterclockwise direction relative to the fixed system running vector V_r. For a slow machine the incoming vector rotates in a clockwise direction.

Before discussing the over-all relay it would be well to consider the operation of the individual units. The time-delay induction disk unit receives single-phase voltages from the same phase on both sides of the breaker. There are two electromagnets in

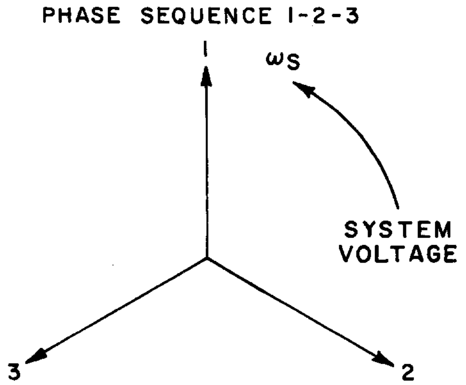


Fig. 1. System voltages: three balanced voltage vectors rotating at speed W_s in a positive sequence direction

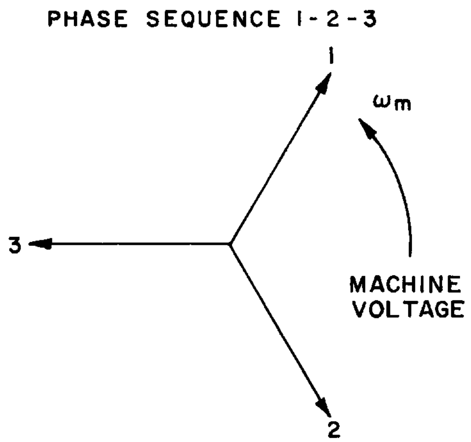


Fig. 2. Machine voltages: three balanced voltage vectors rotating at speed W_m in a positive sequence direction

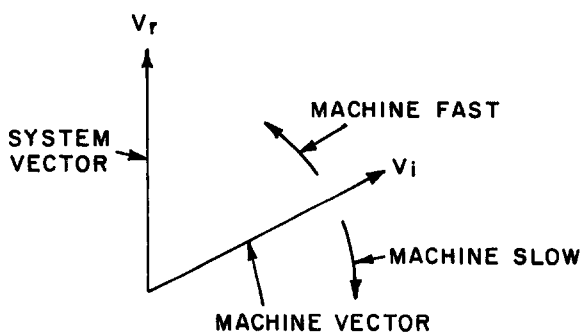


Fig. 3. Result of a frequency difference: V_i rotates with respect to V_r.

the unit, and each electromagnet has two coils. In the first, or operating electromagnet, the coils are connected in such a way that they produce a flux proportional to the vector sum of the two voltages (incoming V_i and running V_r). This electromagnet produces a torque on the disk in the direction to close the contacts of the unit. This operating torque is proportional to the square of the vector sum of the two voltages as indicated in equation (1).

$$T_o = K_o (V_i + V_r)^2 \quad (1)$$

where K_o is a design constant.

In the second, or restraining, electromagnet, the coils are connected in such a way that they produce a flux proportional to the vector difference of the incoming and running voltages from the same phase. This electromagnet acts on the same disk as the operating magnet but it produces torque in the opposite, or restraining, direction. That is, it develops torque that tends to hold the contacts open. This restraining torque is proportional to the square of the vector difference of the two voltages as given by equation (2).

$$T_r = K_r (V_i - V_r)^2 \quad (2)$$

where K_r = a design constant.

In addition to the electrical torques in the unit there is also a mechanical restraint in the form of the control spring (K_s). Thus, the net torque (T) in the unit is the result of all three.

$$T = K_o (V_i + V_r)^2 - K_r (V_i - V_r)^2 - K_s \quad (3)$$

Assuming that K_s is negligible, it should be noted that with equal voltages on the running and incoming busses, ($V_i + V_r$) will be equal to ($V_i - V_r$) when V_i and V_r are 90 degrees apart. As the two voltages approach each other in phase angle, ($V_i + V_r$) will increase and ($V_i - V_r$) will decrease. Thus, the net operating torque increases as the two systems are more in phase with each other. Whether the net torque is in the operating direction ($T>0$) or in the restraining direction ($T<0$), will also depend on the relative magnitudes of K_o and K_r. In the case of all the GXS relays, K_r is designed to be greater than K_o so that the net torque goes from restraining to operating at some angular separation that is smaller than 90 degrees. This angle is called the operating angle. The operating angle of the disk unit in the GXS relay described in this paper is about 85 degrees as shown in Fig. 4.

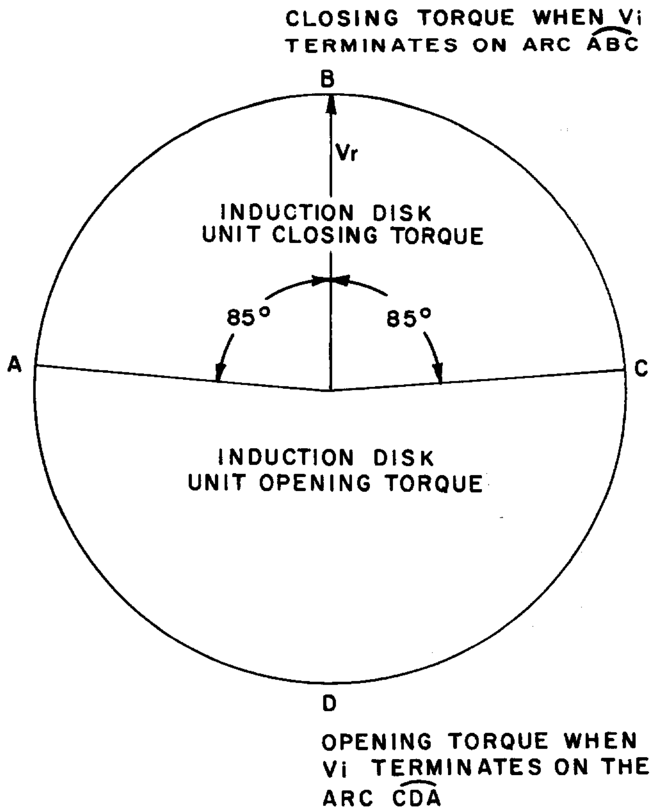


Fig. 4. Time delay disk unit

The length of time required to close the normally open contacts will depend on the time dial setting and the angle between the two voltages. It will take longer for larger time dials and it will take longer for greater separation between voltages. In actual operation, the angle between the machine voltage and system voltage is constantly changing. For this reason, with any given time dial setting the closing time of the induction disk unit will depend on the difference in speed between the two systems. However, if there is too great a difference between the machine speed and the system speed, the induction disk unit will not have sufficient time to close its contacts at all. Thus, the induction disk unit-limits the maximum difference in speeds for which the GXS will permit closing of the breaker. Thus, it fixes the cut-off frequency difference. A larger time dial setting requires a lower slip before the unit will close its contacts. Thus, the larger the time dial setting the lower the cut-off frequency difference.

The instantaneous induction cup unit of the GXS, like the disk unit, is connected to receive both the running and incoming voltages. This unit develops electrical torque (T_e) as given by the following equation:

$$T_e = K V_i V_r \sin \phi \qquad (4)$$

where:

K = a design constant

V_i = magnitude of incoming voltage

V_r = magnitude of running voltage

ϕ = angle by which V_r leads V_i.

Thus, for a condition where V_r leads V_i by 30 degrees, the electrical torque developed is

$$T_e = 0.5 K V_i V_r$$

If, on the other hand, V_r lags V_i by the same 30 degrees, the magnitude of the electrical torque will be the same as before, but it will be negative because ϕ is now -30 degrees.

$$T_e = -0.5 K V_i V_r$$

When the torque T_e is positive, the cup tends to rotate in one direction; if it is negative, the cup tends to rotate in the opposite direction. Thus, the magnitude of the torque developed at rated voltage will be proportional to the sine of the angular separation of the two voltages, but the direction of the torque will depend on which voltage is leading.

Because it is necessary for the cup unit to operate at the proper angle regardless of which voltage is leading, the contact assembly shown in Fig. 5 was developed. As will be noted, the cup shaft is fastened to the lever arm plate so that they rotate together. The lever arms are both fastened to the lever arm plate and move with it so that, regardless of the direction in which the cup rotates, either one or the other lever arm applies torque to the moving contact arm in the direction to close the normally open (a) contact. The spacing of these lever arms relative to the contact arm pivot and the cup shaft is such that for a given magnitude of torque on the cup, equal torque is transmitted to the moving contact arm regardless of the direction of rotation.

A spring with adjustable tension is provided against which the electrical torque on the cup must operate to open the normally closed (b) contact and close the normally open (a) contact. Thus, the balance point (or operating point) of the cup unit occurs when the electrical torque (T_e) on the cup is equal to the mechanical torque of the spring (K_s). Rewriting equation (4), the cup unit operates when

$$K_s = K V_i V_r \sin \phi \qquad (5)$$

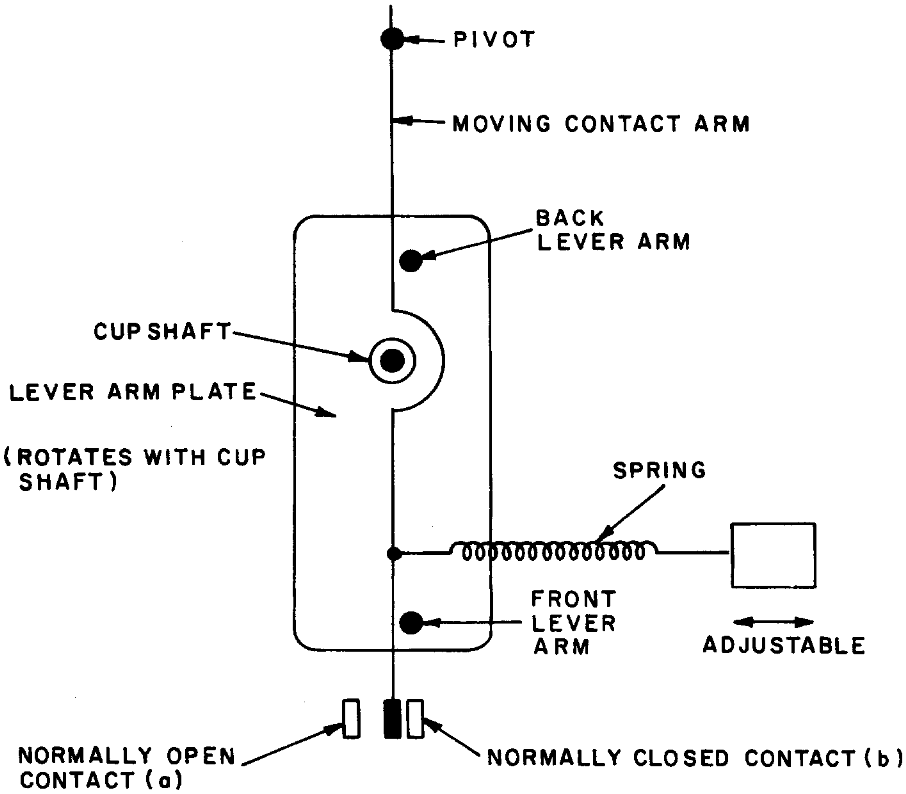


Fig. 5. Contact assembly arrangement

It is obvious from this equation that at rated voltage the angle (ϕ) between V_i and V_r for which the cup unit operates will be directly related to the spring setting. Thus, the desired operating angle of this unit is set by the spring tension.

Consider, for example, that K_s is set for a 30-degree operating angle. This means that the normally closed contact (b) will be closed and the normally open contact (a) will be open whenever V_i is within plus or minus 30 degrees of V_r. It also means that the same will be true whenever V_i leads or lags V_r by any angle between 150 and 210 degrees. This is illustrated in Fig. 6 and it comes about because

$$\sin \phi = \sin (180^\circ - \phi)$$

Figure 7 is a composite of Figs. 4 and 6. It indicates that the normally open contact of the disk unit and the normally closed contact of the cup unit are concurrently closed only in the range where V_i leads or lags V_r by 30 degrees or by whatever is the drop-out setting of the cup unit in the available range of 10 to 30 degrees. In this sense, the disk unit acts as a "directional" unit to block closing in the area of arc GDH as well as providing the slip cut-off function.

At this point it should be explained that the GXS relay gives permission to close when the angle between the two applied voltages V_i and V_r is within the setting of the cup unit. For this condition the disk unit is picked up and its contacts are closed, but the cup unit is in its reset position, and its normally closed contact, in series with the disk unit contact in the closing circuit, permits closing of the breaker.

It should be recognized from equation (5) that the calibration of the instantaneous cup unit is dependent on the applied voltages. For example, if the spring (K_s) is set with rated voltages applied so that the unit resets at 30 degrees, and then one of the applied voltages drops by 10 percent, the sine of the reset angle must increase by 10 percent. Thus, the reset angle ϕ will increase to 33.4 degrees. In other words, the angle at which the relay will permit closing will increase as the applied voltage decreases and vice versa.

The effects of voltage variations on the operating angle of the disk unit are only slight. The reason for this may be noted from equation (3). Since the balance point (T = 0) of this unit is about 85 degrees, K_r is only slightly greater than K_o. (Note that for a balance point of 90 degrees K_o must equal K_r since the vector difference between two voltages

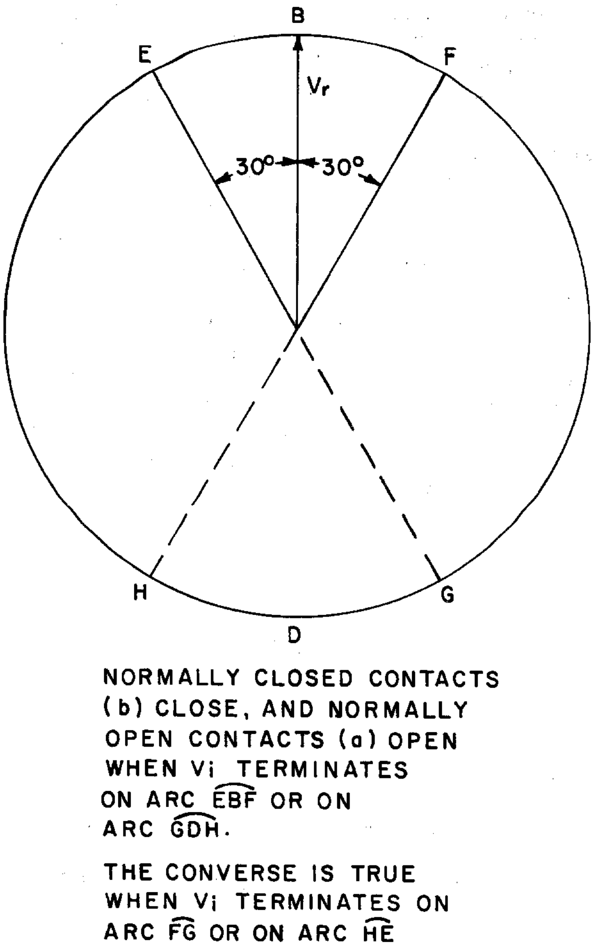


Fig. 6. Instantaneous cup unit

at that angle is equal to the vector sum.) Under such conditions, moderate variations in the magnitude of one or both voltages will have very little effect on the operating angle of this unit. However, variations in the applied voltage will affect the operating time somewhat. Higher voltages will make the disk move faster. Lower voltages will make it move slower.

As noted earlier, the GXS relay also includes a dc auxiliary unit which provides a lockout feature. It picks up immediately when energized and drops out immediately when de-energized.

OVER-ALL OPERATION OF THE GXS RELAY

Figure 7 is a superposition of Fig. 6 on Fig. 4. It illustrates the action of the time delay disk and instantaneous cup units as they are coordinated by the auxiliary unit. Figure 8 shows the external dc connections to the GXS relay.

Referring to Figs. 7 and 8, which illustrate how the GXS11B is used as a synchronizing relay, assume first that the machine is running slow compared to the system. Thus, V_i is rotating in a clockwise direction. For the position shown, the time delay contact T is open while the instantaneous contact I(a) is closed and I(b) is open so that the auxiliary unit X is de-energized. When V_i movig in a clockwise direction reaches point A, the time delay unit starts picking up. If V_i is moving slowly enough, the contacts T will close sometime before V_i reaches point E. If this occurs, auxiliary X will pick up and seal-in around the I(a) contact. When V_i passes point E, I(a) opens and I(b) closes and a closing impulse is sent to the breaker. After the breaker closes, 52/b opens and the d-c circuits are automatically reset. It should be noted that the fact that contact I(a) opens and I(b) closes as V_i passes through arc GDH is incidental and does not affect the operation of the scheme. If V_i moves so fast that the T contacts do not close until V_i reaches,

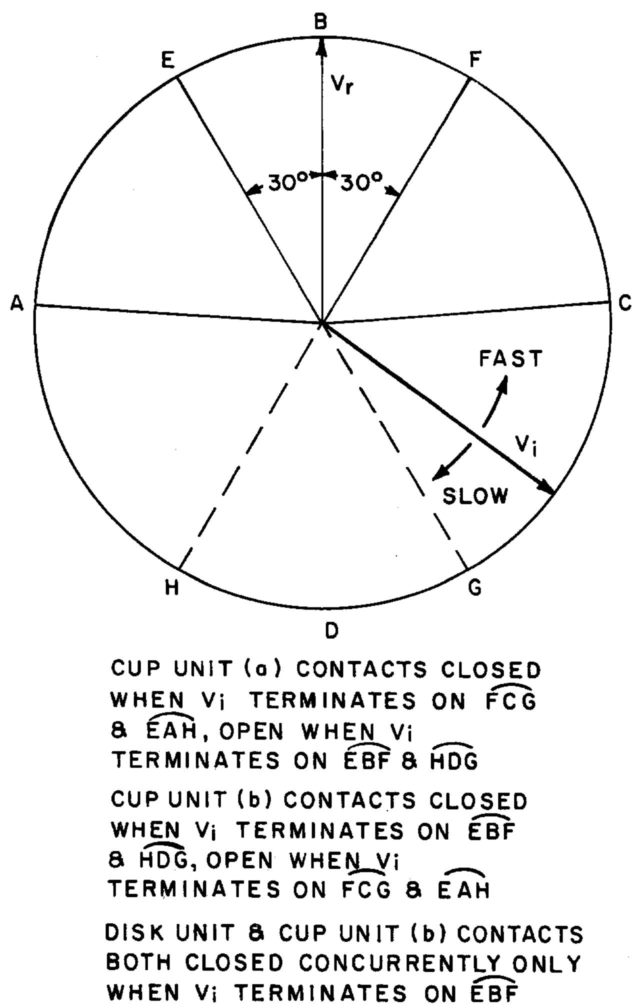


Fig. 7. Composite of cup and disk units

say, some point between E and F, then contacts I(a) will open before contacts T get closed, the X relay would not pick up and there would be no closing impulse until the speed of the machine is brought closer to that of the system. If the machine were running fast (rather than slow) compared to the system, V_i would rotate in a counterclockwise direction and the same operation would result except that the closing impulse would be given as V_i passed F.

Since this scheme requires a proper sequence of operations it will not provide a closing output if V_r and V_i are already in synchronism when the equipment is switched on. There has to be at least a slight difference in frequency between the incoming machine and the running system.

It is important to recognize that the closing impulse out of the relay is given at a fixed angle. This angle is the setting of the instantaneous cup unit, and depending on the speed of the machine relative to the system, the impulse may be given as V_i passes point E or point F. If the speed at which V_i rotates, relative to V_r, is greater than the cut-off frequency, no closing impulse will be given. If the speed at which V_i rotates, relative to V_r, is smaller than the cut-off frequency, the closing impulse will still be given either at point E or point F.

The above discussion points up the fact that the GXS relay will prevent closing if the speed difference is too great and that it will permit closing if the speed difference is not too great. Because the disk unit contact (25/T) must close before the instantaneous cup unit contact 25/I(a) opens in order to get a relay output, the closing angle setting of the instantaneous cup unit will have some effect on the cut-off frequency. The curves of Fig. 17 give the cut-off slip as a function of both the instantaneous unit closing angle setting and the time delay disc unit time dial setting. For example, a cut-off setting of 0.10 slip cycles per second with a closing angle setting of 10 degrees would require a time dial setting of 7.2. With such a setting the relay will provide a closing output signal when the incoming machine gets to within 10 degrees of the in-phase position and the slip has been at 0.10 or less. The closing output will be maintained until the machine moves outside the 10 degree limit.

OPERATION OF DIFFERENT SCHEMES

As noted previously, this paper covers several schemes. They are enumerated below.

Scheme 1A

The external connections for this scheme are illustrated in Fig. 9, which shows the use of an auxiliary NGA15A relay in addition to the GXS11B.

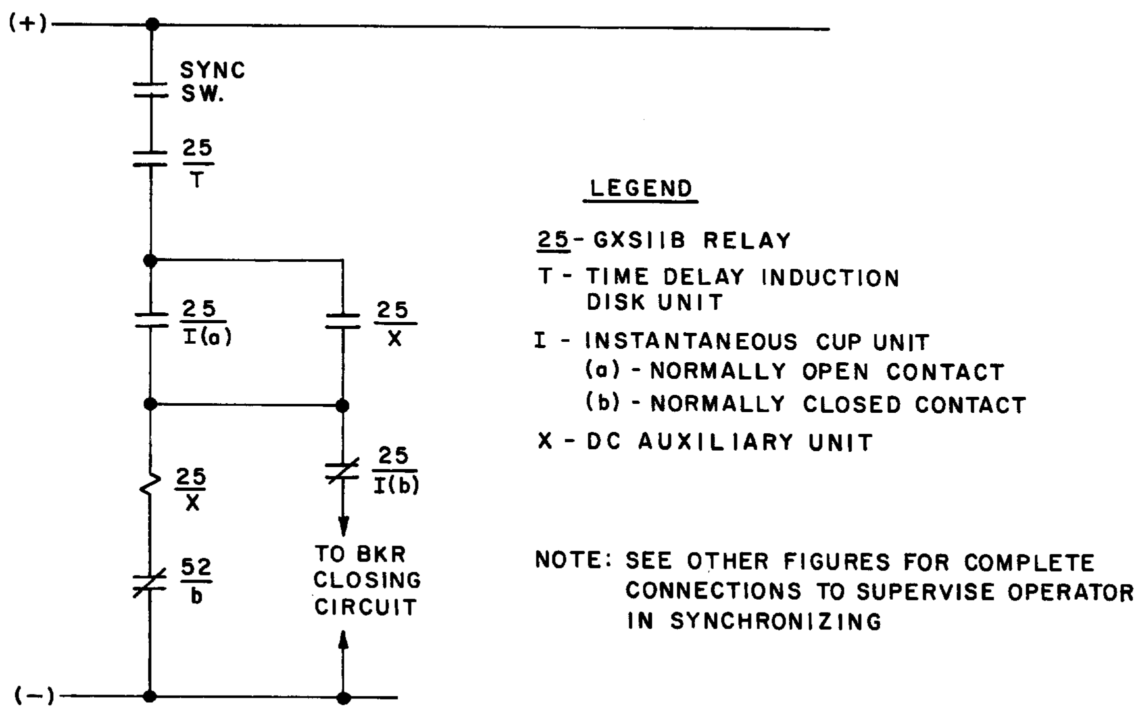
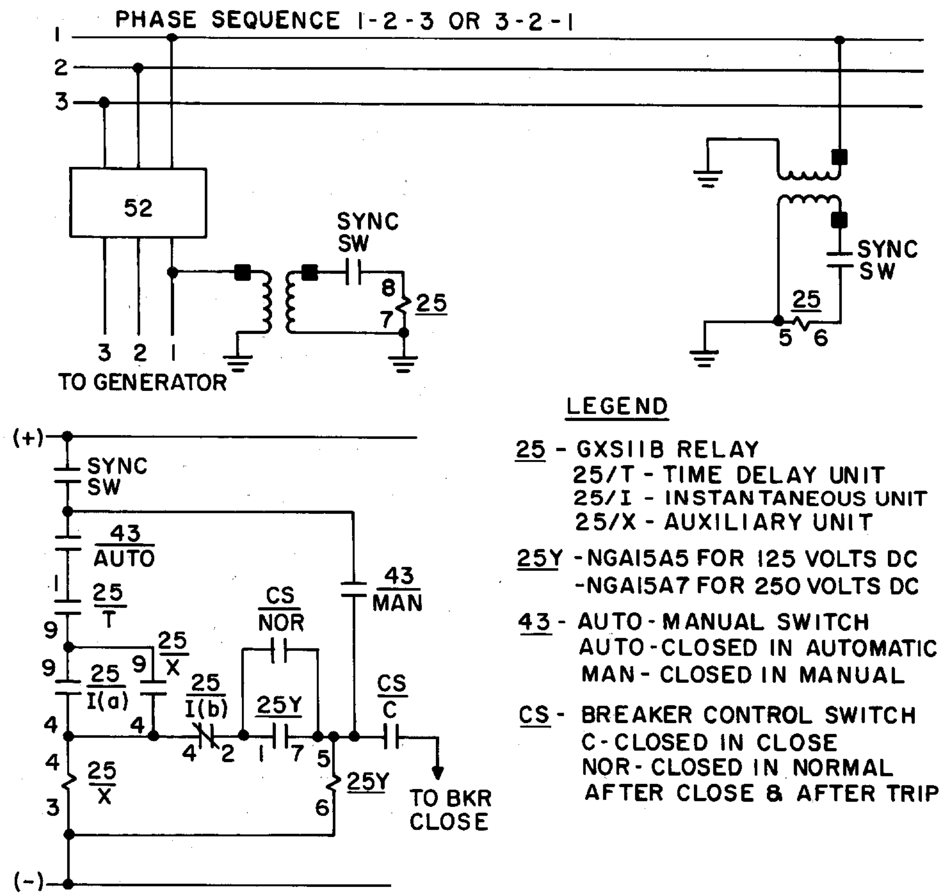


Fig. 8. Dc connections illustrating the operation of the GXS11B when employed as a synchronizing relay



SCHEME 1A

Fig. 9. External connections for GXS11B to supervise the operator when synchronizing a generator onto a system (KW041669A)

The scheme also includes an AUTOMATIC-MANUAL switch. The purpose of this switch, which is not essential to the scheme, is to provide a convenient means for unsupervised (MANUAL) operation if this becomes necessary for any reason. A key lock or removable handle switch would be desirable to prevent inadvertent operation without supervision.

With the 43 device in the AUTO position and the synchronizing switch closed the GXS is ready to function. If the slip is slow enough, the 25/X auxiliary will pick up and seal in around 25/I(a). When the incoming generator reaches the set closing angle of the GXS, contact 25/I(b) will close. This will pick up device 25Y through the normally closed (CS/NOR) contact of the control switch, and if the control switch CS/C is then closed, a closing impulse will be given to the breaker. Note that had the control switch been operated to the CLOSE position prior to the closing of 25/I(b), CS/NOR would have been open and 25Y would not pick-up to permit closing the breaker. With this arrangement the operator cannot hold the control switch in the CLOSE position and wait for the GXS to synchronize the machine on to the system. But rather the GXS must operate first and then CS must be operated before the GXS resets.

It should be recognized that this scheme permits the operator to initiate a closing impulse to the breaker at any instant during the time that the incoming generator is within the closing angle setting of the GXS relay. The breaker will actually close some short time later depending on its closing speed. Thus, in the limit, it is possible for the operator to initiate closing just as the machine gets to within the closing angle or just as it leaves it on the way out the other side. In the former case, with a very slow actual slip, this could result in the breaker getting closed in advance of the in-phase position by an amount only slightly less than the closing angle setting of the GXS. Or in the latter case, with an actual slip equal to the cut-off slip setting of the relay, the breaker could get closed beyond the in-phase position by an amount equal to the closing angle setting of the relay plus the additional travel of the machine after the closing impulse is given and prior to the breaker poles closing. This additional travel (θ) could be as much as

$$\theta = t\,(360)s \text{ degrees}$$

where:

t = closing time of breaker in seconds

s = cut-off slip setting of GXS in cycles per second

For the settings assumed above (10 degree closing angle, and 0.10 slip cycles per second) and a breaker with a 0.30 second closing time, this scheme would permit a range of actual closing angles from 10 degrees in advance to 20.8 degrees beyond the in-phase position. It should be recognized that these boundaries represent the limits of the error permitted the operator in the event that he makes a mistake.

Scheme 1B

The external connections for this scheme are illustrated in Fig. 10. While this scheme is functionally equivalent to scheme 1A it does require one additional auxiliary NGA15A relay but the control switch normally closed (CS/NOR) contact is eliminated. Thus, scheme 1B would be considered in place of scheme 1A when a normally closed contact (CS/NOR) on the control switch is not available.

In this scheme the operation of the GXS relay is the same as in scheme 1A. Here again, if the operator places the control switch in the close position before 25/I(b) contact closes, no breaker closing will take place. However, in this scheme this function is obtained differently. If CS/C is closed prematurely, device 25Z will be energized before 25/I(b) gets closed. This will open 25Z contacts

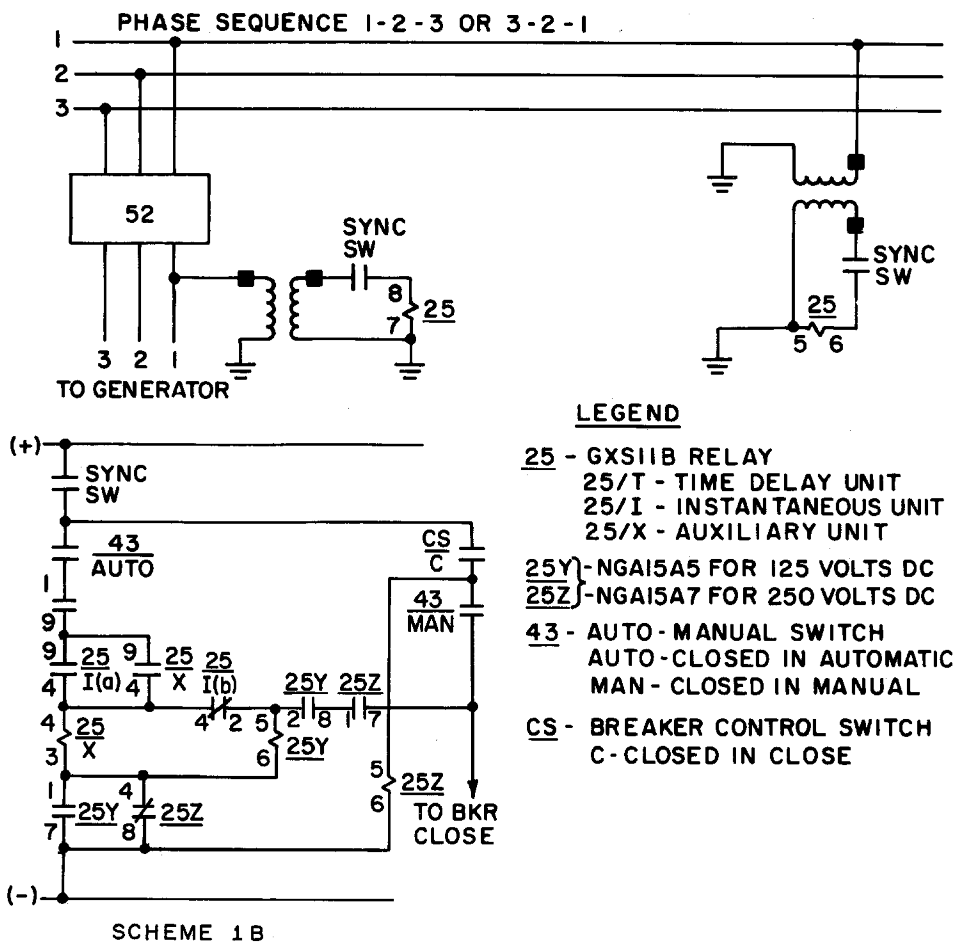


Fig. 10. External connections for GXS11B to supervise the operator when synchronizing a generator onto a system (KW041669B)

4-8 which then prevents 25Y from getting energized. The close circuit to the breaker does not get make-up. Also when 25Z contacts 4-8 open, 25/X gets de-energized which, when 25/I(a) opens (and 25/I(b) closes) will lock out the closing circuit until the next time around.

The same comments regarding the maximum phase angle error that were made for scheme 1A apply equally as well to scheme 1B.

Scheme 2A

Scheme 2A is similar to scheme 1A except that it includes an SAM11A static time delay relay. This scheme performs in the same manner as Scheme 1A except that it sets a time limit on how long after the GXS operates the operator can close the control switch and still produce a closing signal to the breaker. In order for a normal synchronizing operation to take place the GXS must operate prior to the operator placing the control switch in the CLOSE position so device 25Y can pick up through CS/NOR. Contacts 2-8 on device 25Y will then energize timer 2. In order to close the breaker the operator must now operate the control switch to the CLOSE position before device 2 times out and opens contacts 2-3. With proper time setting this would prevent the operator from closing the breaker if he operates the control switch during the last instants before the GXS resets as the machine moves out of range. Thus, it will cut down on the maximum out-of-phase angle for which the breaker can be closed. The proper setting for this timing function will be disclosed in the section under APPLICATION AND SETTINGS. As in Scheme 1A, if the operator closes the control switch too soon or holds it closed continuously, no synchronizing will take place.

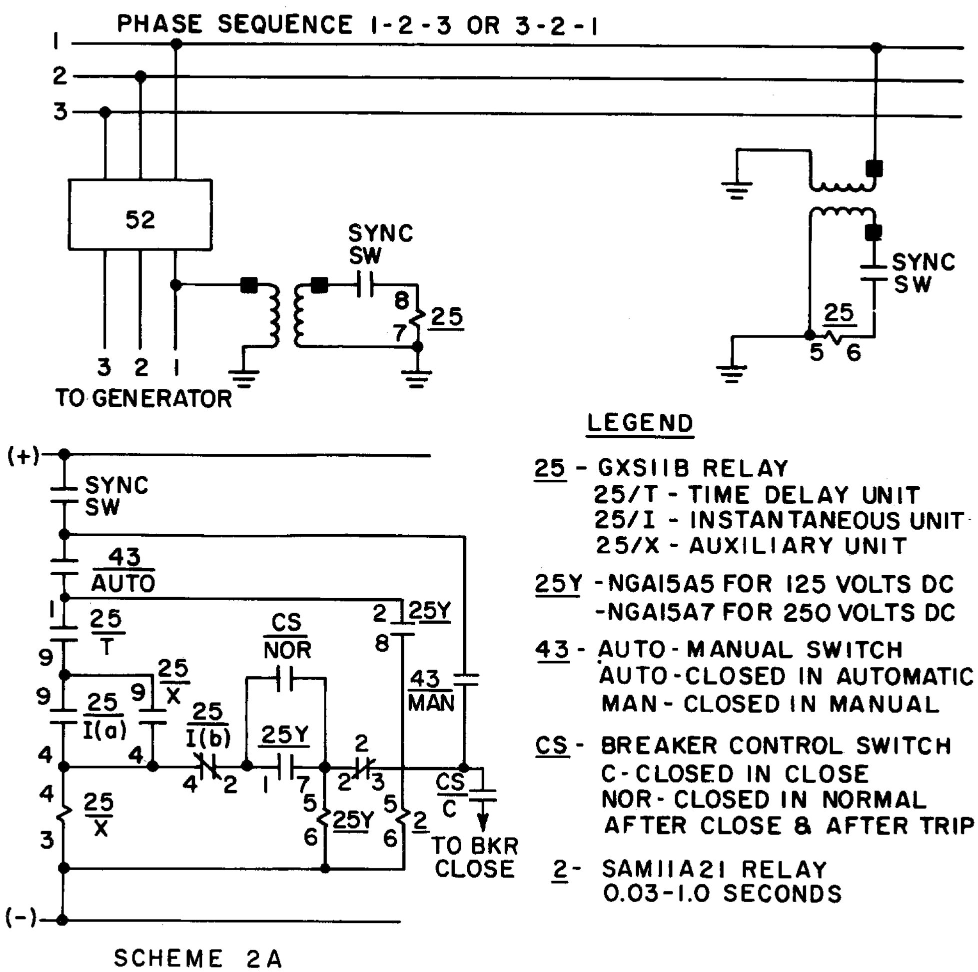


Fig. 11. External connections for GXS11B to supervise the operator when synchronizing a generator onto a system (KW041669C)

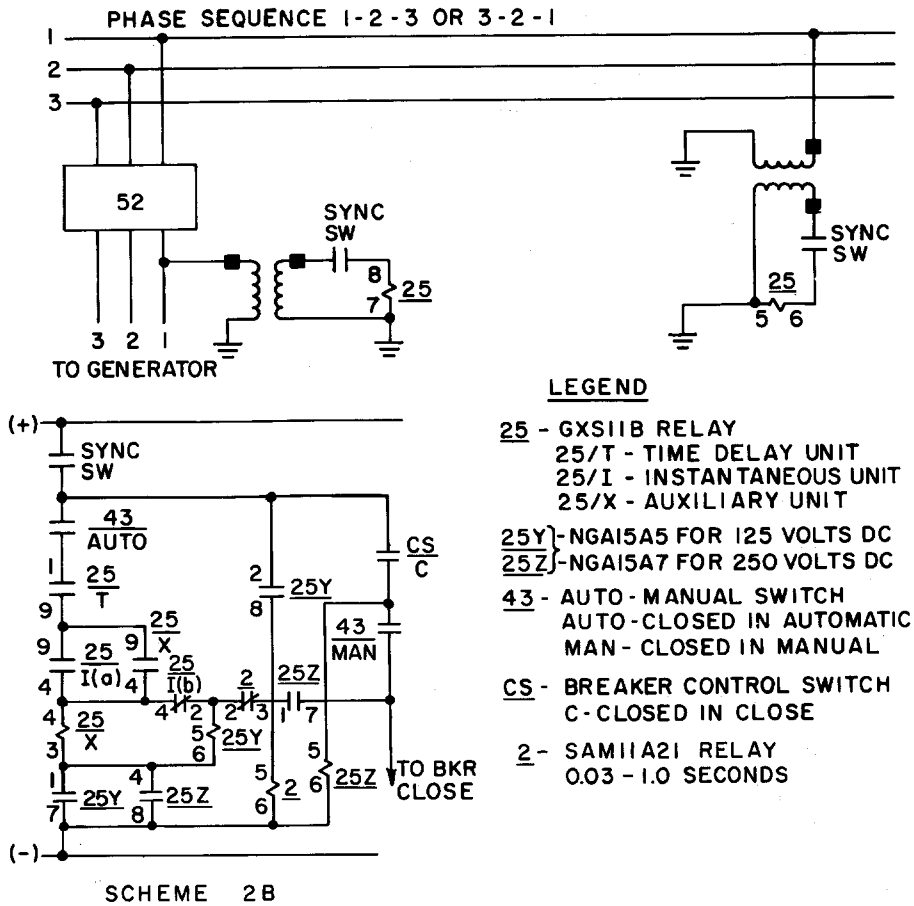


Fig. 12. External connections for GXS11B to supervise the operator when synchronizing a generator onto a system (KW041669D)

Scheme 2B

This scheme is functionally the same as scheme 2A except that it employs a second auxiliary NGA-15A device (25Z) in place of the CS/NOR contact in the control switch. Scheme 2B is to scheme 2A as scheme 1B is to scheme 1A. Scheme 2B would be used in place of scheme 2A when the NORMAL contact on the control switch is not available.

Scheme 3A

This scheme is similar to scheme 1A except that it incorporates a zero angle cut-off and the machine must be running faster (or slower by re-connection) than the system. In order for breaker closing to be initiated the GXS must operate, then the operator must operate the control switch to CLOSE before the machine reaches the in-phase condition with the system, and the machine must be running faster than the system, or if desired, slower than the system by reconnecting the ac circuits. See Note 2 on Fig. 13.

The external dc connections for this scheme are illustrated in Fig. 14, and the ac connections in Fig. 13. This scheme differs from scheme 1A in that it includes a 25X/V voltage sensing unit which provides the zero degree cut-off. This unit and the 25X/A auxiliary unit are both included in the NAA30 relay shown in the internal connection diagram of Fig. 16. The 25X/V unit is connected to measure the difference between the running and incoming voltages. However, as may be noted from Fig. 13, a phase shift is introduced before the measurement is made. That is, the 25X/V coil is connected to measure the difference between the phase 2-1 voltage at the generator terminals and the phase 2-1 voltage on the high voltage bus. Thus, when the machine and the system are actually in phase, the 25X/V will be measuring a difference voltage that is due to a 30-degree phase angle separation. The purpose of this unit in the scheme is to drop out when the machine passes through the in-phase position with the system and so block any attempt to synchronize until the next time around.

The 25X/V unit is set to drop-out when the voltage applied is equivalent to a 30-degree separation at rated voltage. For a 115-volt system this is:

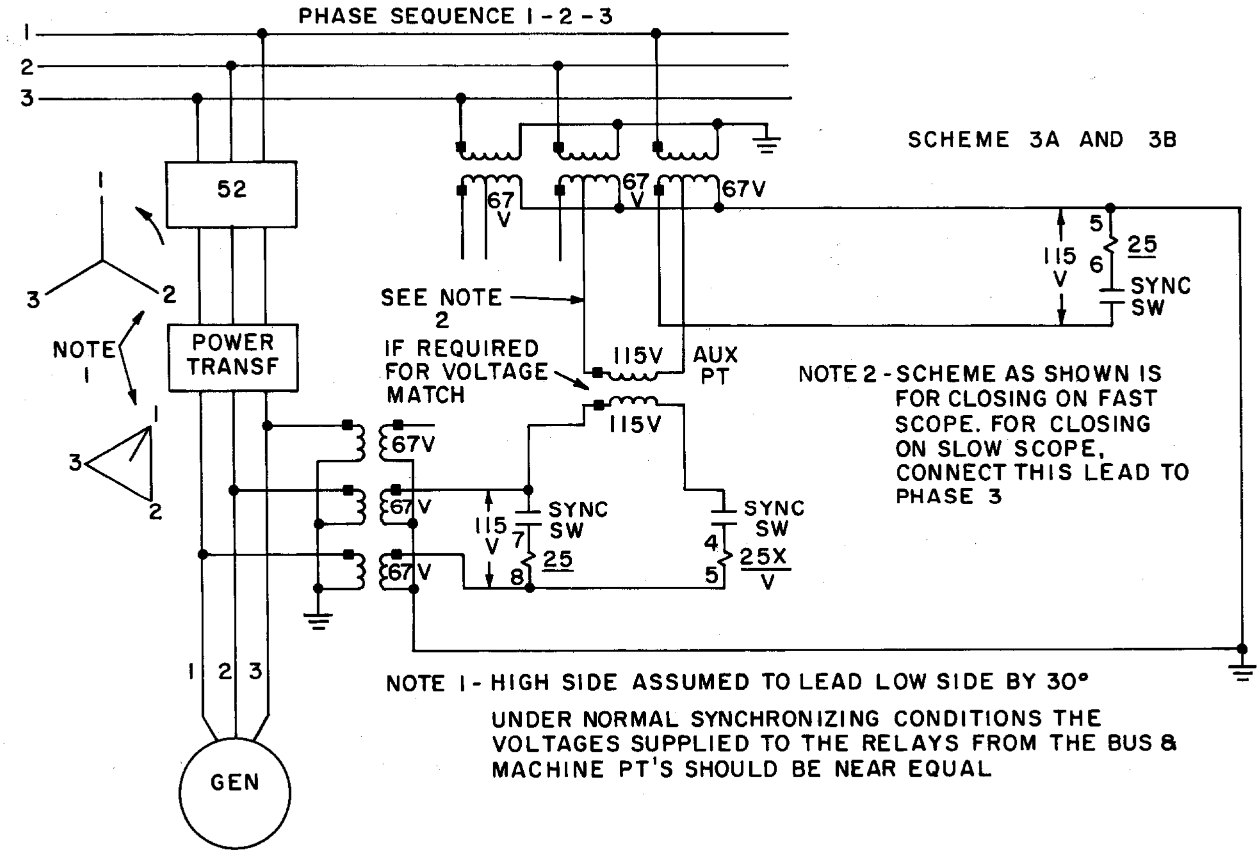


Fig. 13. External ac connections for GXS11B to supervise the operator when synchronizing a generator onto a system, zero degree cut-off (KW061669)

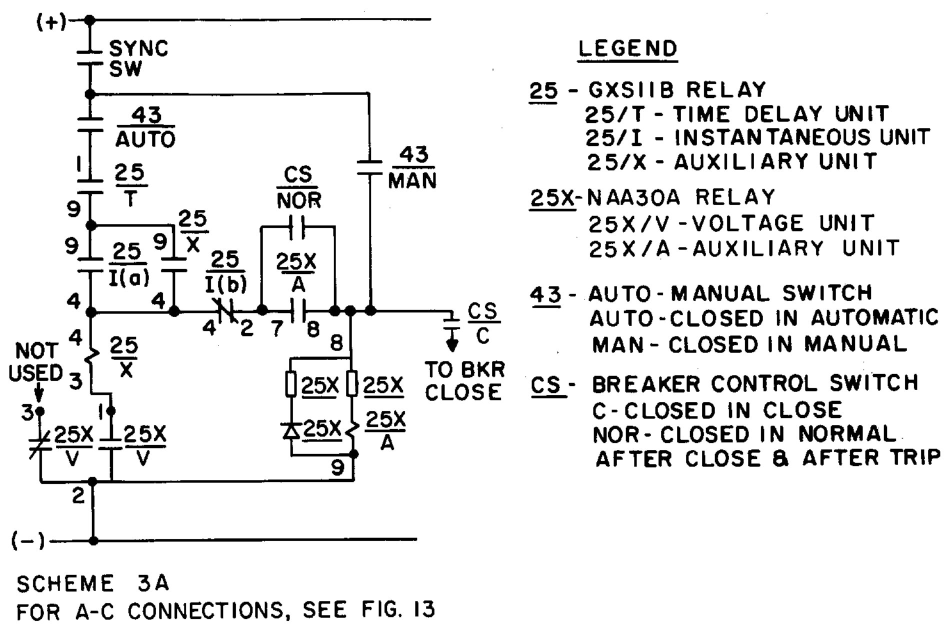


Fig. 14. External dc connections for GXS11B to supervise the operator when synchronizing a generator onto a system, zero degree cut-off (KW060969)

$V = 2\ (115\ \text{Sin}\ 15) = 59.5$ volts RMS

For a 120 volt system this is:

$V = 2\ (120\ \text{Sin}\ 15) = 62.2$ volts RMS

With the machine running faster than the system and approaching the in-phase condition, 25X/V will be picked up and contacts 1-2 will be closed permitting the scheme to function just as scheme 1A. When the machine gets to the in-phase condition with the system, 25X/V drops out and prevents any further closing impulse from reaching the breaker until the next time around. Thus, in order to synchronize the unit, the operator must operate the control switch after GXS operates but before the machine arrives at the in-phase position and 25X/V drops out.

If the machine were running slower than the system the 25X/V unit would be dropped out from the time the machine is within about 60 degrees of the system until it gets to beyond the in-phase condition. This will prevent the GXS from getting set-up because 25/X will not operate before 25/I(a) opens. Thus, with the arrangement shown, the breaker close impulse will be given only on a fast scope (machine running faster than the system) and only if the operator closes the control switch after the GXS operates and before the in-phase position is reached. This severely limits the possible phase angle error in manual synchronizing. Here again, if the operator closes the control switch too soon, or holds it closed continuously, no synchronizing will take place.

If for any reason it is desired to close on a slow scope only, this can be accomplished by making the change indicated in Note 2 on Fig. 13.

The auxiliary PT indicated on Fig. 13 is required only if it is necessary to balance the voltages between the bus side and machine side PT's. This can come about if the ratio of the bus PT's and generator PT's do not perfectly complement the power transformer ratio.

Scheme 3B

This scheme is functionally the same as scheme 3A except that it employs a second auxiliary unit (25X/B) in the NAA30A relay in place of the CS/NOR contact of the control switch. Since the 25X/B function is present in the NAA30A, this scheme could be used whether a CS/NOR contact is available or not.

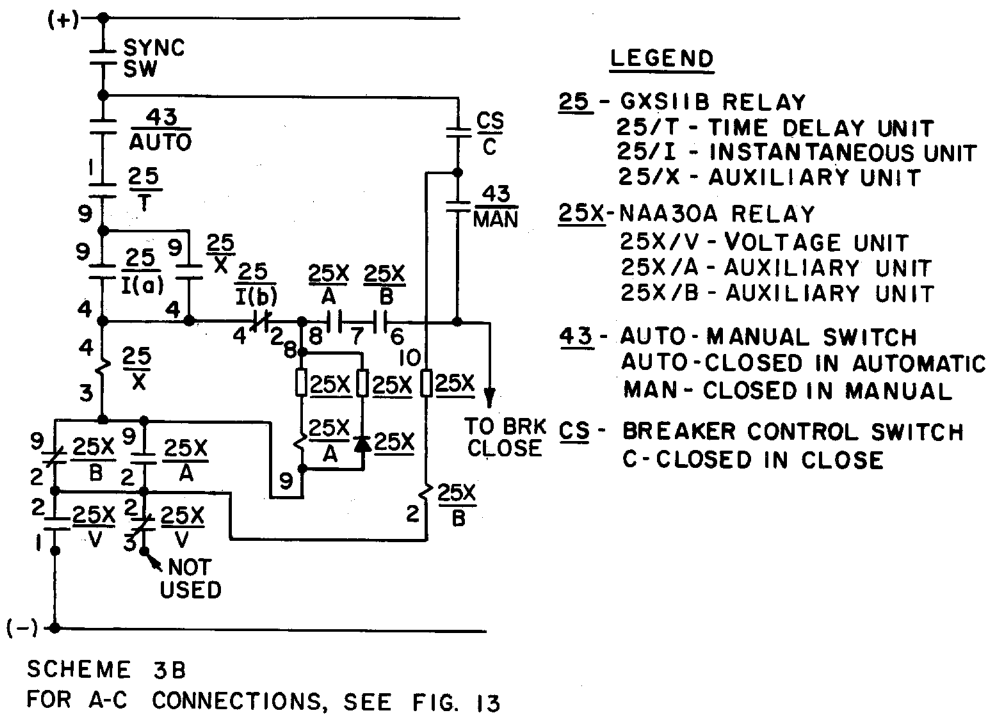


Fig. 15. External dc connections for GXS11B to supervise the operator when synchronizing a generator onto a system, zero degree cut-off (KW061869)

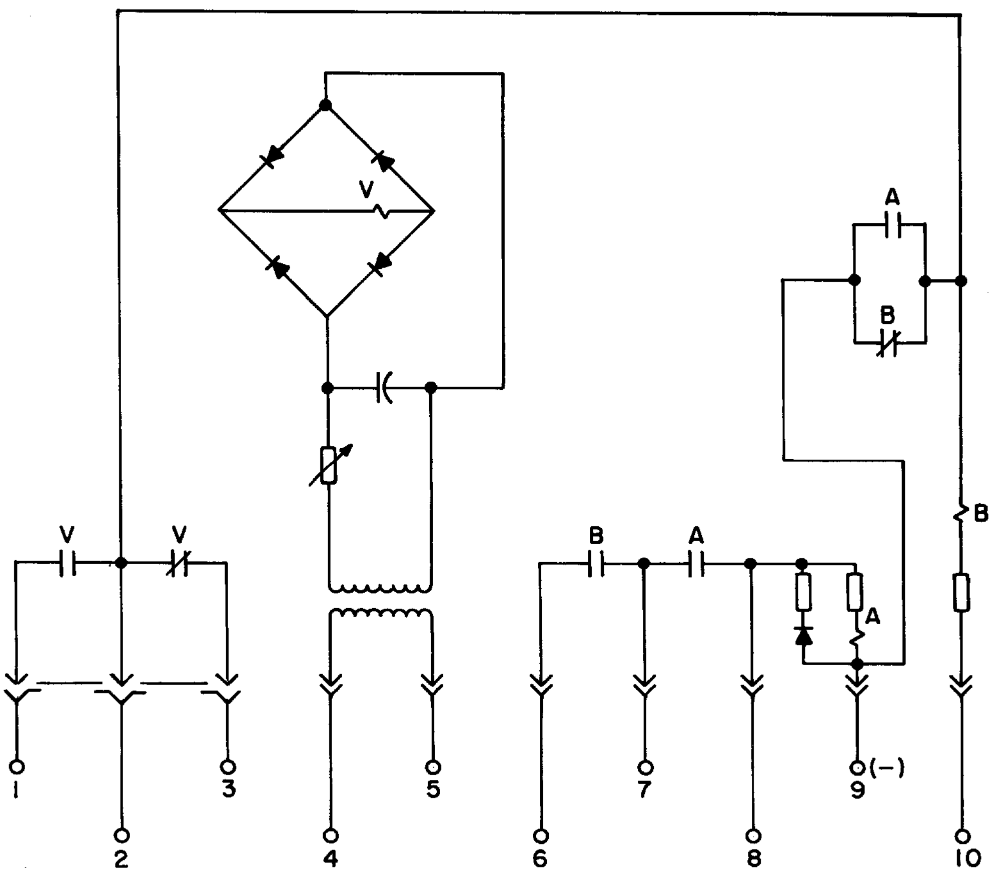


Fig. 16. NAA30A relay, internal connections (KW061369)

APPLICATION AND SETTINGS

The GXS relay is the key device in all the schemes covered by this paper. Its setting will determine the maximum slip and phase angle difference at which synchronizing will be permitted. For optimum performance these settings should be selected with some consideration of the breaker closing times. In general, for long breaker closing times, the cut-off slip setting should be kept low to minimize the possibility of closing error. Conversely for fast closing breakers, faster slips could be tolerated.

As a general guide, for circuit breakers having closing times in the order of 0.16-0.32 seconds, a slip cut-off of 0.1 cycles/second (10 seconds for the synchronscope to go around once) should be considered. For faster closing breakers, slip cut-offs of 0.15 cylces/second and 0.20 cycles/second may be considered. It should be recognized that higher slip cut-off settings will permit faster synchronizing but may also permit larger phase angle errors in synchronizing.

The following formula may be used to calculate the angle in advance of synchronism that a closing signal must be given in order for the main poles of the breaker to close when the machine and the system are in phase.

$$\theta = s\,(360)t \qquad (6)$$

where

θ = advance angle in degrees

s = slip of machine relative to the system in cycles/second

t = breaker closing time in seconds

Thus, for a machine that is slipping at 0.1 cycles per second relative to the system, and a breaker time of 0.32 seconds, the breaker closing signal should be given 11.5 degrees in advance of the in-phase position in order for the breaker to close at the proper instant.

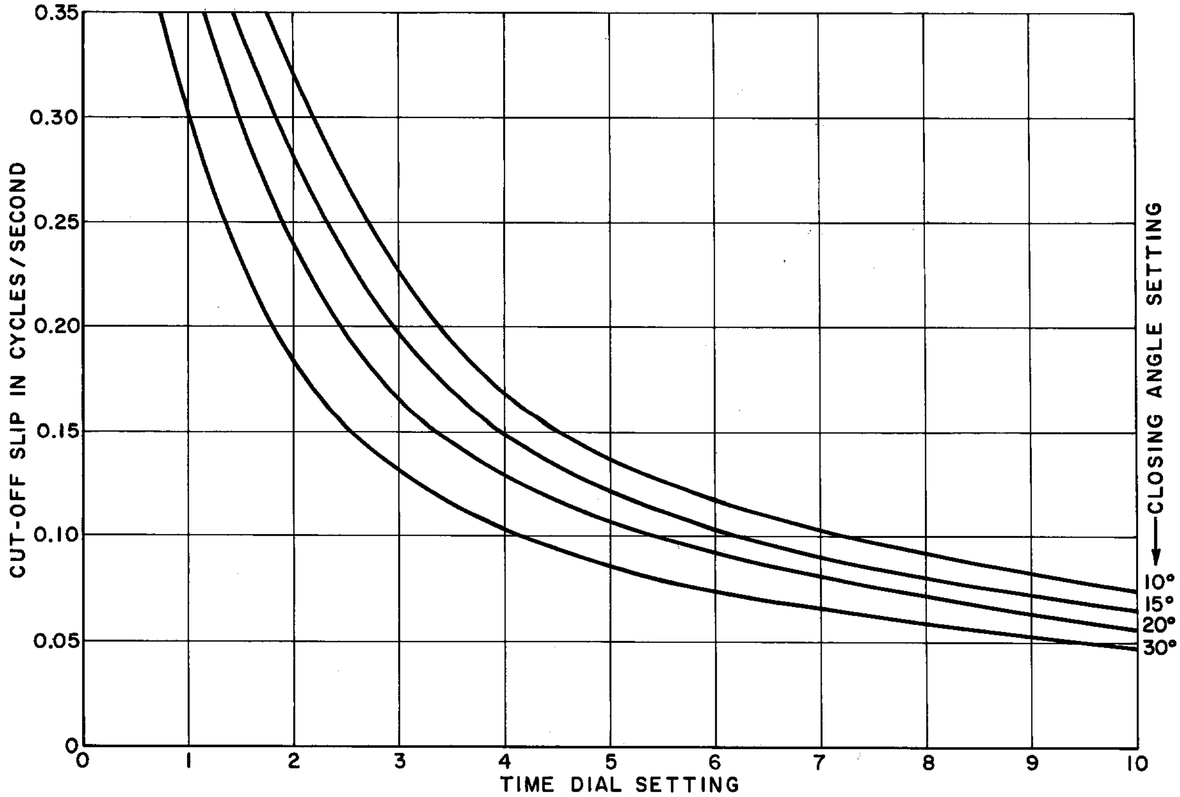


Fig. 17. Cut-off slip as a function of time dial setting and closing angle setting for GXS11B (0178A9108)

θ = 0.1 (360)(0.32) = 11.5 degrees

Since the operator will be "shooting" for this angle and since the GXS must operate first in order to permit synchronizing, the GXS should be set with a closing angle of about 15 degrees to give the operator some "room".

As another example, for a slip of 0.2 cycles per second and a breaker closing time of 0.08 seconds, the closing signal should be given at 5.75 degrees in advance of the in-phase position. Here a 10-degree closing angle setting on the GXS should suffice.

As a general rule, the closing angle setting of the GXS should be about 5 degrees larger than the angle calculated from equation (6) above. Thus:

$$B = 5 + s(360)t \qquad (7)$$

where

B = closing angle setting of GXS - degrees

s = slip cut-off setting of GXS - cycles/second

t = breaker closing time - seconds

Note that it is not recommended that B be set for less than 10 degrees because error due to voltage magnitude variations may be excessive. The curves of Fig. 17 indicate the time dial setting on the GXS that is required to obtain the desired slip cut-off in terms of the closing angle setting. For example, if the desired cut-off slip is 0.1 cycles per second and the closing angle setting is to be 10 degrees, then the required time dial setting is 7.3.

Where fast breakers are available, and a slow cut-off slip which may delay synchronizing is tolerable, the GXS can limit the closing angle error to relatively small amounts. For example, consider a breaker closing time of 0.12 seconds, and assume GXS settings of 10 degrees and 0.1 slip cycles per second. Under conditions of actual slip being equal to cut-off slip, the machine will traverse (0.1)(360)(0.12) = 4.32 degrees between the time that the impulse is given and the main poles of the breaker close. With such an arrangement the error angle can be as much as 14.32 degrees beyond the in-phase position. With these same settings but with an actual slip near zero, the error angle can be as much as 10 degrees in advance of the in-phase position. If this is satisfactory, scheme 1 should be selected. If not, scheme 2 or 3 should be considered.

Schemes 1A and 1B

The only settings required for these schemes are those for the GXS relay. The considerations necessary for selecting these were given in the preceding section.

Schemes 2A and 2B

These schemes require settings for the SAM relay as well as the GXS. The factors affecting the GXS settings are the same as those discussed above. The SAM relay setting, however, will depend on the GXS settings.

If the SAM relay is to be effective in limiting the maximum phase angle error at closing, it must operate to block closing long before the machine swings out of the closing angle of the GXS. It appears desirable to select a time setting for the SAM that will block closing after the machine passes through the in-phase position going at a speed corresponding to the cut-off slip setting on the GXS. This time would be given by the following equation:

$$t = \frac{B}{(360)S} \qquad (8)$$

where

t = time delay setting of the SAM in seconds

S = cut-off slip setting on GXS in cycle/sec

B = closing angle setting on GXS in degrees

For example, if we consider a breaker with a closing time of 0.32 seconds, a GXS slip cut-off setting of 0.1 cycles per seconds, and a closing angle setting of 15 degrees, equation (8) will yield a desired time setting of:

$$t = \frac{15}{(360)(0.1)} = 0.416 \text{ seconds}$$

With this setting on the SAM, and the machine slipping at the cut-off setting of the GXS, the greatest phase angle error in closing beyond the in-phase position will be 15 degrees, which is the closing angle setting of the GXS. With these same settings but an actual slip of near zero, the error angle can be as much as 15 degrees in advance of the in-phase position.

If the machine is slipping at half the cut-off slip setting of the GXS (0.05 cycles per second in this case), this time setting on the SAM will restrict the operator to providing the closing impulse in the range between 15 and 7.5 degrees in advance of the in-phase position because the machine will only traverse 7.5 degrees in the 0.416 seconds time setting of the SAM. For slower actual slips the angular restriction on the operator will be more severe. At 0.05 slip cycles per second and a 0.32 second breaker closing time, the breaker will use up (0.05)(360)(0.32) = 5.8 degrees to get closed from the time the impulse is given. Thus, at 0.05 slip the breaker will close its poles between 9.2 and 1.7 degrees in advance of the in-phase condition.

It should be recognized that the SAM relay scheme will be most effective where long breaker closing times are involved. Where short breaker times are the rule, either scheme 1A or 1B should suffice, particularly if the closing angle setting on the GXS is kept at 10 degrees and the slip cut-off is set at 0.1 cycles per second or less.

Schemes 3A and 3B

These schemes are intended to provide the same advantages as schemes 2A and 2B except that in this case closing impulses are blocked for any angle beyond the in-phase position regardless of the actual slip. This puts less restriction on the operator.

The 25X/V voltage unit that determines when the machine and the system are in phase should be set for:

$$V_r = 2(\text{Sin } 15)V_s$$

where

V_r = Drop out setting

V_s = Normal machine and system voltages assumed equal

It should be recognized that variations in the actual machine and system voltages from those used to set the drop out of 25X/V will introduce a variation in the angle at which the unit drops out. Table I provides an indication of the extent of these variations.

The extent of the error in the drop-out angle of 25X/V, and hence the need for a matching auxiliary PT, may be determined from this table.

TABLE I

INCOMING VOLTAGE*	RUNNING VOLTAGE*	OPERATING ANGLE Δ
0.9	0.9	-3.5°
1.0	0.9	-1.0°
1.1	0.9	$+2.0^{\circ}$
0.9	1.0	-1.0°
1.0	1.0	0
1.1	1.0	$+2.0^{\circ}$
0.9	1.1	$+2.0^{\circ}$
1.0	1.1	$+2.0^{\circ}$
1.1	1.1	$+2.5^{\circ}$

* In per unit of 25X/V calibrating voltage

Δ Positive angle indicates drop out beyond the in-phase position

Δ Negative angle indicates drop out in advance of the in-phase position

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