THE CONSTRUCTION AND CALIBRATION OF A PHASE SHIFTER

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I. Use of A Phase Shifter

In testing and calibrating wattmeters, watthourmeters, relays and other like instruments, it is necessary to obtain various electrical load conditions. That is, a current must be had that has various phase relationships with the impressed electromotive force. To obtain these load conditions with different proportions of resistance, inductance and capacity in the load, is a very tedious and almost impossible operation.

For example, it was desired to obtain data for plotting the opening and closing characteristic curves of a Westinghouse Type CN Automatic Network Relay. This relay is connected between a transformer feeding into a 120 V network and the network. It controls a current which energizes solenoids operating switches between the transformer and the network. When the transformer is connected to the feeding line and the voltage on the transformer rises above the network voltage without too much phase difference, the relay should cause the switch to close, thus connecting the transformer to the network. If for some reason the transformer voltage should fall below the network voltage and current began to flow into the transformer, the relay should cause the switch to open, disconnecting the transformer from the line. The coordinates for plotting the opening and closing characteristic curves are phase displacements between network voltage and the current flowing and the amount of current necessary to open or close the relay circuit. To obtain data for plotting these curves, an emf must be had, that can be changed in time phase, from the current, thruout the 360 electrical degrees. It is much easier to fake the desired load conditions than to make them. This may be done by having the current coils of the instrument in a circuit in which the current is in phase with the impressed emf, and impressing an emf on the potential coils which may be displaced from the current phase by any desired amount. This displacement of emf on the potential coils is caused by means of a phase shifter. It was to meet this need that the phase shifter, to be described in this thesis, was constructed.

Very little printed information on this subject was found. Phase shifters are constructed and marketed by several manufacturers of electrical equipment, but no details as to their construction and operation were included in the catalogues at hand. Only the general theory of the operation and construction of phase shifters was found in a search through the available electrical handbooks and textbooks. With such limited information on the subject it is not probable that the phase shifter constructed would compare favorably with the commercial types. However, it is the easiest constructed and best in its operation that can be made with the material at hand around any electrical laboratory.

II. General Theory

The duty of a phase shifter is to cause an electromotive force which is at a known and variable time phase relationship with the emf impressed on the phase shifter. It may be called a transformer, which not only changes the current and voltage, but also changes the time of the maximum and minimum values of the current and voltage.

There are two methods for phase shifting; the autotransformer method; and the revolving field method. In the former method the emf at the desired phase difference is obtained by adding voltages which are 120° apart. Three autotransformers are connected in delta to three phase feeders, as in Figure 1. Taps leading out from each of the three transformers give intermediate values of the emf in each phase. An emf of any desired phase relationship with any of the primary phases could be obtained if the number of taps were infinite. There are two limitations or objections to a phase shifter of this type. The shifting must be step by step, and the number

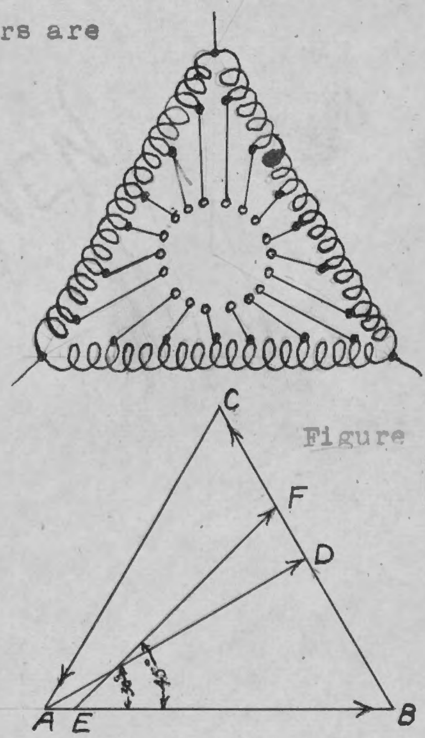


Figure 1.

of steps possible is limited by the number of taps. If the taps were to be arranged so as to keep the secondary voltage constant for each setting, and a setting for every electrical degree, 120 leads from each of the three transformers would be necessary. The second objection is the difficulty of placing the taps so as to maintain a constant secondary voltage. Referring to Figure 1, it is evident that if A-B, B-C and C-A are vectors representing the three primary voltages, then A-D, which is .866 times the primary voltage, is the maximum emf that can be had in all the phase relationships. To keep the secondary voltage constant, at a value equal to .866 of the primary emf at all settings, the primary components must be solved for each setting, and taps provided on the transformers to allow each of these components. For instance, Figure 1, to obtain an emf E-F, leading A-B by 45, the vectors E-B and B-F must be solved, and taps placed on the transformers to give voltages of these values.

The other type of phase shifter may be called a transformer, in which the current in the primary windings sets up a rotating field, that in rotating, cuts the wires of the the secondary, inducing an emf in the secondary. The shifting of the secondary with respect to the impressed primary emf, is accomplished by changing the position of the secondary in the rotating field. This type of phase shifter overcomes the difficulties encountered in the type formerly discussed. The value of the secondary voltage is governed by the ratio of the effective number of turns in the primary and secondary, and is constant for all positions of the secondary in the rotating field. The phase displacement is progressive, and the number of positions possible is unlimited. This was the type selected, and to be described in this paper.

II. Construction.

The materials used in making this phase shifter were a threephase, four pole, 220 V, half horsepower. squirrel cage, induction motor; about 300' of small cotton covered copper wire; a small amount of insulating material such as tape, paper and wooden strips; and a bit of metal and machine work in the indicating dial.

The armature of the motor, with no alterations formed the primary of the phase shifter. As has been stated, its purpose was to set up a rotating field. Discussions as to the cause and nature of such a rotating field can be found in almost any alternating current textbook, therefore the subject will not be discussed in this paper.

The secondary of the phase shifter was wound on the rotor of the motor. The squirrel cage was removed from the rotor, leaving a laminated core with

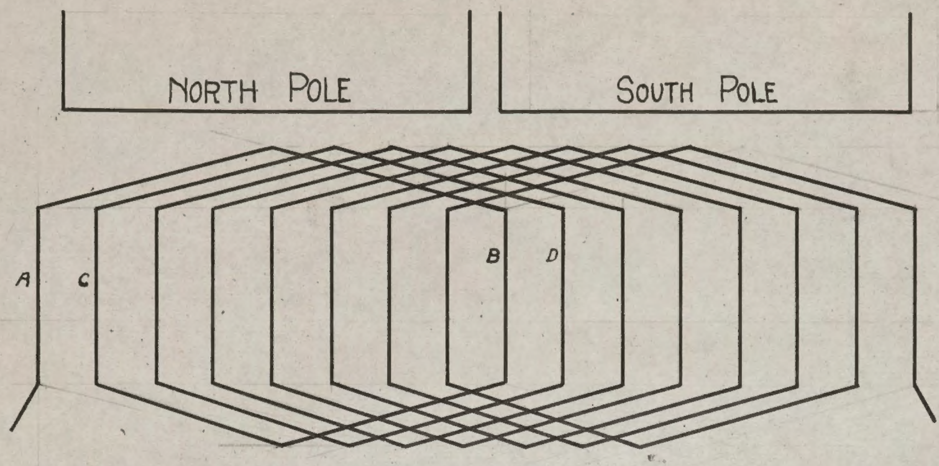


Figure 2.

thirty four, one quarter inch holes around the circumference. With a file these holes were formed into slots. Using the small wire, sixteen coils of seventeen turns each were wound. The number of turns, seventeen, was taken as the largest number of wires with insulating paper that could be placed in each slot. Two slots at opposite ends of a diameter were not used, leaving sixteen slots in each half of the rotor to be used. One side of a coil was placed in the slot next to one of those not to be used, A Figure 2. The other side of the coil returned through the slot B, eight slots to the right of A. The next coil was placed in the slots C and D; and so on progressing half the way round the rotor, eight of the sixteen coils were placed. The other half of the secondary core was wound in the same way, and the windings in both halves were connected in series. The coils were insulated from the core with insulating paper; insulation between coils was tape; and the coils were wedged in the

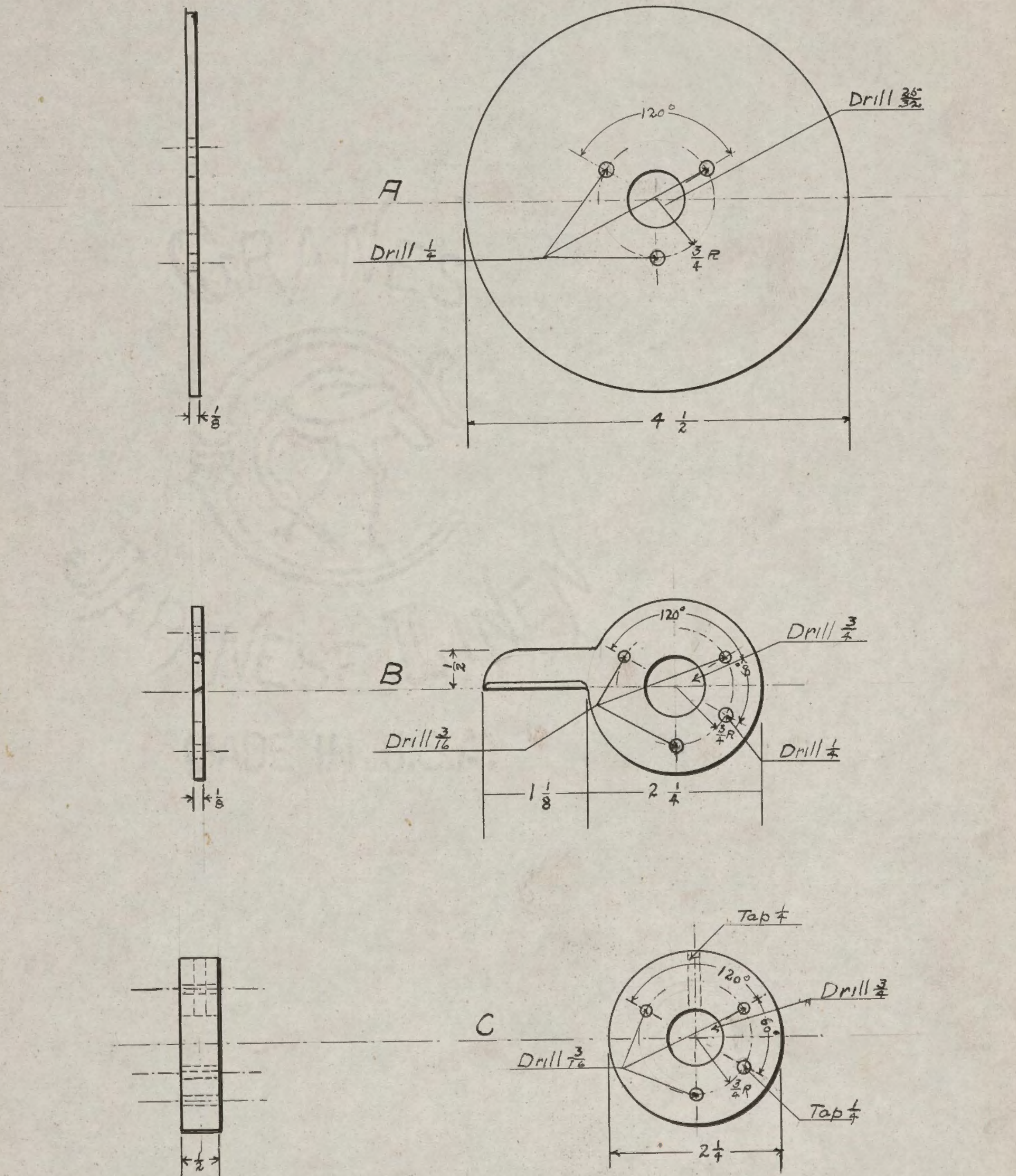

A
120°
Drill 25/32
Drill 1/4
3/4 R
4 1/2
1/8
B
120°
Drill 3/4
Drill 3/16
Drill 1/4
3/4 R
1/2
1 1/8
2 1/4
1/8
C
Tap 1/4
120°
Drill 3/4
Drill 3/16
3/4 R
Tap 1/4
2 1/4
1/2

Figure 3.

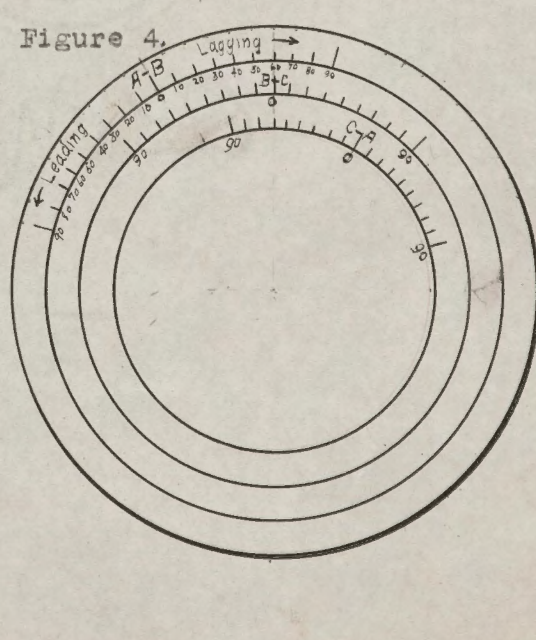
slots with wooden strips. A thick coat of shellac was applied to the windings to insure insulation and hold wires firmly in place.

Figure 3 shows all parts of the phase indicating arrangement. All parts are of steel and finished all over. The dial, Figure 3-A, has a disc of drawing paper glued to one side, to carry the marks indicating phase displacement. Pieces B and C Figure 3 are rivited together, and form the pointer and fastener. One set set screw through C fastens the pointer to core of the secondary winding, and another screw holds the core and pointer in any position.

IV. Calibration.

There are four poles in the rotating field of this phase shifter, the poles being 90 geometrical and 180 electrical degrees apart. Therefore one geometrical degree on the dial represents two electrical degrees. The three primary phases are 120° apart, and by reversing the secondary leads in one case the positions in which the secondary will be in phase with the primary phases will be 60 electrical or 30 geometrical degrees apart. This being known, the

Figure 4.



dial was marked as shown in Figure 4. Having the dial marked and fastened to the armature frame, the pointer must be fastened to the secondary shaft in the correct position, and the dial and primary leads marked to show their phase relationship.

The three primary leads of the phase shifter were marked A, B and C respectively. A 220V three phase emf was impressed on the primary. With a bank of lamps, a current was obtained in phase with A-B of the primary. This current was lead through the current coil of a wattmeter. The secondary emf of the phase shifter was impressed on the potential coil of the wattmeter. The secondary coil was shifted until the point of maximum power indication was found. With the secondary in this position the secondary emf was in phase with phase A-B of the primary. The pointer was fastened to the secondary shaft so as to indicate one of the 0 phase displacement marks on the dial, and this part of the dial was marked A-B to correspond with the primary markings. The current was then taken in phase with B-C of the primary. The secondary was shifted until the wattmeter again indicated maximum power. The pointer necessarily indicated one of the two remaining 0 phase displacement marks, or it indicated a point 90 from these marks. In this instance the pointer indicated one of the 0 phase angle marks. This part of the dial was marked B-C to correspond with B-C of the primary. The 0 phase angle position for the third phase, C-A, was checked in the same way.

The dial, Figure 4, shows that counter clock-wise rotation increases the lead, and reverse rotation increases the lag. The position of the primary phases is considered to remain at the 0 phases angle marks, and the secondary phase position moves with the pointer. If the secondary is shifted in the direction of field rotation, the time of maximum and minimum values of the emf is delayed and the lag of the secondary is increased. Therefore to correspond with the markings on the dial the field rotation should be clock-wise. The direction of the field rotation is governed by the phase sequence of the impressed primary emf. The phase sequence to cause a clock-wise rotating field was found in the following manner. A 220V, three phase emf was impressed on the primary. The secondary was connected to a rheostat, and the resistance was reduced until enough current flowed to cause an appreciable torque on the rotor. The primary leads were connected so as to cause the torque to be clock-wise. The phase sequence of the primary emf was found, and was marked on the primary leads.

Two other methods of finding the secondary positions for 0 phase angle with the primary were used to check the former method. First, a 220V emf was impressed on the primary. One of the secondary leads was connected to a lead of one of the primary phases. A voltmeter was connected between the remaining secondary and primary leads. The secondary was shifted until the voltmeter showed a minimum value. The pointer indicated 0 phase displacement mum value. The pointer indicated 0 phase displacement between this phase of the primary and the secondary emfs. Second, three voltmeters were connected in delta to the primary leads. An emf of 30V was impressed on the secondary. The secondary was shifted until the voltmeter in one of the primary phases showed a maximum value and the other two phase emfs were equal. The pointer indicated 0 phase displacement between the secondary emf and the primary phase showing the maximum emf. With a phase sequence indicator the three induced emfs in the primary windings of the phase shifter were proven to be in phase. There was no phase difference to be indicated, but the position of the secondary was exactly the same as in the two former methods.

The instrument readings in the three methods of calibration are dependent on the cosine of the angle of displacement. The cosine changes much more rapidly near 60° than near 0. Therefore the third method, in which the two emfs to be made equal are displaced from the single phase secondary by 60°, is the most accurate method of calibration.

V. Applied Theory and Calculations.

The primary and secondary voltage ratio is equal to ratio of the effective number of turns times a constant dependent on the magnetic leakage. The number of turns in each phase was determined by an actual count. The secondary was constructed with a definite number of turns. The voltage ratio of the phase shifter was found by experiment. With this data the coefficient of magnetic leakage may be determined. Using this coefficient, another phase shifter may be constructed, with the same type of material, that will have a predetermined voltage ratio.

Three factors enter into the effective number of primary turns. They are the actual number of turns, the distribution factor, and the relative single phase magnetization ratio. The number of turns in each phase was found to be 336. The distribution factor for a three phase winding of this type is .966. The primary windings may be considered as three coils in the relative positions, shown in Figure 5.

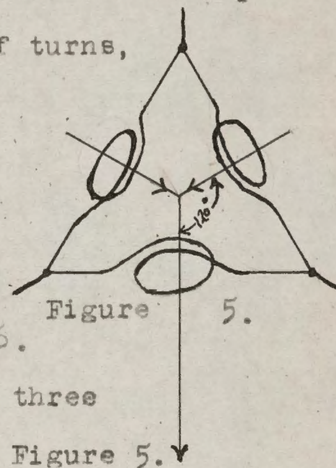


Figure 5.

If at one instant the current in one coil is maximum and positive, the current in the other two coils is one half maximum and negative. It is evident that the magnetizing effect is 1.5 times that of one coil. And the effective number of primary turns is

$$.966 \times 336 \times 1.5 = 487..$$

The effective number of turns in the secondary is the actual number of turns (272) times the distribution factor. From Figure 2, it can be seen that there are eight slots under each pole. These slots are 360/34 or 21.17 electrical degrees apart. The vectors in Figure 6-A represent the emfs in the eight slots

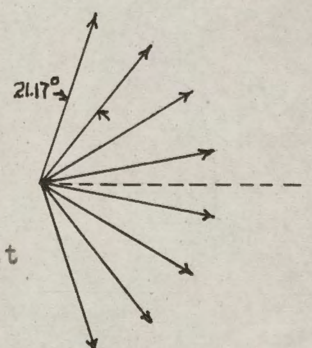
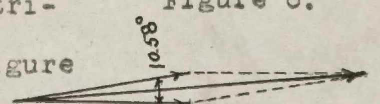


Figure 6.



slots, 21.17° apart. Their vector sum is .682 of their arithmetical sum. The centers of the eight slots under the north and south poles are eight slots apart, but 180 electrical degrees covers 34/4 or 8.5 slots. The sum of the emfs, under the two poles, are out of phase by .5 slot or 10.58°. The total voltage, Figure 6-B, is reduced by the factor cos 10.58°/2 or .995. Therefore the effective number of turns in the secondary is

$$272 \times .682 \times .995 = 185.$$

The primary and secondary voltages were 61.5 and 221. Letting μ represent the coefficient of magnetic leakage, then

$$\frac{61.5}{221} = \frac{185}{487} \times \mu$$

$$\text{or } \mu = \frac{61.5 \times 487}{185 \times 221} = \underline{\underline{.733}}$$

VI. Conclusion.

This phase shifter has two faults. First, as most instrument calibration requires an emf of 110V, the maximum secondary emf, 61.5V is not satisfactory. But with the data in this paper, and making a better choice of materials and construction, a phase shifter having a secondary emf of 110V could be constructed. Second, the resistance of the secondary windings is 11.2 ohms. If more than .5 ampere is required, the dial calibration will not be accurate.

Aside from its use as a phase shifter, the device may be used as an instrument transformer. If 50V is impressed on the single phase of the shifter, an emf can be had in any of the three primary phases, that can be varied from 0 to 155 volts.

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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