THESIS

ALTERNATING CURRENT WAVE FORM

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Alternating Current Wave Form.

-Thesis-

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-by-

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Introduction.

The great importance of wave form in alternating current work is never denied, though it is very often overlooked. In fact no references are available in which the question is put in a form understandable to the average man who might have to deal with this work. It is true that some very complete treatises have been written on the subject but in most cases they are too full of complex mathematical formulae for the ordinary person to understand and an attempted study often becomes discouraging. It is to fill this demand that this thesis has been written, and while it is impossible to explain some of the phenomena in simple language we have, to a great extent, used only simple terms that should be understood by any student of Electrical Engineering.

Now the question of wave form is of special interest to the power-plant engineer. Upon it depends the answers to the questions: whether he may ground his neutral wires without getting large circulating currents; whether he may safely run any combination of alternators in parallel; whether the constants of his distributing system are of an order liable to cause dangerous surges due to resonance with the harmonics in the pressure waves; what stresses he is getting in the insulation of the apparatus due to surges when switching on and off.

These are but a few of the questions that may arise and which may be answered only b. a study of the wave-forms involved, Furthermore, an oscillograph study will often explain in a simple and conclusive manner the theory of operation of certain apparatus and the condidions for best operation. For instance it has been shown that the luminous efficiency of the alternating current arc may be 44% higher with a flat topped wave than with a peaked pressure wave, while on the other hand it is a well known fact that transformers are more efficient on a peaked wave. also the accuracy of many alternating current instrumants depends upon the wave form. All these and numerous other questions should be answerable by the engineer and it is to take up this practical side of the question that the work on this thesis was done.

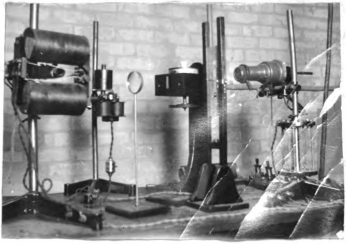
Laboratory Apparatus.

The photographs obtained were made with an oscillograph that was originally designed for lecture work only, where the wave form was projected upon a large screen. This fact necessitated the making of a suitable apparatus for obtaining the photographs clearly on a small film. To do this a small drum was made upon which a strip of motion-picture negative about 12 inches long could be mounted. By means of a suitable containing box, manipulation was made very simple as far as the handling of the film was concerned, a dark room being necessary only while the film was being mounted on the drum and this was done in the developing room. This drum carrying the sensitive film was then rotated in front of the oscillograph ribbons and by means of a timed shutter exposure was made for one revolution of the drum. Because of this single exposure a synchronous drive was not necessary on the drum but to approach very nearly this condition an induction motor was used with a belt drive to reduce the speed from 1150 to 400 rpm. This speed spread the wave out enough to show harmonics as high as 3000 cycles per second.

Due to the fact that the oscillograph elements were not oil immersed they were not well damped and some trouble was encountered when the wave form under observation contained harmonics of an order that would cause resonance with the ribbons. The operation of the instrument in all other respects was better than expected and this one defect was not at all serious.

The transformern and other apparatus that was used in the work were all of ordinary design such as would be found in practice and we are sure that conditions obtained are as they would be in commercial work.

No attempt was made to obtain quantative measurements of any kind for this would have carried us beyond the scope of our work and far beyond the limit of time which was available. Load tests on transformers were not made for the same reason, furthermore, the operation under load could easily be determined without the use of the oscillograph. We are more interested in the study of the apparatus under no-load conditions in this work.



Alternator Wave Form.

In any circuit the first source of voltage wave distortion is in the alternator. In any machine on open circuit, the voltage generated is directly proportional to the instantaneous rate of cutting lines of force. A simple conductor revolving in a uniform magnetic field at a uniform velocity will generate a sine voltage wave. Hence any in any machine distortions may be caused by;

1) Lack of uniformity or pulsation of the field;
2) Variation in the speed;
3) The distribution of the conductors on the armature which are connected in series.

In present-day machines the speed remains so nearly constant that distortion from this source need not be considered.

The slotted armature however effects the distribution of the flux causing it to be concentrated at the teeth which are directly under the pole face. It is quite evident that if the number of teeth under the pole face is different at different positions of the armature there must be a corresponding variation in the flux, which in turn must cause distortions in the voltage wave. This may be plainly seen in the accompanying figure (Fig.1) where the size of the teeth have been exaggerated to more clearly bring out the point.

In figure 1 the width of the pole face is such that in the first position a_1 there are two teeth directly under the pole and with a reasonable allowance for fringing, the two teeth may

be considered as carrying a flux about as shown. Consider then the same pole moved to a position a_2 one tooth distant. There is at this time but one tooth directly under the pole face and the fringing to the adjacent teeth is not enough to make up for the loss. Under this condition it is evident that there will be pulsations of the magnetic reluctance of the field circuit ant with constant excitation a pulsation of the magnetic flux. This pulsation will be at a frequency of 2S in a machine with S slots per pole, and the harmonic of e.m.f. induced will be 2S-1 and 2S+1 times the fundimental frequency.

Fig. 1. Fig. 2.

In order to reduce the amplitude of these pulsations the pole face could be made as shown in the figure 2 where it covers an additional width about equal to the width of a tooth. In this case it can be seen that the variation of flux between the positions of maximum and minimum reluctance is not nearly so great as was the case in fig.1.

It is also evident that an increase in the number of slots per pole would have the effect of reducing the amplitude of the pulsations and at the same time would increase the frequency of the pulsations, both of which would be desirable. In the design of a machine both the shape of the pole face and the number of slots must be considered with respect to the harmonics that will be introduced in the voltage wave form.

Besides this pulsating of the flux due to variations of the reluctance of the magnetic circuit there is a to and fro motion of the flux under the pole due to the action of the teeth as they come under the pole tip. This to and fro motion will be at a frequency of 4S and hence will induce an EMF of 4S-1 and 4S+1 times the fundimantal frequency. The amplitude of this harmonic will in most cases be such that it will not appear in the terminal voltage wave. In the photographs taken these higher harmonic ripples, together with the ripples due to pulsation were found only on the converters and it is very likely that the D.C. comutation had a pronounced influence.

The third condition that may effect the presence of harmonics in the terminal voltage of an alternator is the distribution of the conductors on the armature which are connected in series.

A full pitch concentrated winding will have generated in it an EMF wave of the same shape as the field distribution and will be symetrical. A fractional pitch or "chorded winding" will have the effect of smoothing out the wave to conform more nearly to a sine form and while it is possible that the wave will not be symetrical during both halves of the cycle the probility of this distortion is very remote.

Further, if there are a number of conductors per pole which are spread over a number of slots as in a "distributed winding" the effect will be much the same but more pronounced, the greater the distribution the more nearly will the EMF wave approach a sine form regardless of the flux distribution.

It is possible by proper selection of distribution and pitch of windings to suppress certain undersireable harmonics so that they do not appear in the terminal voltage of the machine. This may be shown in the following illustration;

Assume that the flux distribution of a particular machine is such that an undesireable third harmonic is generated in the windings. It is desired to eliminate this harmonic from the terminal voltage.

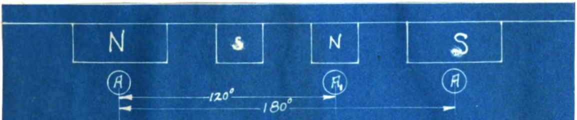


FIG. 3

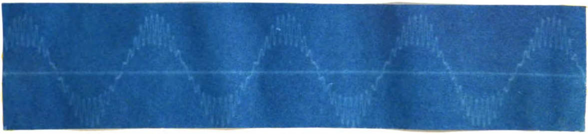
In figure 3 are shown two poles of an alternator and a full pitch windingsrepresented by the conductors AA. Under the assumption that the flux distribution of these poles is such as to generate a third harmonic we may consider that this third is generated by auxiliary poles as shown ,instead of a distorted flux in the main poles. A full pitch winding under such an arrangement will have generated in it a third harmonic superimposed on the fundimental. Now if we replace the full pitch winding with one spanning only 120 fundimental degrees or 2/3 pitch as shown ,A_1A, no triple frequency can appear at the terminals of the winding for as far as the third harmonic is concerned the conductors are passing under like poles at the same instant and the e.m.fs. generated in each are neutralized.

This is of course only a rough illustration but it is acceptable because of its simplicity. It might be said then that a winding of 2/3 pitch and distributed over 60 degrees can have no third harmonic appearing at the terminals. At the same time the ninth, fifteenth, and other odd multiples of the third are eliminated.

In the same manner a winding could be designed to eliminate other harmonics instead of the third and its multiples, Or, if not entirely eliminated may be reduced to such a low value as to have little or no effect in distorting the terminal e.m.f. Distribution of the windings will have this effect and may even eliminate some of the harmonics entirely. In a distributed winding the e.m.fs. generated in the several coils are out of phase by an amount depending upon the number of slots included in 180 electrical degrees on the armature. The resultant of these several e.m.fs. will then be less than would be the case where the e.m.fs. are in phase. The greater the distribution the greater will be this reduction. Furthermore, the reduction factor is not the same for the fundimental as for the higher harmonics but will be far greater for the latter. This may be illustrated by considering a winding which is distributed over 60 degrees. This winding will be distributed over 180 third harmonic degrees with a consequent greater reduction factor.

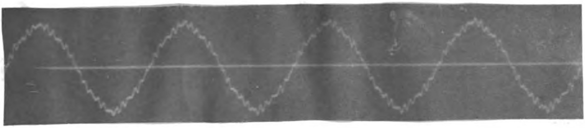
Thus it is evident that the wave form of an alternator may be so regulated by proper design as to be almost entirely free of undesirable harmonics, especially those of the lower orders.

To show the application of the principles outlined above we have photographs of the terminal e.m.fs. of all the generators in the laboratory. These are shownin the following pages together with a brief explanation of the cause of the distortions where they appear.



Fort Wayne Alternator Type TAB Form ML
25 KW, 120 Volts, 120 Amps, 1800 RPM.

This is a four pole revolving-armature type with 48 slots making 4 slots per pole per phase. An examination of the wave shows a good sine form but with a pronounced 23 harmonic. The amplitudesof these "tooth ripples" are a about 15% of the fundimental. The source of the ripples is easily found from the formula given on page 6. The machine has 48 slots and four poles hence S= 48/4 or 12 slots per pole. The tooth ripples due to pulsations of the field would then be 2S-1 or a twenty-third harmonic. An examination of the poles showed a design which would give a maximum of pulsation. The pole-face could have been made slightly wider or narrower and the amplitude of the ripples would probably be reduced considerably. Furthermore, the narrow air-gap employed is most favorable to the production of flux pulsations. If a wider air-gap could be used it would also help in eliminating the ripples.



-2-

General Electric 10 Kw Rotary Converter.

DC Volts -220 Amps- 45.5

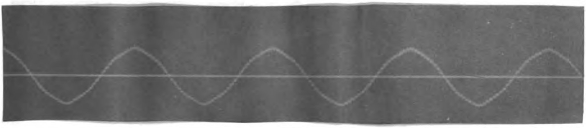
AC Volts -147 Amps-43

1800 RPM.

This machine is also a four pole machine with a 48 slot armature making four slots per pole per phase. The photograph shows a slightly peaked wave form containing a twenty-third harmonic of about 9% amplitude. These ripples again follow the formula f= 2s-1, S being equal to 12 as in the previous case. The peaked wave is due to a fifth harmonic in the flux distribution.

The phase-belt of a converter is necessarily a span of 120 degrees which for the third harmonic corresponds to 360 degrees. Hence any third harmonic will be neutralized and can not appear in the terminal e.m.f. as is also the case of any odd multiple of the third.

But even if at were possible for the third harmonic to appear at the terminals of the windings it could not appear in the terminal voltage of the machine due to the delta connection which would cause the third and any multiple of it to be short-circuited in the closed delta.



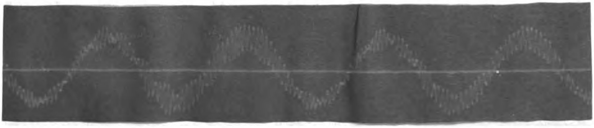
-3-

Western Electric Converter 5½ K.W.

This machine was built from a 7½ hp motor and hence has no special name-plate data.

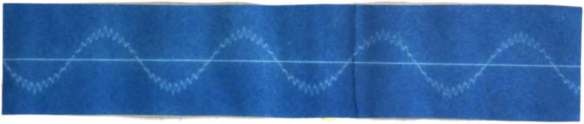
The wave form is very similiar to that obtained from the G.E. machine except that the tooth ripples are not as prominent and are of a higher order coming perhaps from the to and fro motion of the flux which would give a 47th or 49th in a 48 slot machine with four poles as explained on page 7. Sparking at the commutator also seemed to contribute to this action.

(These double frequency harmonics were also found to appear in the e.m.f. of the G.E. converter during later runs and with too great a consistency to be chargeable to a resonant condition in the ribbons of the oscillograph.)



-4-

From a 1½K.W converter built as a thesis experiment by one of the students. This is a 31 slot machine and plainly shows a 31st harmonic due undoubtedly to the to and fro motion of the flux.



-5-

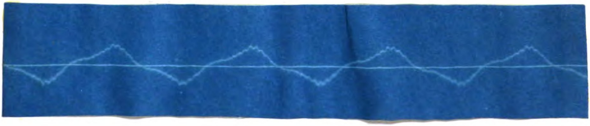
Fort Wayne Alternator #17088 Type TRB Form BS

50 K.W. 2300 Volts, 12.5 Amps 1200 R.P.M. (Star connected)

This machine is a six pole revolving-field type with 72 slots . Again we have 12 slots per pole and from the formula 2S+1 we obtain a 25^{th} harmonic which is that present in the photograph.

-6-

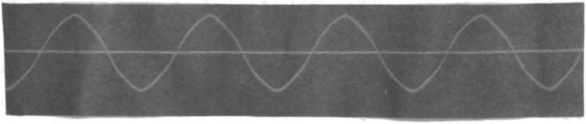
No-load voltage from line to neutral of the above alternator. This wave is slightly flat topped due undoubtedly to a third harmonic in the flux distribution. This distortion cannot appear in the line voltage of the machine because of the star connection which elliminates the third.



-7-

This shows the voltage from line to neutral of the same machine when under approximately full-load. The very pronounced third harmonic present is due to armature reaction and will be found in the neutral voltage of any alternator under load. The magnitude of this third will depend not only on the load but upon the power-factor, a lagging current producing much greater distortion than the same current at unity power-factor. Of course it is also fundimentally dependent on the design of the machine. Special design to eliminate this harmonic is possible and forms an exception to the above statement.

The presence of this third harmonic at the neutral of an alternator forms a most interesting problem in the interconnection of the neutrals of machines when operating in parallel. This will be taken up briefly in the following pages.



-8-

This photograph is of interest merely to show how the "tooth ripples" are eliminated on the line when several alternators are operated in parallel. This must of course be accompanied by an equalizing current in the connecting lines.

Parallel Operation of Three Phase Generators, with Neutrals Interconnected.

The subject of neutral currents has been discussed in considerable detail in the following work on transformers so a complete discussion will no t be placed here. It is generally understood that they are of triple frequency and are produced by those harmonics of e.m.f. which cannot exist in the lines of a three phase system. We will take up the subject as related to the parallel operation of alternators.

Consider a three phase star-connected generator in whose windings e.m.fs. are generated containing triple harmonics. The e.m.fs. in the coils differ in phase by 120 fundimental degrees, the third harmonics differ by 3× 120 or 360 degrees, the ninth harmonics by 9×120 or 1080 degrees, or, the triple, ninth, fifteenth and all odd multiples of the third harmonic are in phase in all three coils. Since the potential difference between the outer terminals of the two windings is equal to the potential difference between the the e.m.fs. generated in the coils- the triple harmonics and its odd multiples will disappear. Other harmonics will not be eliminated and will appear in the same magnitudes as in the coil voltages. Thus in a 3 phase star connected system no triple harmonic voltage can exist between the lines.

If this generator is connected to a balanced star-connected load currents will flow in the lines of such wave-form and magnitud that the potential dif erence between the terminals and neutral point (of the load) will differ from the coil e.m.fs. of the generator only by containing no triple harmonics. There can be no currents of these frequencies because they would be in phase in all three lines and hence could have no return path. It is evident that there will exist between the neutral of the generator and that of the load, a voltage made up of the triple harmonics generated in the coils of the alternator. If these points are connected currents of corresponding frequency will flow. The current in this interconnection will be three times the triple frequency in the lines.

If instead of a load another generator is connected to the first a difference of potential will exist between their neutrals equal to the vector difference between their coil emfs. With the neutrals interconnected a current will flow limited by the impedances of the machines to triple harmonics. These impedances are in general much smaller than the synchronous impedances.

If the triple frequency e.m.fs. in the two machines are equal and in phase there can be no neutral potential difference and hence no current in the neutral. This ideal condition can exist in general only when one or more of the following conditions are observed;

1. Equal instantaneous angular velocities,
2. Similiar wave forms,
3. Equal loads,
4. Excitation corresponding to the load,
5. Absence of all triple harmonics.

1) Reciprocating machines whose angular velocities pulsates will produce surging between the alternators operated by them.

It has been found by experience to be more troublesome in producing neutral currents than interchange between phases. Machines that will operate very satisfactorily without neutral connections have caused serious trouble when operated with them. The obvious preventative for trouble of this kind is more uniform rotation - the use of turbine drive.

2) Machines frequently differ considerably in wave form. They may be similiar at no load but differ when loaded on account of armature reactio n. Attempts to operate generators thus differing have resulted in enormous neutral cutrents. The preventative in this case is careful adjustmant of wave forms.

3) As stated above, generators may have the same wave forms at no load or at equal loads yet the forms at any two different loads may be dissimiliar. Machines thus operated at unequal loads will show neutral voltage or currents. These load differences are easily controlled except in the case of surging mentioned above,so no trouble should arise. At the instant of synchronizing however, the load difference is a maximum and serious trouble may occur. Difficulties of this kind has made the operation of synchronizing impossible with several machines on the line. The obvious preventative is to close the neutral connection after the loads are adjusted.

In all the above cases the interchange of triple harmonics may be reduced by using impedances which are inserted in the neutral connection. These impedances may be objectionable on account of their size or the voltage drop in case of unbalanced load. The neutral currents may be eliminated by the connection of but a single generator to the neutral bus but this method has its limitations. If more than one generator must be operated with neutral connection and if impedances are undesirable then the only remedy is to obtain machines generating no triple harmonic e.m.fs.

It is unsafe to depend on satisfactory operation of alternators with interconnected neutrals unless triple harmonics are eliminated by proper design. Such machines are practicable and should be specified whenever parallelling of neutrals is required.

Alternator Wave Form.

The following oscillograms were obtained at the Ottowa Street station of Lansing Municipal Power Co. They are especially interesting and valuable because they show what may be expected from large well designed turbo-generators.

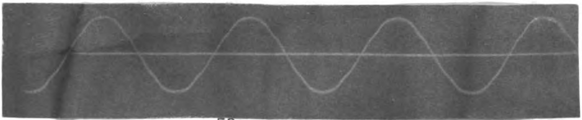
We had also hoped to study the current wave-forms in the various lines and tie-lines between neutrals of the machines. At the time the instruments were set up there was nothing of special interest to be obtained so we were obliged to abandon this idea.

Unit #2.

-Name-plate Data.-

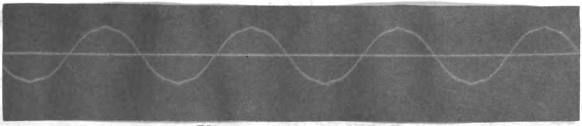
Westinghouse Alternator
Serial No. 702222
2500 K.W. 4000 Volts, 361 Amps.
3 Phase, 60 Cycle, 1200 R.P.M.
(Y-Connected.)

This machine had been in operation in the plant for a number of years but is of comparatively recent design.



Phase Voltage of above Alternator. (No load)

This oscillogram shows a slight fifth harmonic which produces a flat-topped wave. It is undoubtedly due to a fifth harmonic in the field distribution.

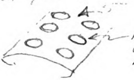


-39-
Voltage- Line to neutral.

Westinghouse 2500Kv.A. (No load.)

While the chording and distribution of the windings tend to reduce distortions produced by the non-sinusoidal flux distribution there is still evidence of it in the terminal voltage as shown by the above photo.

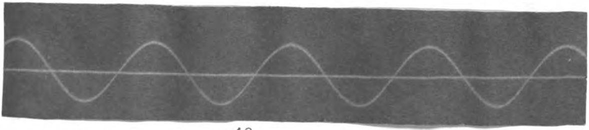
It would seem that since the wave is peaked, that the the field must contain this same distortion. It is probably due to the rotor not being slotted uniformly around the circumference but having the iron left solid at the center of each pole. ; Inspection at a later date shows salient pole construction, with pole [illegible] as sketched.



Unit #3. -Name-plate Data-

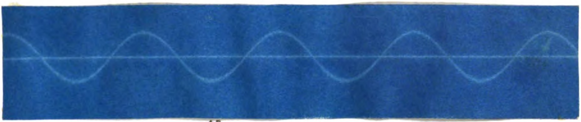
General Electric Alternator.
Serial No. 889489.
Type ATB-2-6250-3600 Form HT.
3600 R.P.M.
P.F. .8 5000 K.W.
2300/4000 Volts.

This machine was installed about 1917 and consequently represents a very recent design.



-40-
Phase Voltage 5000K.W. Gen. Elect.

This shows a very good wave form with no visable harmonics. The tooth ripples are hardly discernable on the film and to all practical purposes, have been effectively eliminated.



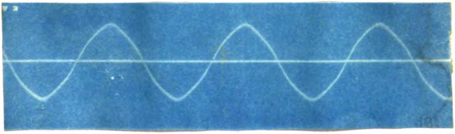
-41-

Voltage- Line to Neutral. (No load)

5000 K.W. Gen. Electric.

As was the case with the phase-voltage, this wave is free of harmonics and represents the results of good design.

It would be very interesting to see the line-neutral voltage under full load but this was impossible to obtain at the time. It is probable that very little if any third-harmonic would be present . If this were the case one could be certain that several machines of this type could be operated in parallel and with neutrals interconnected without danger of excessive circulating currents.

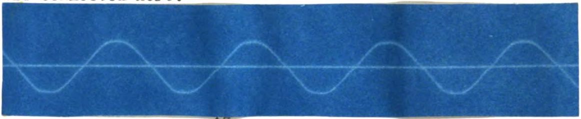


-42-

Phase-Voltage (Incoming Bus)

This voltage was taken from the buses that tie in with the machines at the Cedar St. station. At the time the oscillograph was taken there were three machines connected to the lines.

These were a 2500 KW and a 2000 K.W. machine at Cedar Street station connected to a Delta-Delta step-up bank and transmission line to a step-down bank connected Delta-Star with the neutral grounded. (This secondary voltage is thereby made suitable for connecting in with the 4000 volt machines at the Ottowa street station.) A small water-power plant is stationed near this last bank of transformers and a 700KW. machine with grounded neutral was connected here.



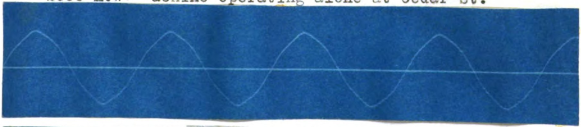
-43-

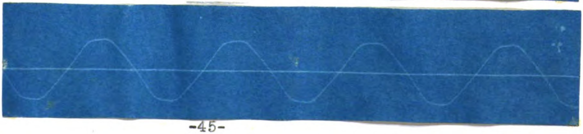
Line to Neutral. (Incoming Bus.)

Taken at the same time as No. 42, we find the same wave shape as was obtained in the laboratory for the delta star connection, that is, the wave is slightly flat-topped.

-44-

Phase voltage (Incoming Bus)
2000 K.W. Machine operating alone at Cedar St.





-45-

Line to neutral voltage. (Incoming Bus.)
2000 K.W. Machine operating alone at Cedar St.

From a study of these curves it will be apparent that they are not similiar and that in parallel operation, circulating currents are bound to exist. This will be especially true of the neutral tie lines due to the greater difference between the wave form of the neutral voltage in the different units and from the transformer bank. Furthermore, when loaded, this difference in wave form may be greatly increased beeause of the difference in characteristics betweent the alternators and the transformer, the latter having the same through all ranges of load while the neutral voltage of an alternator under load will very often contain a strong third-harmonic due to armature reaction.

At various times trouble has been experienced in this plant besause of the excessive circulating current in the neutral wire.

Wave form in Alternating Current Circuits.

Distortion of wave form will occur whenever a sine e.m.f. is impressed upon a circuit containing;

1) Pulsating inductance,
2) Pulsating Resistance,
3) Pulsating condensance.

In many commercial circuits one or more of these conditions may be found with consequent distortion of either current or voltage waves.

1) Thus in any circuit containing an iron-clad inductance the reactance varies while the current changes from its zero to its maximum values. Moreover the variation is not the same for the decreasing as for the increasing values of the current.

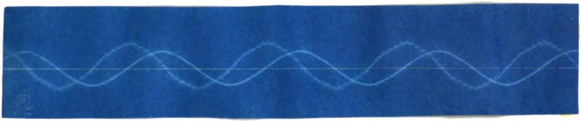
2) Likewise the resistance in the vapor of an arc lamp decreases with increase of current and produces interesting distortions of the current or voltage waves.

3) Similarily under conditions where corona is produced at the crest of the voltage wave the condensance pulsates during the voltage cycle. In a long high voltage transmission line this produces distortions in the charging current.

It is evident that in the discussion of current wave shapes we must divide them into two groups;

a) Circuits with constant resistance, inductance and capacity.
b) Circuits with pulsating resistance, inductance and capacity.

a) If the voltage applied to a circuit containing constant r, L and C is of sine form, the current will necessarily be of sine form of the same frequency but differing in magnitude and phase position. (Photo 9.)



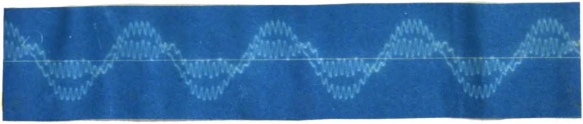
-9-

But if a complex wave of e.m.f. be applied each harmonic will produce its own current independent of the fundimental or any other harmonic. However, the relative magnitude of the harmonics will not be the same as for the voltage wave for in each case the maximum current for each harmonic depends upon the impedance of the circuit to that harmonic. It is readily seen that the relative values of r,L and C are of great importance in determining the current wave from a given impressed voltage wave.

Thus a circuit containing resistance only will have a current which is in phase with the voltage wave and of the same form.

In a circuit having both resistance and inductance the current wave differs from the impressed voltage. The higher the harmonic the less current flows for the same impressed voltage due to increase in reactance with increased frequency. For this reason the current harmonics are smaller than those in the voltage and the current wave more nearly approaches the sine form.

In a circuit having resistance and condensance the reverse is true because with an increase of frequency the impedance is lowered with a proportionate increase in current. Hence a complex voltage wave impressed upon such a circuit will give a current wave in which the relative values of the harmonics will be far greater than were found in the voltage wave. This is shown in photo 10 which is the impressed voltage and the line current of a transformer which has a small condenser connected across the secondary. While this does not show a sinusoidal current wave due to the presence of iron in the transformer it does show the amplification of the harmonics by the condenser.



-10-

(Such would be the effect if this e.m.f. was applied to a long transmission line- the charging current would contain very pronounced harmonics.)

If a circuit contains resistance, inductance and capacity, the wave form of the current with a given impressed voltage will be determined by the relative values of these quantities.

Distorted current waves in circuits with pulsating inductance.

The main sources of pulsation in inductive reactance in a circuit are;

1) Variation of the reluctance around the armature conductors due to synchronous rotation.

2) Variation in permeability and the hysteresis with the flux density in iron-clad circuits.

The pulsation of the generator field caused by the relative position of the armature slots as a primary source of voltage distortion is discussed in the previous work on alternators. It is evident that a similiar effect is produced by a synchronous motor or any other synchronous apparatus with slotted armature in the circuit. The harmonics introduced are obtained form the same formulae that are applied to generators. With a large air gap, large number of slots per pole, proper shaping and spacing of the armature slots and using fractional pitch windings the distortions produced by pulsations in the synchronous reactance may be reduced to practically negligible values.

The second factor producing pulsations of inductive reactance is present in all iron-clad circuits. The value and nature of the distortion depending upon the hysteresis loop of the particular iron used.

Consider an iron-clad circuit having an alternating e.m.f. applied. The impressed voltage must at each instant be balanced by the induced or counter e.m.f. produced by the increasing or decreasing magnetic flux. Hence a magnetizing current will flow in the circuit just sufficient to produce the flux required to balance the impressed voltage.

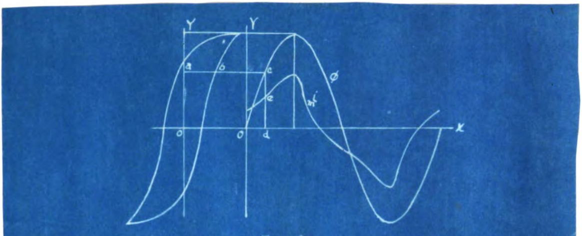


Fig. 4.

With a given hysteresis loop and sine flux the magnetizing current corresponding to any point on the flux wave is found by drawing the horizontal line ac Fig.4, and taking the distance ab from the hysteresis curve. By laying off on ordinate dc the distance equal to ab one point on the current wave is found. The maximum of the current will come at the same time as the maximum of the flux wave but the current wave will not be of sine form. It will consist principally of a third and a smaller fifth harmonic superimposed on the fundimental sine wave.

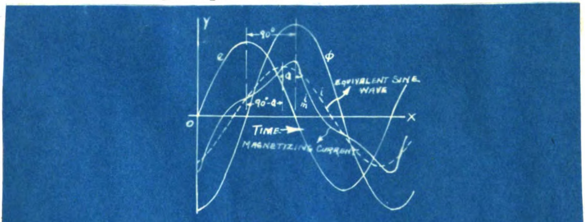


Fig 5

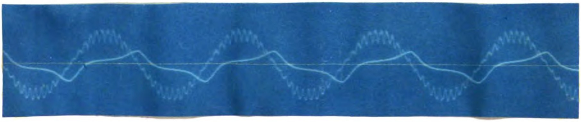
In figure 5 are shown the impressed voltage, magnetizing current and flux in an iron-clad circuit. The equivalent sine wave of current is drawn to show that there is a power component consumed by hysteresis. It is equal to the product of the current, voltage and cosine of the phase angle,($90^o-\alpha$).

Transformers.

The single phase transformer is the simplest and most efficient of alternating -current apparatus. It consists of a magnetic circuit interlinked with two electric circuits,a primary and a secondary. At full load both the leakage flux and the power loss in the transformer are small compared with the total flux and the power transmitted and in a preliminary discussion need not be considered.

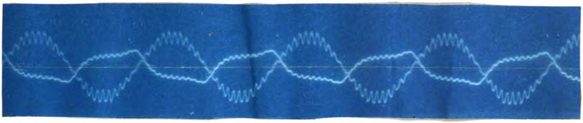
In an "ideal" transformer (one having no losses) the voltage ratio is directly and the current ratio inversely proportional to the number of turns. The ratio between the number of turns on the primary and secondary may be any value and in commercial designs it varies within wide limits.

The current and voltage relations in the primary and secondary windings are clearly shown in the following oscillograms.



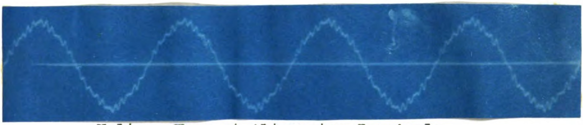
-11-

Here it is evident that the primary magnetizing current lags the impressed voltage by 90° as shown by the fact that the maximum of current occurs when the impressed voltage is passing through the zero value. The distortion of the current wave due to the variation in permeability of the core, is also plainly shown.

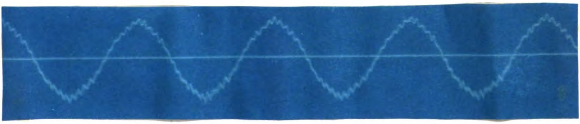


-12-

This shows the primary magnetizing current and the secondary e.m.f. A comparison of 11 and 12 shows conclusively that the secondary e.m.f. is 180° out of phase with the primary impressed voltage.

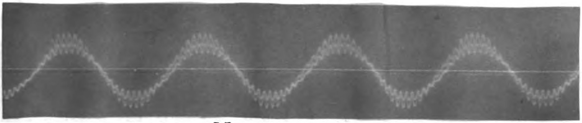


Voltage Wave at Alternator Terminals.
-13-



Voltage Wave at Secondary of Transformer.
-14-

Photograph 14 shows the same voltage wave that is shown in 13 except that it has been through a transformer. It is merely to show that the secondary voltage is an exact duplicate of the impressed voltage under ordinary conditions-when operated single phase.



-15-

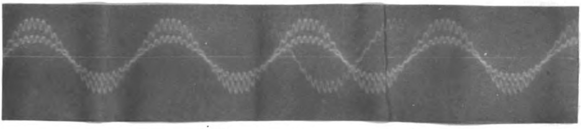
Secondary e.m.f. of transformer and secondary amps. with a light load at unity power-factor. It is interesting to note the duplication of voltage harmonics in the current wave.

Current Transformers.

The above transformers are all of the constant potential type. In power measurement work transformers are necessary to allow the measurement of heavy currents with small meter elements. It is common practice to use 5 amp. meter elements and depend upon current transformers to increase the range of the instrument. These transformers are usually built with ratios of 5/1, 10/1, 20/1, etc.

The accuracy of the measurements is of course dependent upon the accuracy of the ratio. At full load this is less subject to error than at lower loads. The chief cause of error in ratio is the employment of an impedance in the secondary circuit higher than that for which the transformer was designed.

For power measurements it is necessary to know that not only the ratio of transformation is correct but that the phase relation of the primary and secondary currents are correct. In other words, the secondary current must be an exact image of the primary current.



-16-

To show this we have taken an oscillogram showing the line voltage and the secondary amps. from a 5/1 current transformer. The load was about 20 amperes at unity power-factor. (Photo 16.) The current wave from the secondary of the transformer is not appreciably out of phase with the voltage and a comparison with the oscillogram 15 shows that it is an exact image of the line current.

Transformers in Three Phase Circuits.

The wave shape distortion in an iron-clad magnetic circuit has a very important bearing on transformer connections in three phase circuits.

The e.m.f. and currents in a three phase system are displaced from each other 120 degrees. Their third harmonics differ by 3×120 or 360 degrees,or,are in phase with each other. That is, whatever third harmonic of e.m.f. or current may exist in a three phase circuit must be inphase with each other in all three phases, or in other words, for the third harmonics the three phase system is single phase with no return circuit.

1) The sum of the three emfs. between the lines of a three phase system is zero. Since their third harmonics would be in phase and so add up, it follows;

That the voltages cannot contain any third harmonic or overtones. (3^{rd}, 9^{th}, 15^{th}, 21^{st} etc.)

2) Since in a three wire three phase system the sum of the three currents is zero but the third harmonic current would be in phase and their sum therefore not zero, it follows;

That the currents in the lines of a three wire three phase system or in other words the Y current cannot contain a third harmonic.

Third harmonics however can exist in the Y voltage or the voltage between line and neutral of the system and since the third harmonics are in phase with each other, in this case a potential difference of triple frequency exists between neutral of the system and all three phases as the other terminal, In other words, the whole system pulsates against the neutral at triple frequency.

Third harmonics can also exist in currents between the lines or, delta currents, since the two currents from one line to the other two lines are displaced 60 degrees from each other their third harmonics are in opposition and therefore neutralize. That is, the third harmonic in the delta currents of a three phase system do not exist in the Y currents in the lines but exist only in the local closed circuit or delta.

Third harmonics can exist in the line currents in a four wire three phase system or a system with grounded neutral. In this case the thirds of current return jointly over the fourth or neutral wire, and even with balanced load on the three phases the neutral carries a current of triple frequency.

With a sine wave of impressed e.m.f. the current in an iron clad circuit such as the exciting current in a transformer, must contain a strong third harmonic otherwise the e.m.f. cannot be a sine wave. Since in the lines of a three phase system the third harmonic cannot exist, interesting wave-shape distortions result in transformers when connected to a three phase system in such a manner that the third harmonic of exciting current is suppressed.

For instance, connecting three reactors as the primary coils of three transformers- with secondaries open-circuited- in star or Y into a three phase system with a sine wave of e.m.f. impressed on the lines; normally the voltage across each transformer should be a sine wave also and equal to $E_{line}/\sqrt{3}$. This however, would require that the current taken as exciting current

contain a third harmonic. As such a current cannot exist in a three phase circuit the wave of magnetism cannot be a sine wave b but must contain a third harmonic. The e.m.f. generated by this flux and therefore the transformer or Y voltage must contain a third harmonic and its overtones, and of an amplitude three times as great as that of the flux because of the triple frequency.

With three transformers connected Y into a three phase system with open secondaries we have then, with a sine wave impressed on the lines, the conditions:-

1) The voltage at transformers or Y voltage cannot be a sine wave but must contain a third harmonic and its overtones, but can contain no others as the fifth, seventh etc. would not eliminate by combining two Y voltages to the delta or line voltage and the latter was assumed to be a sine wave.

2) The exciting current in the transformers cannot contain any third harmonic or overtones but may contain all the others.

3) The magnetic flux is not a sine wave but contains a third harmonic and its overtones corresponding to those of the Y voltage but contains no other harmonics and is related to the exciting current by the hysteresis cycle.

The practical importance of this is that by suppression of the third harmonic of exciting current in the three phase system the effective value of the voltage per transformer or between line and neutral, is increased by perhaps 10% while the maximum value increases to perhaps 50% higher than normal and the voltage wave is very peaked by a pronounced third harmonic of about 40% of the effective value of the total wave.

The very high peak of e.m.f. produced by this wave-shape distortion is liable to be dangerous in high potential three phase systems by increasing the strain on the insulators between line and ground and leading also to resonance phenomena with the third harmonic.

Assuming now ~~that in~~ such transformers connected primary in Y and the secondaries delta;

The third harmonic of e.m.f. generated in the transformers secondaries are then in series in short-circuit and thus produce a local current in the closed secondary delta. This current is of triple frequency and hence supplies the third harmonic of exciting current which was suppressed in the primary. That is, by connecting the transformer secondaries in delta the wave-shape distortion disappears and the voltage and magnetism are again sine waves and the exciting current is that corresponding to a sine wave of magnetism except that it is divided between the primary and secondary; the third harmonic of exciting current does not exist in the primary but is produced by induction in the secondary. Obviously in this case the magnetic flux and the voltage are not perfect sine waves but contain a slight third harmonic which produces the triple frequency exciting current.

If the primary neutral of the transformers is connected to a fourth wire as in a four wire three phase system or a three phase system with grounded neutral, and this fourth wire leads back to the generator neutral or a neutral of a transformer in which

the triple frequency current can exist- that is,in which the secondary is connected delta- the wave-shape distortion also disappears.

It follows therefore, that in a three phase system attention must be paid to provide a path for the third harmonic of the t transformer exciting current either directly or inductively, otherwise a serious distortion of the e.m.f. wave of the transformer occurs.

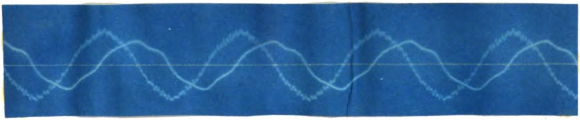
(Oscillograms were taken with different transformer connections to show that the theory given above is true. These photographs will be shown as the various methods of connecting are taken up.)

Three Phase Transformer Connections.

Delta-Y.

Connecting the primary in delta and the secondary Y becomes necessary in feeding four wire three phase systems. The Y connection of secondaries allows the bringing out of the neutral wire while the delta connection of the primaries maintains the voltage balance at unequal distribution of loads.

The delta-Y connection of step-up transformers is frequently used in long distance transmission to allow grounding of the high potential neutral. (Under certain conditions it is liable to induce excessive voltage by resonance with the line capacity.)



Prim.-Delta, Sec.- Open.
Primary line volts and amps.
-17-

Assuming a sine wave of current, the current-voltage relations in a three phase star connected circuit would make the line current at unity power-factor lead the voltage by 30°. But since the magnetizing current of a transformer is nearly 90° lagging we would expect to find the current in the above oscillogram leading the voltage wave by 30° - 90°. This would mean a lag of 60°. Apparently the lag is greater than this, but it must be remembered that the theory assumes a sine wave and if we reduce the current wave in the above photo to equivalent sine wave it will be found to lag almost exactly 60°.

It is also apparent that the harmonic present is a prominent fifth which may be expected in the exciting current of a transformer, but the third which is most prominent in single phase circuits is entirely absent in the three phase circuit. This is further support for the theoretical explanation of the fact that a third harmonic of current cannot exist in a three wire three phase line. (See (2) Pp.28.) The suppressed third harmonic of current will flow, however, in the closed delta as explained on Pp.31, for it is immaterial whether the delta circuit be on the primary or secondary side. (See photo 20.)

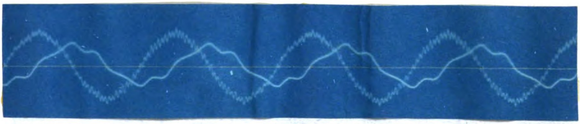
Y-Delta.

The Y-delta connection is, in general, not permissible since it gives what has been called a floating neutral; the three primary Y voltages do not remain even approximately constant at unbalanced loads on the secondary delta, but the primary voltage corresponding to the heavier loaded secondary and therefore also the corresponding secondary voltage collapses. Thereby, the common connection of the primary shifts towards One corner of the e.m.f. triangle or even outside of it. As a result the secondary triangle becomes very greatly distorted even at moderate unbalancing and the system loses all ability to maintain constant voltage at unequal distribution of the load and becomes inoperative.

For instance, if only one phase of the secondary triangle is loaded, the other two unloaded, the primary current of the loaded phase must return over the other two transformers which at open secondaries act as very high reactances, thus limiting the current and consuming practically all the voltage, and the

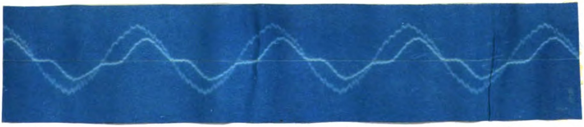
loaded primary, and thus its secondary, receives practically no voltage.

Y-Delta is feasible only if the secondary load is balanced or if primary neutral is connected with the generator neutral or the secondary neutral of a step up bank in which the primaries are connected delta, and the unbalanced current can return over the neutral. If with Y-Delta connection in addition to unbalanced load the secondary carries polyphase motors, the motors take different currents in the different phases so that the total current in all three phases is approximately the same. That is, the motors act as phase converters and so partly restore the balance of the system.



Prim.-Y, Sec.-Open. (isolated neutral)
Primary line volts and amps.
-18-

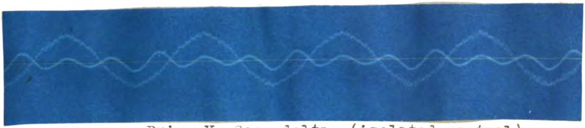
The fifth harmonic of magnetizing current is very pronounced just as in #17 and also the fact that no third can appear in the current in the lines is further substantiated.



Prim.-Y, Sec.-Open. (isolated neutral)
Line volts, Line-neutral volts.
-19-

This shows the presence of a very pronounced third harmonic in the voltage across the transformer primaries.

Due tb this peaked form the maximum value of the e.m.f.
im
impressed on the transformers is considerably greater than would be expected from the given line voltage.

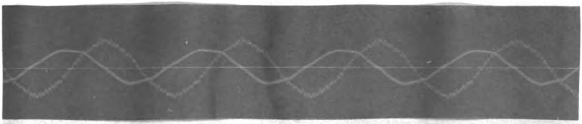


Prim.-Y, Sec.-delta. (isolated neutral)
Prim. line volts, Current in closed delta of sec.
-20-

This photo clearly shows the triple frequency current that flows in the closed delta when the third harmonic is suppressed in the primary. The variation in amplitude of the third harmonic wave is due to the slightly different operating characteristics of the three transformers, working perhaps at slightly different flux densities.

Prim-Y, Sec- Delta. (isolated neutral)
Prim. line volts, Prim. line to neutral volts.
-21-

By comparison with photo no. 19, the effect of the closed delta is apparent. The third harmonic component of magnetizing current being supplied by the triple frequency current in the d delta, the flux and hence the secondary voltage is no longer distorted, As explained on page 31 there is a slight distortion from true sine form, for it is this distortion which produces the triple frequency current by induction. The oscillogram shows this as a slightly flat-topped wave on the secondary.



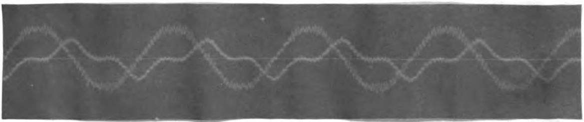
Prim- Y, Sec- Delta. (isolated neutral)
Prim.line current, Prim.line voltage.
-22-

This wave shows a slight fifth in the line current but not as pronounced as when the delta in the secondary is opened.

Y -Y Connection.

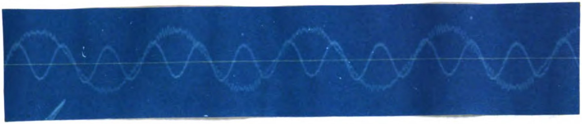
In this case if the neutral is not fixed by connection with a fixed neutral either directly or by grounding it, the neutral is also "floating" and so abnormal voltages may be produced between the lines and neutral without appearing in the voltage between lines, and may lead to disruptive effects or to overheating of the transformers. Hence it is not safe to use this connection without fixing the neutral.

To show how interconnection of the neutral eliminates the undesirable harmonics, we have taken the following oscillograms. Due to the fact that all of the generators in the laboratory were without neutral connections, the neutral obtained to tie in with was from a Delta-Star bank of step-down transformers.



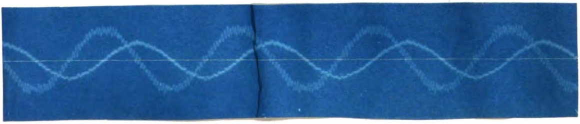
Prim- Y, Sec- Open (isolated neutral)
Prim.line volts, Prim.line to neutral volts.
-23-

This photo (no.23) shows the same distortion of the neutral voltage as we would expect to obtain with isolated neutral and open secondaries.



Prim. Y, Sec- open. (Interconnected neutral)
Prim.line volts, Current in neutral connection.
-24-

A triple frequency current is found to exist in the neutral wire. This current is the triple frequency component of magnetizing current and we would expect no distortion of the line-neutral voltage with this connection in. This is shown in the next photo (no.25).



Prim-Y, Sec- open. (Interconnected neutral)
Prim-line volts, Prim-line to neutral volts.
-25-

Where in transformer connections in polyphase systems a neutral or common connection exists, care must be taken to have this neutral a fixed voltage point irrespective of the variation of the load or its distribution, otherwise harmful phenomena may result from a "floating" or unstable neutral.

Open- Delta Connection.

The operation of the open-delta or V-V connection on a three phase system is slightly different from that of the three transformer method in that the third harmonic is not suppressed in the lines. This is due to the fact that only two transformers are used, one phase being transformed by two transformers in series. Hence the third harmonic of exciting current may be supplied by two of the phase wires and the third wire will act as a return, and because the third harmonics are in phase in all three phases there will be no distortion of the voltage in that phase which is transfor ed by the two transformers in series or in either of the other two.

Open delta.
Prim-line volts, Prim- outside line amps.
-26-

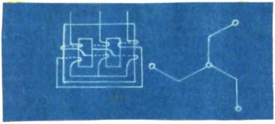
This shows plainly that the outside line is carrying a third harmonic of exciting current exactly as in a singl phase transformer.

Open delta.
Prim-Line volts, Prim- common or middle line amps.
-27-

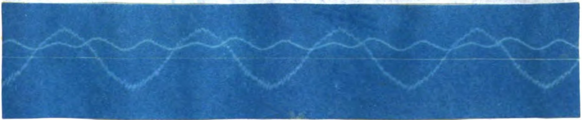
The current in this middle ,or common wire from the V is apparently a resultant of two waves shown in 26, and shows that this wire acts as a return for the current in the other two lines.

Interconnected-Star or Zig-Zag.

This connection is especially useful in connection with a converter in deriving a neutral for operation of a D.C. three wire system. When the load is placed on the D.C. side even tho it is unbalanced the current from the neutral through the transformer windings flow in opposite directions in each transformer and the magnetic effects on the core are neutralized and hence cause no saturation of the cores as in the case of the plain Y connection. Furthermore there is no third harmonic present in the voltage to neutral although it is present in the voltage across each coil or a single secondary coil placed on the core. This is because of the fact that the E.M.Fs. in the coils connected in series are 60 degrees out of phase, hence the third harmonics are 3 X 60 or 180 degrees out of phase and therefore neutralize and cannot appear at the terminals. This relation is clearly shown in the accompanying figure.

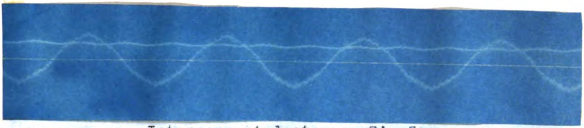


To show the application of the interconnected-star to the three wire D.C. system we have taken the following oscillograms.



Prim- Plain Y, Sec-open.
Prim- A.C.volts, Volts-neutral to D.C.line.

Showing the D.C. voltage pulsating at triple frequency due to the triple harmonic e.m.f. at the neutral of a plain Y connection.



Interconnected star or Zig-Zag.
(secondary open)
Prim-A.C.volts, Volts- neutral to D.C.line.
-29-

Showing almost entire absence of pulsation in the D.C. voltage. The slight pulsation is due to a slightly unbalanced operation of the three transformers, probably because of the presence of slightly different amounts of iron in the cores.

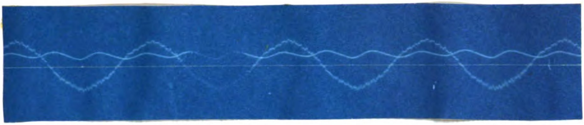
Interconnected star.
Prim-applied volts, Prim- line current.
-30-

Showing the absence of the third harmonic of magnetizing current as in all three-transformer connections and leading to a belief that there must be a distorted voltage across a primary coil.

Interconnected star.
Prim-applied volts, Prim- volts across a single coil
-31-

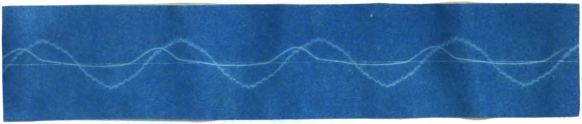
Showing the expected third harmonic in the voltage across one coil or across a single coil which would be used as a secondary. The resultant of two such waves 60 degrees out of phase would eliminate the third harmonic. This is done in the interconnection.

To further point out the importance of using the inter-connected star transformers for deriving the D.C. neutral we have taken the following oscillograms;



Prim- Y, Sec- open.
Prim- A.C.volts, Current in D.C.circuit to neutral.
-32-

This photo was taken to show that the pulsations of the D.C. voltage is carried thru into the current wave with very slight if any decrease in amplitude with increase of load.



Prim-Y, Sec-open
Prim-A.C.volts, Prim-A.C.line amps,(load on D.C. to neutral)
-33-

Showing the <u>very</u> pronounced second harmonic in the line current due to saturation of the core of the transformers by the direct current. This conditionis eleminated in the inter-connected transformers.

In this connection it may be interesting to mention the fact that practically the only source of even harmonics in commercial lines is due to saturation of the cores in a transformer bank by direct current. Since it takes but a slight current to produce saturation it is possible when the transformers have a grounded neutral in the vicinity of a grounded D.C. system and stray currents from this system flow thru the transformers and into the transmission lines.

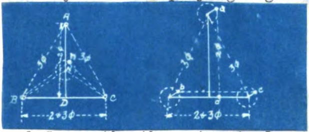
Dta

Three-Two phase Transformation.

Balanced T or Scott Connection.

This connection is in common use in changing from three to two phase or visa versa. It requires two transformers one of which carries a 50% tap and one an 87% tap on the three phase side. As was the case with the open-delta connection where only two transformers were used, this connection reduces the capacity of the units to 86.6 per cent of the combined K.V.A. capacity.

Because of the fact that exciting current is furnished by all three lines with a neutral point within the windings which is not "fixed", the third harmonic of exciting current is suppressed and an interesting distortion occurs in the voltage on the two phase side. One phase comes through without distortion but the other has a flat-topped e.m.f. wave. This may be explained by the accompanying figures.



A,B,and C are the three terminals and N the neutral point within the windings.

Because of the suppression of the third harmonic of exciting current, this neutral will pulsate with triple frequency just as in the case of the Y connection with isolated neutral and open secondary. The shifting of this neutral may be represented by the point n revolving about the small circle as shown- or by the revolution of the points a, b, and c about their respective centers with triple frequency. Since all three points revolve in synchronism the e.m.f. between the points a, b, and c remain the same but since the point d is fixed with respect to A the e.m.f. between a and d will contain a triple harmonic, as will be obvious by carrying the figure through a complete revolution of the points about their centers . This distortion appears in the line voltage on the two phase side in the form of a flat-topped wave, the other phase having a wave which is not distorted. This is clearly shown in the oscillogram shown below. (No.34.)

Three -Two phase, Scott Transformation.
Secondary voltages on Two Phase side.
-34-

It is obvious that a distortion must also occur when changing from two to three phase with this connection.

It is possible to eliminate this distortion by bringing out the neutral and grounding it or by direct connection with generator neutral thus providing a path for the third harmonic of exciting current and as in the case of the Y connection eliminating the flux distortion and hence the voltage distortion across the transformer.

Special Uses of Transformers.

Static Frequency Converters.

It is possible by means of special design and connection of transformers, to use them as frequency converters. By this means the frequency may be doubled with two transformers. The effiaciency of the set is low however, and for ordinary commercial work is impractical.

One valuable application of the method is found in radio work where the production of high frequency current of the order of 20,000 to 50,000 cycles is necessary. To do this by means of a generator alone is very difficult because of the excessive speeds at which the generator must be run. But by building a 10,000 cycle machine and stepping up the frequency by means of t transformers, quite satisfactory results are obtained.

The principle of operation for doubling the frequency is as follows;

A set of transformers as shown in the accompanying figure is made and Direct current is applied to the windings so as to saturate the cores. If an alternating current is then applied to the primary windings a very distorted e.m.f. wave will appear at the secondary terminals. It will be a wave containing a very pronounced second harmonic. Now if the secondaries are connected in series and with the fundimentals 180 degrees out of phase they will neutralize. The second harmonics will be 2 X 180 or 360 degrees out of phase or in other words they are in phase and will add up, appearing at the terminals as a double frequency e.m.f.

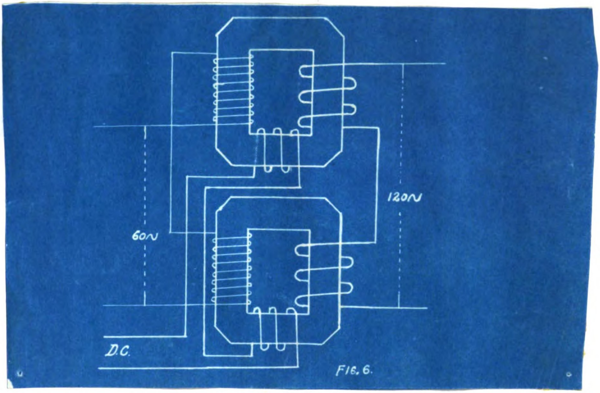


FIG. 6.

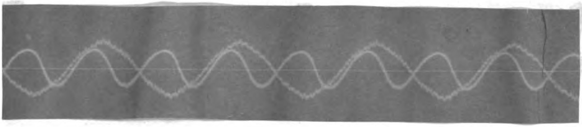
The following oscillograms analyse the operation in a clear manner.

60 cycle, volts,- e.m.f. at secondary of transformer #1.
-35-

This shows a very pronounced second harmonic.

60 cycle,volts,-e.m.f.at secondary of transformer #2.
-36-

The same pronounced second harmonic as obtained in No. 35.



-37-
60 cycle applied voltage and the double frequency obtained at the secondary terminals. Obtained by combining Oscillograms 35 and 36 with a phase displacement of 180 degrees.

Triple Frequency Transformation.

In obtaining triple frequency by means of two transformers the principle is somewhat the same. Two special transformers are designed so that when their primary windings are connected in series and an alternating current applied, the flux density of one transformer is much greater than that of the other. The secondary e.m.f. wave of the transformer working at high density will be flat-topped while that of the other will be peaked. Both of these waves contain a pronounced third harmonic and the phase relationsof these harmonics are such that if the secondary windings of the two transformers are connected in series with the fundimentals 180 degrees out of phase, the fundimental e.m.f. waves will neutralize while the third harmonics will carry through and appear as a triple frequency e.m.f. at the terminals.

(Due to the special design of transformers required, oscillograms were not taken to illustrate this method.)

Characteristics of Some Polyphase Transformer Connections.

(General Electric Co.)

Three phase transformer connections.

1. Delta-Delta Connection.

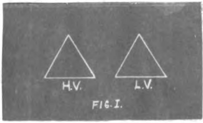


FIG. I.

Advantages:

1. Any three similiar single-phase transformers can be connected in delta at their rated voltage, whereas it would not always be possible to connect them Y.

2. The bank can operate in open-delta when one of the units is disabled, delivering 86.6 per cent of the rated K.V.A. capacity of the remaining units. Shell-type three-phase units must have their disabled phase disconnected from the others and short circuited. Core-type three-phase units must have their disabled phase disconnected and open circuited, which however, is not always practicable.

3. This connection is free from all third harmonic voltage trouble. The primary and secondary deltas carry all the third-harmonic magnetizing current which cannot appear on the lines.

4. For relatively low voltages and high currents the delta connection gives a more economical design than the Y connection.

Disadvantages;

1. The neutral cannot be derived.

2. Differences in the voltage ratios of the units cause a circulating current in both primary and secondary windings limited only by their impedance.

3. Differences in the impedances cause unequal load division among the units.

4. For very high voltages the delta connection costs somewhat more than the Y connection.

5

II. Y-Y Connection.

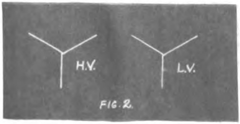


FIG. 2.

Advantages:

1. The neutral can be brought out for grounding.

2. The differences in ratio and impedance of the units do not cause any circulating currents or appreciable unequal load distribution.

3. For relatively high voltages and small currents the Y-connection is generally more economical than the delta connection.

4. A short circuit in or on one phase does not cause a power short circuit; except a very large magnetizing current due to the over excitation of the remaining units at 1.73 times the rated voltage.

Disadvantages:

1. The neutral is unstable.

2. The machines cannot be loaded single-phase line to neutral unless the neutral of the primary is connected to that of the generator.

3. There is a third harmonic voltage from line to neutral (altho it does not appear between lines) amounting to as much as 50 per cent in single-phase units and shell type three-phase units, and 3 or 4 per cent in core type units.

4. If the neutral is grounded this third harmonic voltage may be aggravated by the capacitance charging current of the lines, and may also cause telephone interference.

5. The Y-Y bank cannot operate temporarily with two units when one unit is disabled.

6. A short circuit on one unit raises the voltage of the other units to 1.73 times normal value.

Recommendations.

Due to the third harmonic voltage troubles, the Y-Y connection of high-voltage single-phase units or shell-type three-phase units is not to be recommended except under the following conditions in which a low-impedance path is offered to the flow of the third-harmonic excitation current and thereby the third-harmonic voltage is suppressed. Thus:

1. When the neutral of the primary Y is permanently connected to the neutral of the generator. If this connection is opened for any reason the third-harmonic voltage reappears.

2. If the neutral of the secondary Y of a step-up bank is grounded and is also permanently connected to a grounded Y-primary, delta-secondary transformer. The third-harmonic exciting current then circulates between the two banks. In this case, however;
   a) Telephone interference should be taken into consideration.
   b) If the Y-delta transformer is disconnected from the lines or the ground on its neutral disconnected, or its delta opened, the third-harmonic voltage reappears on the former with the accompanying dangers of resonance.

3. If the secondary Y is permanently connected to a synchronous converter in diametric fashion. (See Sec. XXIV, Y-diametric Conn.)

4. If the neutral of one Y is permanently connected to the neutral of a zig-zag auto-transformer (directly or thru ground) on the same lines.

5. If auxiliary windings (tertiary windings) are proveded connected in delta.

The Y-Y connection of core-typr three-phase units is always safe whether the neutral is grounded or isolated, so far as the third-harmonic voltage stresses are concerned. However, when such a unit is grounded with a low-impedance return path such as mentioned above, the third-harmonic current in the neutral will be appreciable and telephone interference may need consideration.

III. Y-Zig-Zag Connection.

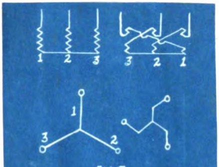


FIG. 3.

Advantages:

1. The neutral of the zig-zag can be grounded without any third-harmonic voltage trouble. A third-harmonic voltage appears in each coil but not from line to neutral on the zig-zag side.

2. The machine can be loaded with a single phase load from line to neutral of the zig-zag.

Disadvantages.

1. The connection requires 15 percent more copper for the zig-zag than for the equivalent Y.

2. The regulation and efficiency are liakly to be somewhat poorer than those of the equivalent delta-Y.

Recommendations:

As a standard connection delta-Y is preferable to the Y-zig-zag connection. The latter, however, may be advisable in some exceptional cases as, for instance, when a change in system voltage is comtemplated and the transformers may be temporarily operated delta-zig-zag to be changed later on to the Y-zigzag.

IV. Delta -Y Connection.

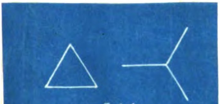


FIG. 4.

Generally considered to be the best three-phase connection.

Advantages:

1. The neutral can be brought out both for grounding and for loading.

2. The neutral is stable, being locked by the delta.

3. The connection is practically free from third-harmonic voltages. The delta circulates the necessary third-harmonic exciting current.

4. Differences of magnetizing current, voltage ratio, and impedance in the different units are adjusted by a small magnetizing current circulating in the delta.

5. A short circuit in one leg of the Y does not effectnthe voltages on the secondary lines.

6. A single-phase short circuit on the secondary lines causes a smaller short-circuit stress on a delta-Y bank than on a delta-delta connected one.

Disadvantages:

1. The delta- Y bank cannot operate temporarily with two units when one of the units is disabled.

2. A short-circuit in one unit is extended to all three units.

3. If the delta on the primary side should accidently become opened the unexcited leg on the Y side may resonate with the line capacitance and cause damage.

V. Open-Delta or V-V Connection.

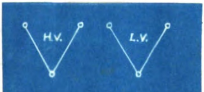


FIG.5.

Advantages:

This connection requires only two units and is, therefore, useful as an emergency connection.

Disadvantages:

1. The internal power-factor being only 86.6 per cent (assuming unity power-factor load) it can deliver only 86.6 per cent of the rated K.V.A. capacity of the units. Hence it is not very desirable for continuous operation.

2. Load voltages become unbalanced under load, even with balanced three-phase load, the magnitude of the unbalancing depending on the impedance of the units and the power-factor of the load.

3. Being electrostatically unbalanced, the V-V connection is not recommended for very high voltage systems.

VI. T-T Connection.

Advantages:

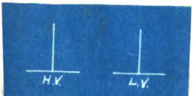


FIG.6.

1. This connection is similiar to the V-V in that it requires only two units.

2. The voltage across the teaser being only 86.6 per cent of that of the main, the core loss in this connection is less than in the V-V connection, assuming similiar or interchangeable units.

3. The neutral point can be derived and brought out for grounding, although not for loading unless the two halves of the main are interlaced.

Disadvantages:

1. Both primary and secondary sides require 50 per cent taps which are not required by the V-V connection.

2. The corresponding halves of the primary and secondary of the main must be interlaced, although the two halves of one winding need not be interlaced with each other unless the neutral is b brought out on that side and it is desired to be able to load the neutral.

3. Similiar to the V-V connection, the ratio of output to K.V.A. rating is only 86.6 per cent and the regulation is poor.

Three-Phase Auto-Transformer Connections.

General Characteristics.

Advantages:

1. For a given output, auto-transformers are much cheaper than transformers. This economy is greater the nearer the high and low line voltages approach each other.

2. Auto-transformers give better efficiency and regulation than transformers. This advantage also increases as the ratio of the high and low line voltages approaches unity.

Disadvantages:

1. The high and low-voltage windings being continuous the low-voltage circuit and connected apparatus are liablt to be subjected to abnormal voltages due to disturbances and grounds on the high-voltage circuit. This is particularily objectionable when there is a large difference of potential between the high and the low sides.

2. Short-circuit currents at normal excitation of the unit are larger with auto-transformers than with transformers and the more so the nearer the high and low voltages are alike. It is often impracticable to design autottransformers to withstand the thermal and machanical effects of short circuits.

Since as the ratio of low-voltage line potential to high-voltage line potential decreases and insulation dangers increase, auto-transformers are usually considered only when the low voltage is as much as 80 to 90 per cent of the high voltage. A low voltage not less than 50 percent of high voltage may be considered a good engineering limit for the use of auto-transformers under very favorable conditions.

Recommendations:

Auto-transformers may be recommended for isolated systems provided that the low-voltage circuit and the connected apparatus are designed to stand the high-voltage test potential. They may be recommended for grounded systems provided that the neutral of the auto-transformer is also grounded.

VII. Y-Connection.

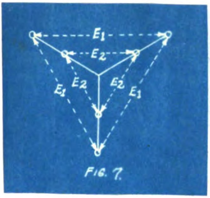


FIG. 7.

Advantages:

1. This is the most economical and therefore the most common auto-transformer connection. The ratio of rating to output is E_1-E_2/E_1, where E_1 is the high-voltage line potential and E_2 is the low-voltage line potential.

2. The neutral may be derived and grounded for the protection of the low-voltage circuit if the generator neutral is also grounded.

Disadvantages:

1. Similiar to the Y-Y connection of transformers (see Sect. II) there is a third harmonic voltage from line to neutral. Single phase and shell type units are not recommended, especially if the neutral is to be grounded. Core-type units (three phase) may safely be used either grounded or ungrounded.

2. The machines cannot be loaded single-phase from line to neutral. This is especially true for single-phase units and for shell-type three-phase units. Core-type three-phase units may give tolerably good results. The best results are obtained by the zigzag connection.

VIII. V or Open-Delta Connection.

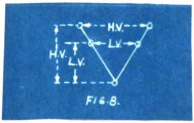


FIG. 8.

1. This connection is free from third-harmonic voltage,

2. The ratio of rating to output is 15 per cent more than in the Y-connection.

IX. Delta Connection.

FIG. 9.

This connection has characteristics similiar to those of delta-delta connected transformers

1. It is free from third-harmonic voltage.

2. The ratio of rating to output is $(E_1^2-E_2^2)/1.73E_1E_2$

3. For a given load, the ratio of the K.V.A. rating of this connection to that of the Y-connection is equal to:- $(0.577+0.577E_1/E_2)$ Thus, id the low-voltage line potential is 50 per cent of the high voltage, the delta connection requires 1.73 times the kv-a. rating of the Y-connection.

Therefore, when the Y-connection is undesirable on account of third harmonic voltage, the V or extended-delta connections figure out more economical than the delta connection.

X. Extended-Delta Connection.

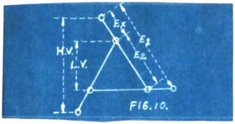


FIG.10.

The ratio of rating to output is;

$1.73E_x/E_1$, where E_x is the voltage of the extended portion and E_1 is the high-voltage line potential.

Recommendation:

When the low-voltage is less than 92 per cent of the high voltage, the extended-delta connection requires a smaller rating than either the straight-delta or V connections. When this ratio is greater than 92 per cent, the V-connection requires the least rating of the three.

XI. Zigzag Connection.

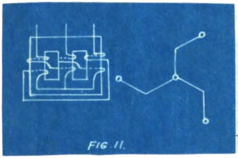


FIG.11.

1. This connection is used to derive a fourth wire for four-wire three-phase distribution systems, such as 2300/4000 Y distribution systems, when this wire is not available at the generator or step-down transformer.

2. With balanced three-phase load, neither the neutral wier nor the coils carry any current.

3. An unbalanced load flows in the neutral and is distributed equally in all three phases.

4. The neutral may be grounded.

5. The neutral can also be used to derive the neutral of converters for the return of the unbalanced direct current in a three-wire direct current distribution system. A straight Y could not be used for this purpose (excepting three-phase core-type units), it being necessary to prevent the saturation of the transformer core by direct current.

6. With the neutral grounded, a ground on one of the lines extends the short circuit to all three phases.

XII.
Extended Zigzag Connections.

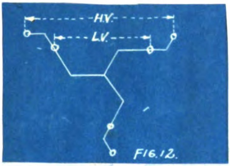


FIG. 12.

When it is desired to transform a given line voltage to some other value for four-wire distribution the extended Zigzag may be used.

The Extension shown in the figure is better than a straight extension for it distributes the neutral current equally in all three phases and maintains better regulation thereby.

The straight extention is easier to build but does not completely eliminate the third harmonic voltage from line to neutral and in addition has a poorer regulation for unbalanced loads.

Three-Phase Two-Phase Transformer Connections.

XIII. Balanced T or Scott Connection.

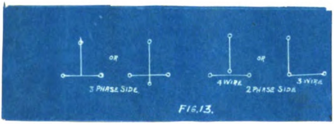


FIG. 13.

Advantages:

1. This connection requires only two single-phase units or one two-phase unit.

2. It is adaptable to either three-wire or four-wire two-phase service.

3. Both two and three-phase voltages can be obtained on the primary using only four line wires if the 86.6 per cent tap of the teaser is connected to the middle of the main.

Disadvantages:

1. The two halves of the main winding on the three-phase side must be interlaced.

2. With interchangeable units, there must be provided one 50 per cent tap and one 86.6 per cent tap in each unit.

3. The three-phase side carries 15 per cent more current than that corresponding to the two-phase side, and, therefore, requires 15 per cent more copper.

4. If the interlacing of the halves of the three-phase side of the main is effected by using two coils in multiple on the two-phase side, then the latter also carries 15 per cent more current and therefore requires 15 per cent more copper.

5. Combining the features of the above items 3 and 4, two single-phase units in Scott connection can deliver only 86.6 per cent of their combined single-phase rating.

XIV. Woodbridge Connection.

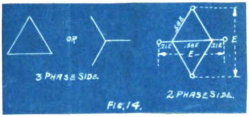


FIG. 14.

Advantages:
1. This connection has an internal power-factor of 100 per cent and will therefore, deliver two-phase three-phase power equal to its single-phase rating.

2. The three-phase side can be connected delta or Y, making it possible to change the system voltage without discarding the transformers.

Disadvantages:

1. This connection is not adaptable for three-wire two-phase service, and has, therefore, not become popular.

2. Taps are impracticable except on the three-phase side.

3. The multiplicity of windings required generally more than offset the advantages in econmy of material and for this reason is seldom used.

4. This connection requires three single-phase units or one three-phase unit.

XV. Combined Two and Three-Phase.

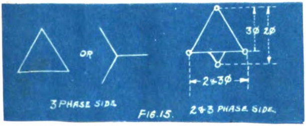


FIG. 15.

Of the connection shown in Fig. 15, the straight three-phase side may be Y or delta. On the other side, both two and three-phase power may be obtained from four wires. It is suitable when the three-phase load is predominant. The dimensions of the smaller delta are 15 per cent of those of the larger delta, and the windings whose voltages are parallel are wound on the same core leg.

XVI.

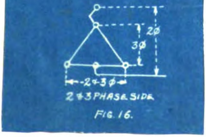
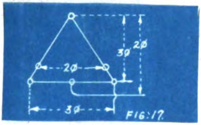


FIG. 16.

This connection is similiar to that of fig.15 except that it requires five wires instead of four.

XVII. Taylor Connection.

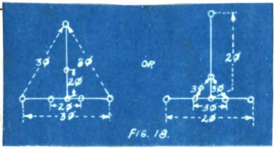


This connection is similiar to those of Fig.15 and 16, except that the two-phase threepphase side requires six wires.

Three-Phase Two-Phase Auto-Transformer Connections.

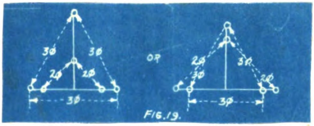
Scott Connected Auto-Transformers.

XVIII.



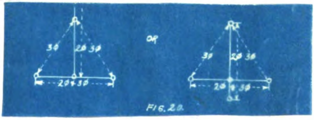
Three-wire three-phase to four-wire two-phase.

XIX.



Three-wire three-phase to three-wire two-phase.

XX.



This connection is the same as that of Sec. XVIII, except that the ratio of voltages is 1 to 1. The main carries only the teaser current which divides equally in the two halves of the main.

XXI.

This connection is the same as that of Sec.XVIII except that the ratio of voltages is 100per cent three-phase to 70,7 per cent two-phase.

XXII.

FIG 22.

This connection is the same as that of Sec. XIX, except that the ratio of voltages is 100 per cent three-phase to 86.6 per cent two-phase. The teaser then becomes unnecessary and can be left out, the bank operating with only one single-phase unit. One phase of the two-phase load takes the place of the teaser.

Three-Phase to Six-Phase Connection.

XXIV. Y-Diametric Connection.

Advantages:

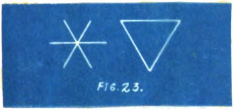


FIG. 23.

1. The delta connection of one side eliminates third-harmonic voltage troubles.

2. The diamatric connection of the six-phase side requires only three coils as against six required by the double delta connection and hence is more economical.

3. The diametric connection lends itself more conviently for starting-taps and switchgear.

4. The neutral of the diametric connection can be brought out to derive the neutral of the converter for three-wire d-c. service except in ine case of split-pole converters.

Disadvantages:

The bank cannot operate with two units when one breaks down.

XXIV. Y-Diametric Connection.


FIG. 24.

This connection has the advantages of the diametric secondary, and is free from third-harmonic voltage trouble when operating converters, except split-pole converters. In the first case, the third harmonic excitation current circulates through the diametric coils and converter ; in the latter case, the third-harmonic voltage is made use of in regulating the voltage of the converter and is then a desirable feature.

Recommendations:

Delta-diametric and Y-diametric are the most common three-phase to six-phase connections. Whether primary should be Y or delta is determined by either the convenience of design or the users preferences.

XXV. Delta-Double-Delta.

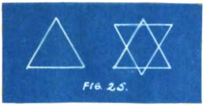


FIG. 25.

Advantages:

1. The bank can temporarily operate with two units when one breaks down.

2. The secondary side can be operated three-phase without change of voltage and will deliver one half rated load operating only one of the deltas. If the diamatric is connected in delta for three-phase service the voltage is increased 15 per cent but it will deliver full rated load.

Disadvantages:

1. The multiplicity of coils in the secondary tends to make the cost somewhat higher than that of the diametric connection.

2. The double-delta secondary is illadapted for starting taps or for deriving the neutral of converters for three-wire d-c. service.

XXVI. Y-Double-Delta.

FIG. 26.

This is a possible connection that is seldom used. It may have an advantage in design and cost if the three-phase voltage is very high and the six-phase voltage very low.

XXVII. T-Double-T Connection.

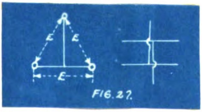


FIG. 27.

This connection is not much used for three-phase to six-phase transformation on account of its low ratio of output to rating, which, similiar to the T-T connection is only 86.6 per cent; and it is not well adapted for starting taps.

Two-Phase to Six-Phase Connections.

XXVIII.

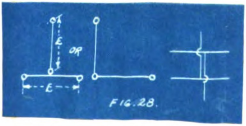


FIG. 28.

This connection is the one commonly used for two-phase to six-phase transformation.

USE ONLY