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# AN IMPROVED TECHNIQUE FOR CALIBRATING AND TESTING POWER SYSTEM GENERATOR AUTOMATIC SYNCHRONIZING AND SPEED MATCHING RELAYS

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## ABSTRACT

The design of a unique special purpose instrument for calibrating and testing power system automatic synchronizing and speed matching relays is described. The unit is constructed using inexpensive integrated circuit components and provides a direct digital readout of slip frequency from 0.05 Hz to 0.50 Hz resolution and advance angle from 0 to 99.9 degrees with 0.1 degree resolution. This device eliminates the need for expensive test equipment previously required, expedites the test procedure and solves the problem of referencing against a variable bus frequency source.

## INTRODUCTION

Large generating units require the use of automatic speed matching and synchronizing relays to minimize power surges and system disturbance when units are coupled to the system network. The synchronizing function senses the frequency of the machine and the system bus and initiates a closing impulse at the proper point just ahead of phase coincidence to compensate for the finite operating time of the connecting circuit breaker. The speed matching function serves to accelerate or decelerate the machine via turbine valve control and maintains a frequency difference between the machine and system bus. (There must be a frequency difference between the machine and system bus for the synchronizing element to perform its function.) Figure 1 illustrates ideal synchronizing relay characteristics with terms defined as follows:

Slip Frequency - the difference between the machine frequency and the system network frequency.

Advance Angle - the electrical phase angle of the machine with respect to the system network at the instant the circuit breaker close impulse is generated.

Circuit Breaker Closing Time - the overall closing impulse resoponse time of the circuit breaker, including mechanism travel.

The figure shows that as slip frequency increased the advance angle at which the circuit breaker closing impulse occurs increases, allowing for the constant circuit breaker closing time.

Early synchronizers were constructed using vacuum tube technology and mechanical relay sequencing, however, modern solid state electronic devices are now available which provide synchronizing, speed matching and voltage matching functions.

In order to simulate the operating conditions for initial setting and periodic checking of synchronizers, a number of test methods have been developed. The first method is diagramed in Figure 2. With any convenient 60 Hz source as a bus reference a machine simulation is made with a manual phase shifter rotated approximately at the desired slip frequency as indicated by the movement of the phase angle meter. When the close impulse is generated the angle at that instant is noted and accepted as the advance angle.

Disadvantages of this method are:

1. The phase shifter is not an accurate source of constant slip.
2. The phase meter cannot be read with accuracy because it is rotating.
3. The phase shifter requires a 3 phase source.

Figure 3 shows a more convenient test configuration using a signal generator and amplifier for the machine input with a frequency counter as a slip indicator. Disadvantages using this simulation are:

1. The counter must be used in the period mode to resolve fractional cycles per second. This is an awkward indication and requires external calculations when changing values.
2. The phase meter cannot be read with accuracy because it is rotating.
3. The bus input to the relay is assumed to be 60.00 Hz.

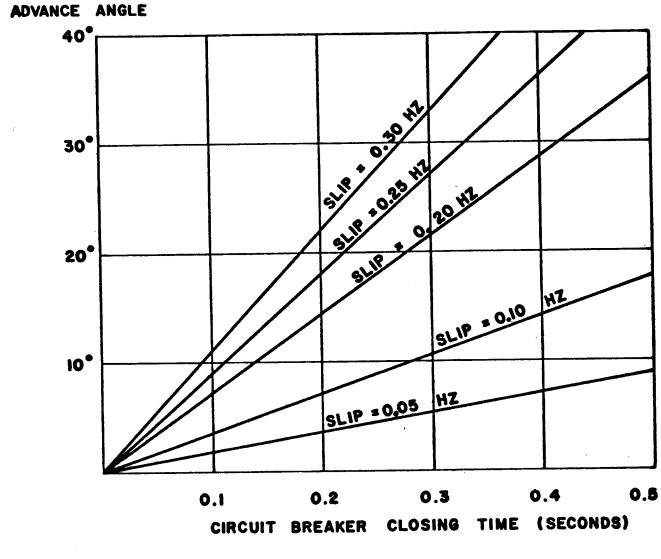


Figure 1. Ideal Synchronizing Relay Characteristics - Advance Angle vs. Circuit Breaker Closing Time

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Other methods employ a small generator with speed control to model a machine and rely on recording oscillographs to measure the advance angle against a timing reference oscillator. While these methods offer more accuracy, they are difficult to implement in the field for periodic maintenance. In addition, all of the methods discussed require lengthy set-up time and expensive instrumentation.

The need for an improved method in testing power system automatic synchronizing and speed matching relays is significant. An error of 0.05 Hz in slip frequency during simulation tests could result in an advance angle calibration error of 50%. Modern electronic circuit designs have been incorporated in synchronizer modules which require comparable test equipment for evaluation and maintenance. In addition, dollar savings can be achieved by establishing a procedure that can be implemented rapidly using inexpensive equipment.

Phase angle instruments with digital electronic circuitry like that described by Dranetz and Cox (1) have proved to be a valuable tool for use in testing and calibrating protective relay devices both in the laboratory and in the field. However, the periodic display characteristic of such devices make them unsuitable for synchronizing and speed matching relay calibration because they cannot track the continuously varying phase of two independent frequency sources. Also, there is no provision for freezing an instantaneous phase reading by any triggering inputs.

Power system frequency deviation is monitored at central dispatching locations to provide indication that generation matches load requirements and also serve as an input to load frequency computing equipment for automatic generation control. Kumar, S. Gupta and B. Gupta (2) have developed a device with a precision frequency reference that drives an analog meter calibrated in frequency deviation. Metering such as this would be necessary in any synchronizing device testing scheme that does not feature instantaneous absolute slip frequency indication.

Analog and digital electronic circuit techniques are being applied successfully for use in various types of protective relay devices which require frequency sensing elements. The relay designed by Widrevitz and Armington (3) for precision rate-of-change of underfrequency detection and the elaborate Grand Coulee mini-computer synchronizers described by Berger (4) serve as examples of the need for power frequency simulation test equipment commentsurate with relay design technology.

The research of this topic was undertaken to develop a method for testing synchronizing and speed matching relays at reduced costs and provide a means for checking frequency sensitive elements during reference input frequency swings. As a result, performance evaluation tests and calibration adjustments can be made with more precision by simpler means.

## TEST INSTRUMENT DESIGN

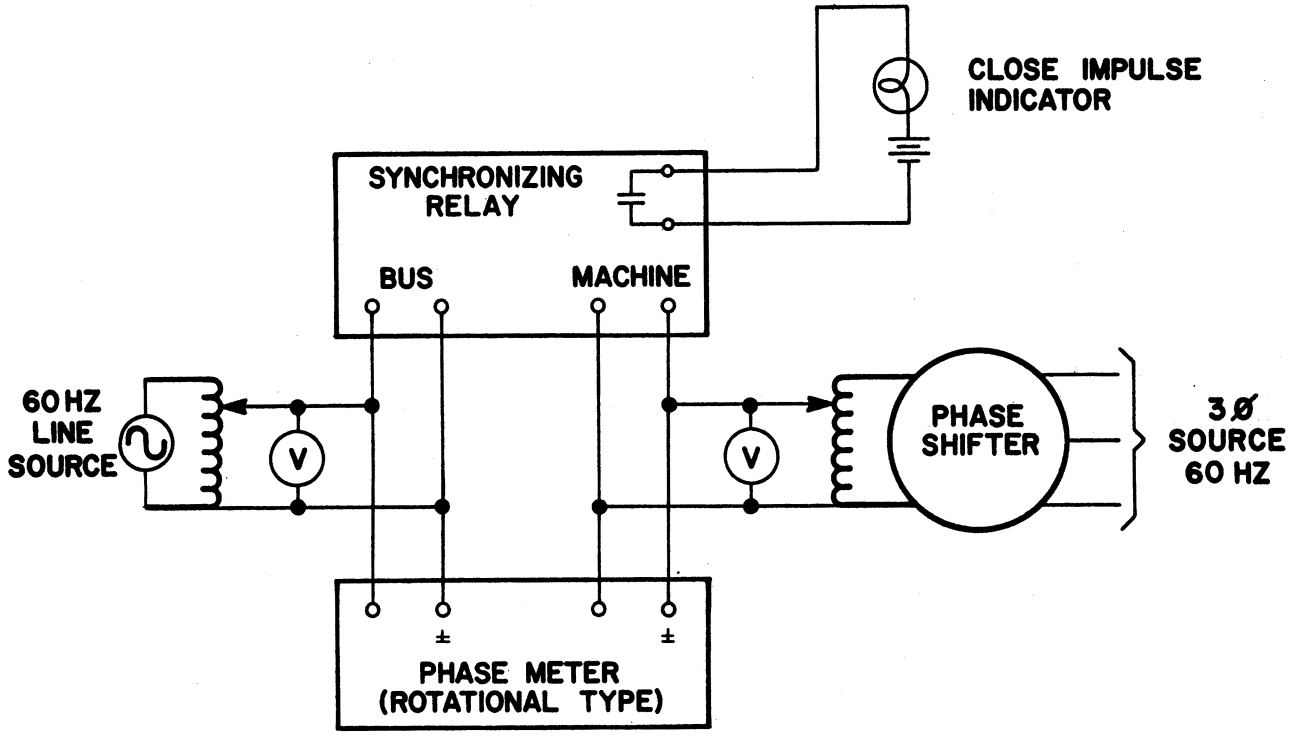


**Figure 2. Phase Shifter Method for Testing Synchronizing Relays**

To improve upon established methods of testing synchronizing relays a test instrument was developed with the following features:

1. Direct digital display of slip frequency with a resolution of 0.01 Hz.
2. Digital display of advance angle in electrical degrees - resolution to 0.1 degree.
3. Small, stable 60 Hz machine simulation oscillator.
4. Slip test range 0.01 to 0.05 Hz.
5. Continuous tracking of actual slip frequency.

The circuit breaker closing contacts of the synchronizing relay trigger the advance angle display counter which stopped when phase coincidence occurs between machine and bus inputs. Tracking circuits for actual slip frequency display also provide the input for the electrical degree advance angle translation logic. This instrument is unique because, unlike a frequency counter or timer, its time base for advance angle indication varies in direct proportion to the difference between two independent frequency sources. That is,

$$f_{AAT} = K \cdot (f_b - f_M) \qquad f_B > f_M$$

$$f_{AAT} = K \cdot (f_M - f_B) \qquad f_M > f_B$$

Where $f_{AAT}$ = frequency of advance angle time base in Hz.

$f_B$ = frequency of bus input to synchronizing relay in Hz.

$f_M$ = frequency of machine input to synchronizing relay in Hz.

K = constant chosen so that one complete slip cycle is equivalent to 360 electrical degrees on advance angle read out.

The development of the instrument now discussed.

Initial design effort was concentrated on establishing a workable slip frequency indication and advance angle time base module. Table I shows the relation between slip frequency values and time base requirements for an advance angle indication with $0.1^{\circ}$ resolution. The time base oscillator must generate 3600 pulses for each slip period, translating to 360.0 electrical degrees. A study was made of readily available digital and linear integrated circuits suitable for implementing the time base and the Signetics type 565 phase locked loop and Signetics type 566 voltage controlled oscillator were incorporated into the design shown in Figure 4.

A phase locked loop (PLL) frequency multiplier served as a direct mixer consited of series connected transformers feeding a filtereed full wave bridge rectifier. This design proved to be impractical because:

1. The pull-in time of PLL 1 operating at fo = 0.25 Hz was too long.
2. The capture range of PLL 1 was dependent on supply voltage in the desired range of k0.01 to 0.50 Hz.
3. The low pass filter required for PLL 1 could not be selective enough to provide a proper input for the Signetics type 566 voltage controlled oscillator.
4. The Signetics type 565 phase locked loope is difficult to implement as a multiplier beyond X8.

Another configuration for the slip indication and advance angle time base module

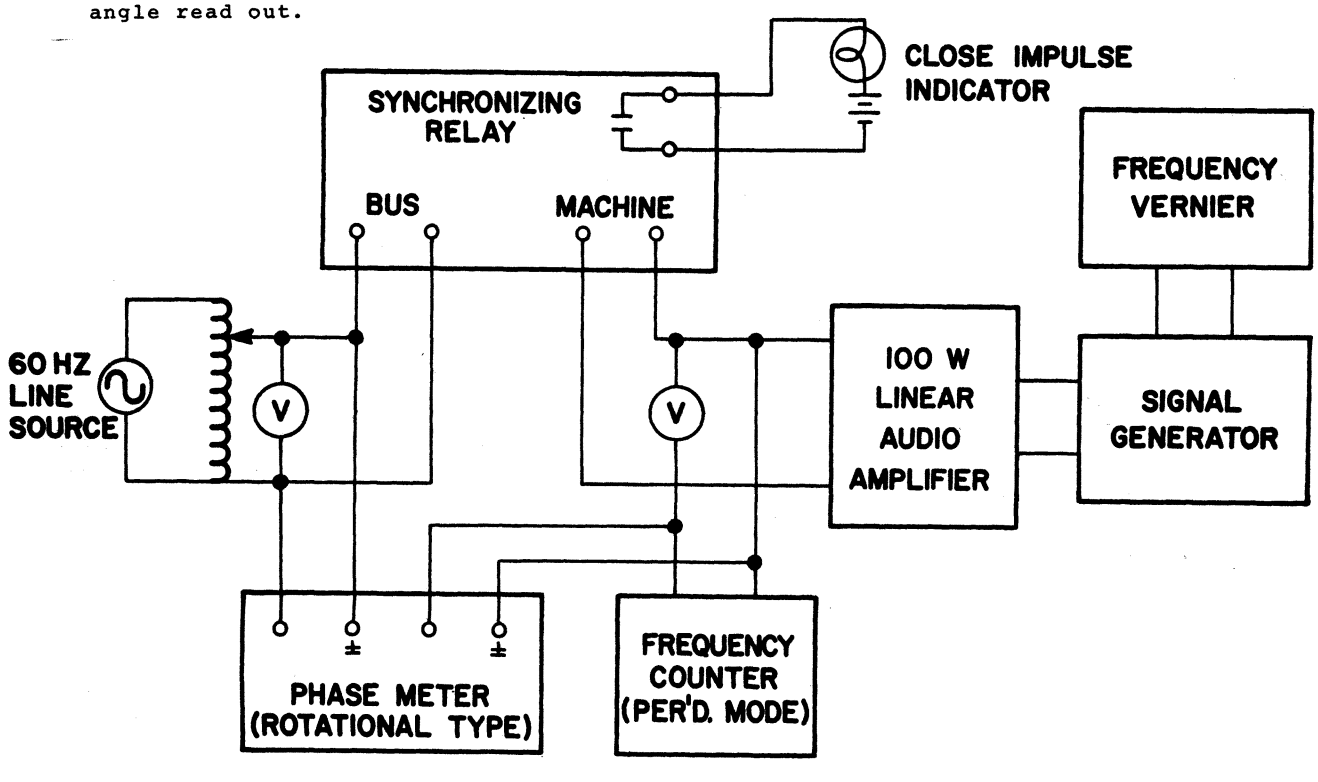


**Figure 3. Synchronizing Relay Test Setup Using Signal Generator and Amplifier to Simulate Machine Input**

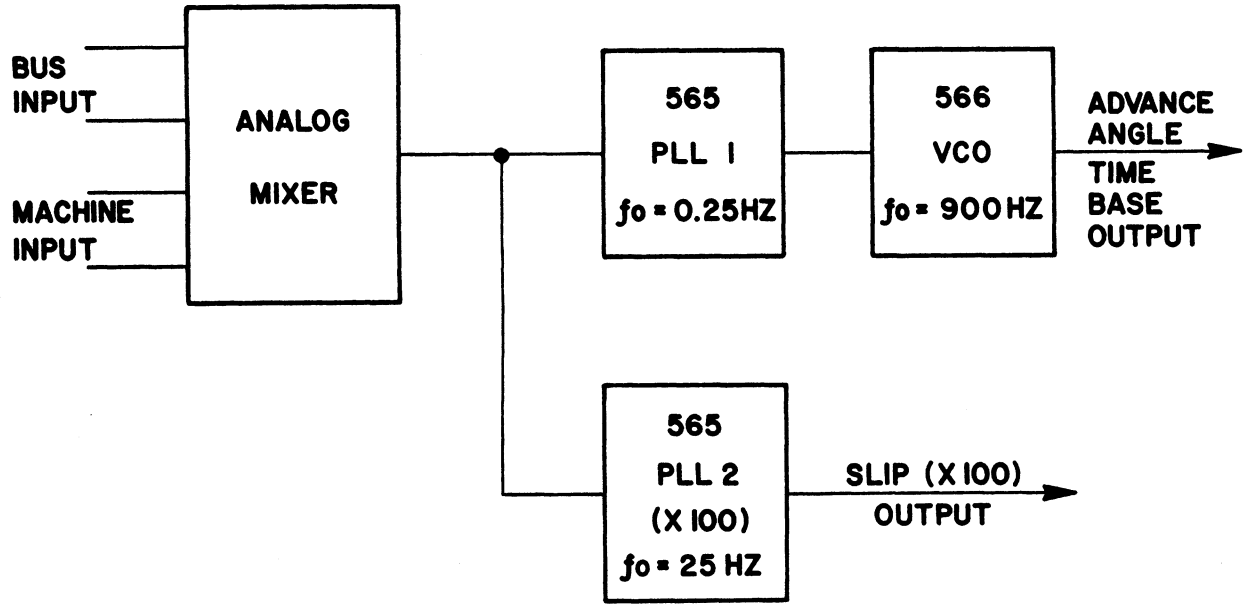


**Figure 4.** Initial Time Base Design Using 565 Phase Locked Loop and 566 Voltage Controlled Oscillator

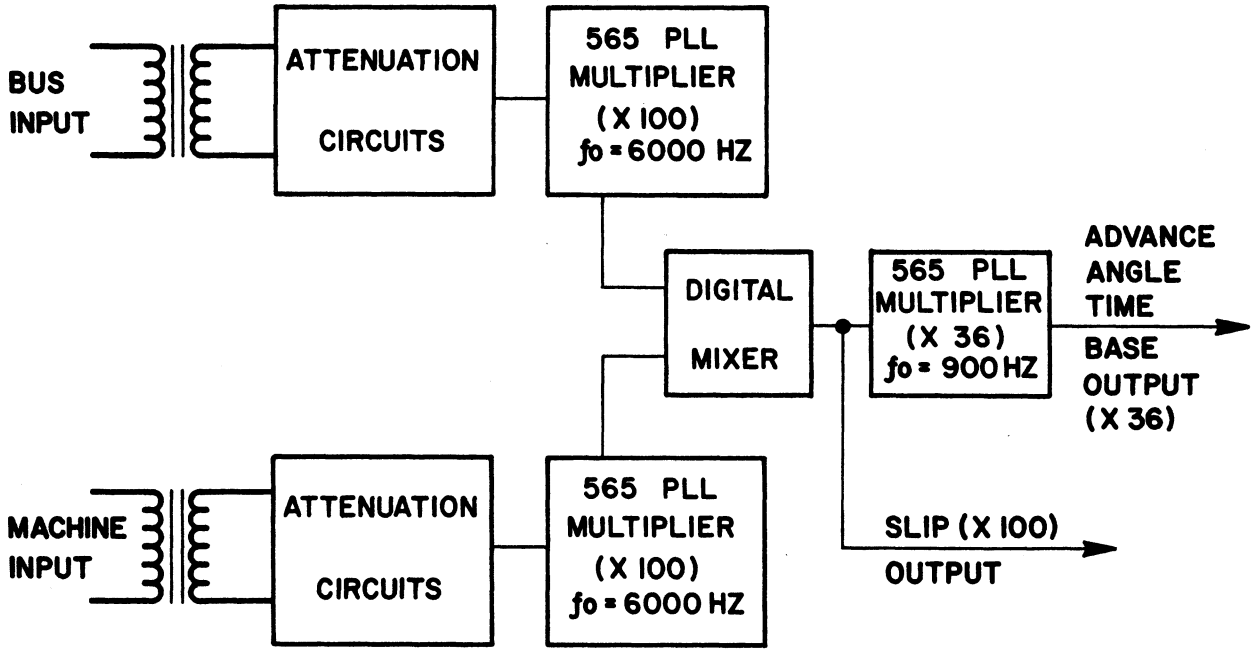


**Figure 5.** Time Base Design With Premultipliers and Digital Mixer

TABLE I

TIME BASE REQUIREMENTS FOR ADVANCE ANGLE INDICATION WITH 0.1 RESOLUTION

| SLIP FREQ. (HZ) | PERIOD (SEC) | TIME BASE (HZ) | NO. OF TIME BASE PULSES PER PERIOD |
|---|---|---|---|
| 0.05 | 20.0 | 180 | 3600 |
| 0.10 | 10.0 | 360 | 3600 |
| 0.20 | 5.0 | 720 | 3600 |
| 0.25 | 4.0 | 900 | 3600 |
| 0.30 | 3.33 | 1081 | 3600 |
| 0.40 | 2.50 | 1440 | 3600 |
| 0.50 | 2.0 | 1800 | 3600 |

was then developed to improve the pull-in time and eliminate the use of a voltage controlled oscillator in the itime base circuits.

This second design for obtaining slip frequency indication and advance angle time base is illustrated in Figure 5. Both input circuits were premultiplied by a factor of 100 to atake advantage of faster pull-in times and to form the slip indication output of 100K the fractional slip. Additional mulitiplication of the slip (X100) output by 36 was intended to give the advance angle time base as required. Digital mixing was accomplished using a D type flip-flop.

Two major difficulties were encountered in this design. The first stage phase locked loop multipliers would not consistently lock at 100 times the input frequency and a capture range of 180 to 1800 Hz could not be obtained in the time base multiplier (X36) phase locked loop. Further experiments were performed until a functional module was demonstrated utilizing an RCA type CD 4046 phase locked loops and CMOS logic elements in the same configuration. Use of CMOS integrated logic provided stable operation with higher noise immunity at lower power levels.

An Intersil type 8038 integrated circuit function generator furnishes a low distortion sine wave for the machine simulation module. Nine additional components were required to provide distortion, symmetry, level, coarse frequency and fine frequency adjustments. The unit generates a high level output suitable for driving a high impedance amplifier and exhibits low frequency drift characteristics due to temperature and power supply fluctuations.

A block diagram of the working design for direct slip and advance angle indication is given in Figure 6. The CMOS squaring circuits provide the CD 4046 phase locked loop multipliers and phase coincidence detection logic with fast rising square waves. To compensate for unequal phase shift both input networks a potentiometer in each squaring circuit allows for exact phase coincidence adjustment. First stage (X100) CD 4046 multipliers track and scale bus and machine input frequencies translating them to 100 times their actual rate. The mixing stage is then used to obtain a signal pulsing at a rate of 100 times the actual slip frequency for input to an indication counter and further multiplication for advance angle time base generation. Translation to a frequency relating slip with eletrical degrees in the desired range is accomplished by centering the advance angle time base phase locked loop free runnning frequency at 900 Hz and implementing multiplication by 36. (See Table I.) Advance angle counting window circuitry provides contact buffering and debouncing through an edge triggered latch. Only one advance angle count window is allowed per slip cycle to prevent continuous addition of counts. A manual reset is required to arm the entire count window logic for each detection of phase coincidence. Three cascaded RCA CD 4033 decade counter-decoder drivers and three RCA CA 3081 Transistor arrays couple to common anode seven segment light emitting diodes to form a three digit display for a maximum indication of 99.9°.

Since the CD 4046 phase locked loop multipliers contain fixed external components, only the phase coincidence logic may require periodic alignment in the slip indication and advance angle module. This is easily done with an oscilloscope by applying a common 120VAC source to the bus and machine inputs and adjusting the squaring circuit sensitivities until a phase coincidence pulse output is observed. (The sensitivity adjustment also sets the input squaring amplifier threshold point, however, beyond the point of sufficient amplifier bias, further loading results in a shift of output phase.) Symmetry, level, total harmonic distortion and coarse frequency calibrations must be made initially for proper operation of the machine simulation oscillator.

## FIELD TESTING AND CONCLUSIONS

Field tests were conducted on the instrument in the Union Electric Company relay test laboratory with the test connection diagrammed in Figure 8. A calibration was applied to a General Electric type GES-21A2D synchronizing relay using a recording oscillograph to measure advance angle and a frequency counter in the period mode to set slip frequency. The same relay characterisitics were then checked with the instrument for comparison and no deviation in slip frequency indications were detected. The largest deviation in digital advance angle measurement was 0.5°and as expected, relay performance measurements could be made much more rapidly with the special test instrument.

In addition to the savings incurred facilitating overall relay test time, application of this testing device eliminates the need for costly phase meters, oscillographs and signal generators.

The prototype advance angle indication and machine simulation oscillator was constructed at a cost of $115.

The final design presented in this effort could also be enhanced by adding a dual purpose counting module to serve as a selectable frequency indicator, and

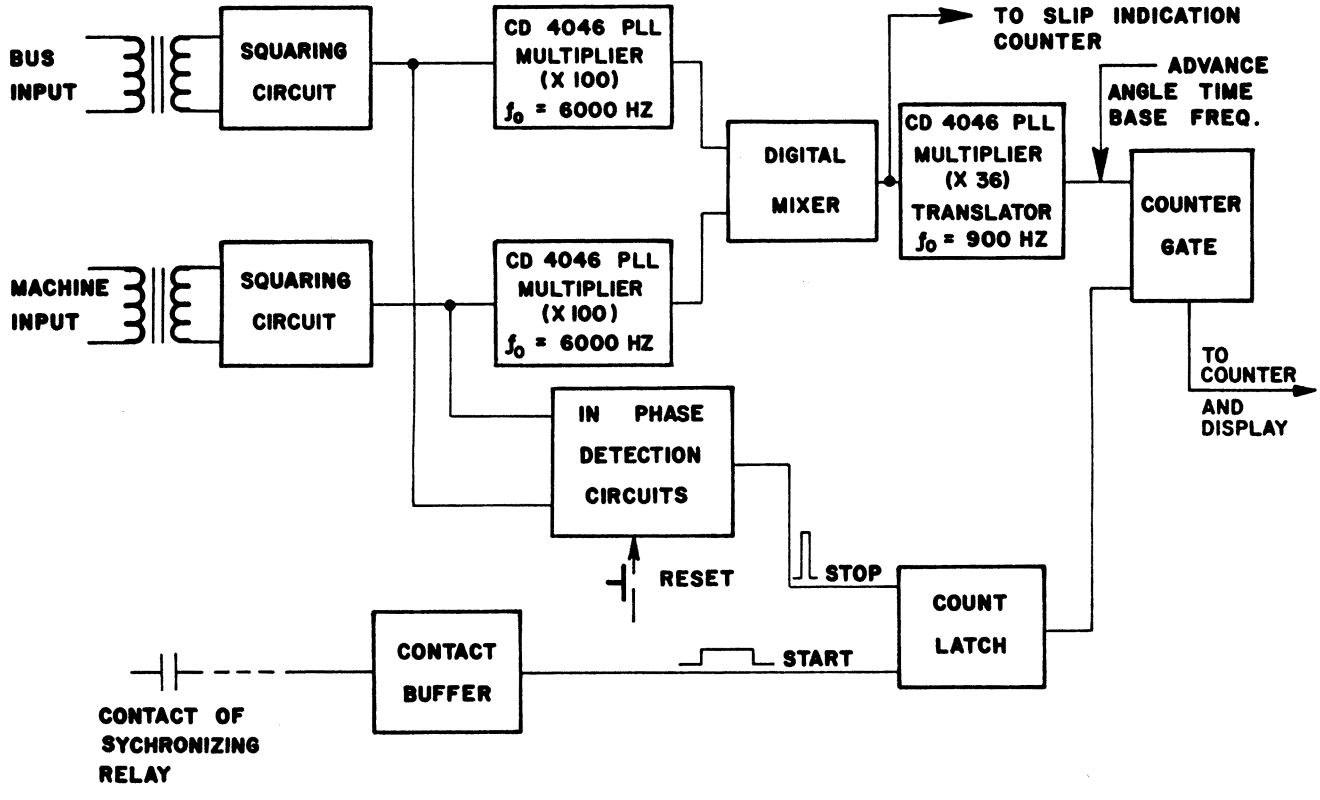


Figure 6. Block Diagram of Working Design for Direct Slip and Advance Angle Indication

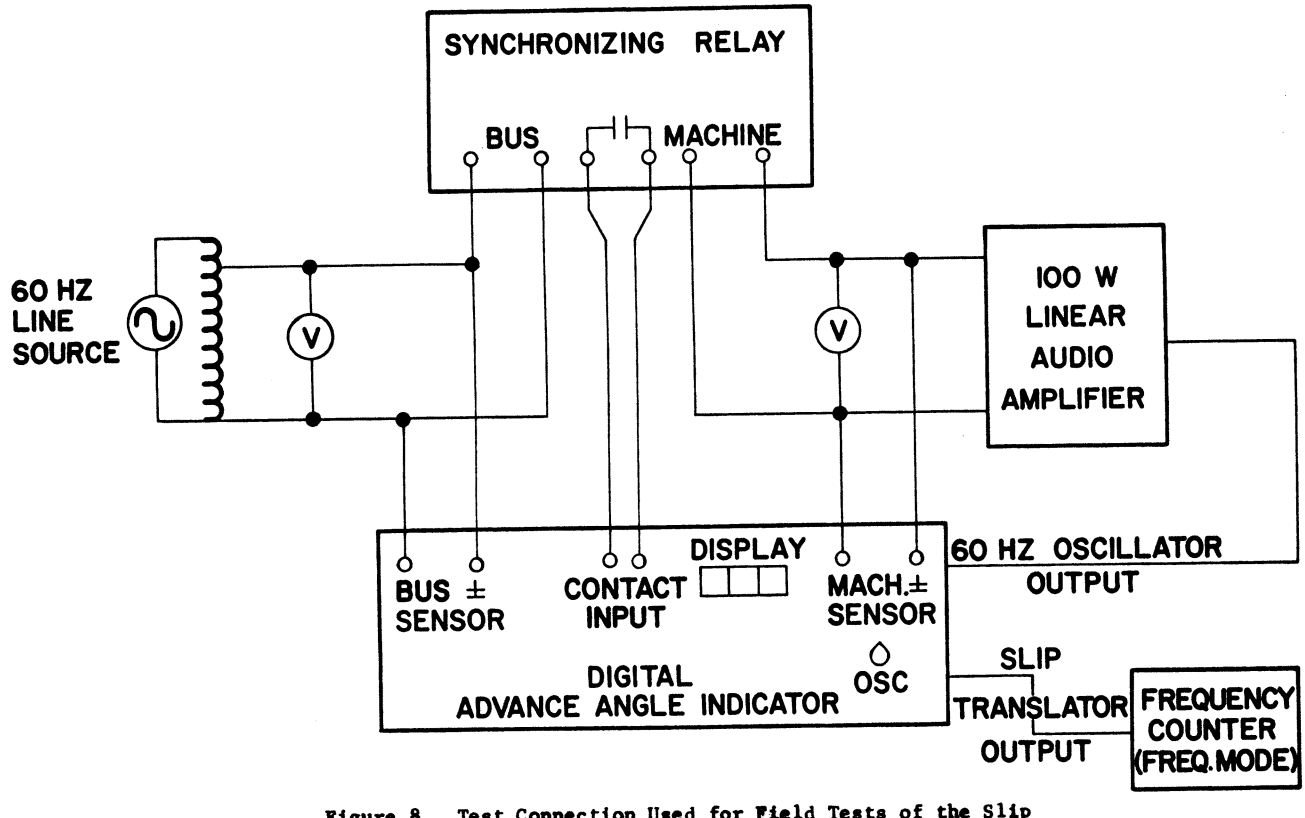


Figure 8. Test Connection Used for Field Tests of the Slip and Advance Angle Indication Unit

resolution could be improved by incorporating higher multipliers in the phase lock circuits. The advance angle counter incorporated is capable of supporting an interval timing function for more precise applications or use where advance angle is desired in terms of breaker closing time.

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