The Analysis of Electrical Phenomena

with

The Oscillograph.

Thesis Submitted to

The Faculty of

MICHIGAN AGRICULTURAL COLLEGE

by

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Introduction

Inthe classroom we have studied certain theoretical and mathematical aspects of electrical phenomena. It is the purpose of this thesis to illustrate in a more tangible manner the same phenomena by oscillograms, supplemented with analyses and explainations.

This type of analysis is of importance because it affords a physical conception of what occurs in a phenomena, which occurrence would otherwise be unthought of and overlooked.

This method is more interesting and more certain in its results than the method of analysis and mathematical solution. It is more interesting than the mathematical solution for one is working with concrete things, and it is more certain in its results because it pictures what actually takes place, whereas at the completion of a mathematical solution one has a result which may not necessarily explain the intricasies at hand.

We have taken oscillograms of transient phenomena in circuits of known in order to verify the analytical and mathematical analysis. We have taken curves of flux distribution in various machines in the laboratory in order to study the voltage waves with the possibility of correcting undesirable harmonics.

In the working out of this thesis we have encountered many interesting problems and while they may not be entirely new, their application is, nevertheless, important.

Laboratory Apparatus.

The apparatus with which the oscillograms were taken was of the lecture table type of Duddell Oscillograph with which the wave was thrown from a revolving mirror onto a screen, but this had benn transformed by Messers yokoff and Heasley into a photographic outfit in which the ray of light was thrown from the vibrating mirror directly upon a rotating drum carrying motion picture film. A slotted shutter falling under the action of gravity allowed light to pass from the arc lamp to the vibrating mirrors for only the short interval of time (approximately one-tenth second) that it took the revolving drum to rotate only once, so that the picture would not be repeated. The shutter, which was of sheet-iron, had a rubber bumper at the bottom, and at first difficulty was encountered from the shutter rebounding and passing light to the film for the second time, but by proper adjustment this was eliminated.

As our oscillograms were for the most part to be of the transient phenomena in which we wanted a continuous picture from the beginning to the end of the film, it was necessary to have the picture start at one end of the film or next to where it was wedged in the drum which carried the film. So by means of a rotating contact on the bottom of the drum spindle and a magnetic trip for the shutter, the shutter was started on its fall at the same time that the end of the film passed the opening in the film-box.

Transient Phenomena.

An electric system through which energy flows has , at a certant point, a potential e and current i. If the conditions of the circuit are changed, the potential and current at the poit under consideration will notlonger be e and i, but will assume new values after the system has reached its new position of equilibrium. Although the change which disturbes the equilibrium of the circuit may be instanteous, a definite length of time is required, by the system to adjust itself to the new conditions. If, therefore, these new conditions require that at the point under consideration the voltage be e_1 and the current i_1 , these values are not obtained at the instant the change is made, but after some time has elapsed. During this time the voltage and current assume transitory values, which start from e and i and end with e_1 and i_1 .

These transitory values of the voltage and current can be divided into two components. One component is e_1 and i_1, that is to say, the final values required by the new conditions, and which could not be reached instantaneously. The second component constitutes the transient terminal voltage and current. For instance, if we apply to an inductive circuit suddenly a constant electromotive force, the current grows from zero to its final value , i . according to figure one. "The transient" in this case is the current i_0 shown in figure one.

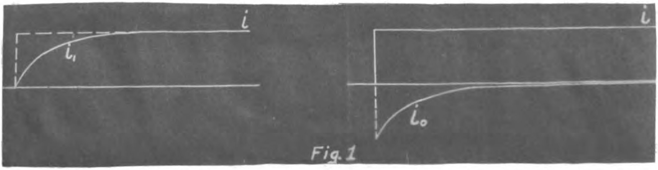

Fig. 1

The presence of transient phenomena, when a system passes from on position of equilibrium to another, is not a peculiarity of the electric system, but occures in other forms of energy.

In an electric system energy is generally formed in two forms, electromagnetic and electrostatic. The electromagnetic energy is $\frac{1}{2}Li^2$ and the electrostatic energy is $\frac{1}{2}Ce^2$. This means that when e and i are changed the energy stored in the system must also change. Such change of stored energy can not happen instantaneously, because an instantaneously change of stored energy necessitates infinite supply of power. A definite length of time is then necessary to bring about the variations in the stored energies. Hence the transient.

Since the static energy can be stored up in two different forms, the electric transients can be of two kinds, single-energy transients and double energy transients. In a single energy transient only one form of energy is varied, and a single energy transient therefore, consists only in the increase or decrease of one form of energy. The transient shown in fig 1. is a single energy transient, because in that case the magnetic energy of the circuit was changed from zero to $\frac{1}{2}Li^2$ and the citcuit was assumed to have zero capacity, therefore no electrostatic energy was stored up in it. Double energy transients consist in a variation of both forms of energy, or in a transformation from one form of energy into the other. The transient which transforms energy from electromagnetic into electrostatic, or vice versa, it is an oscillation.

During this process, however, energy losses occur in the circuit or around the circuit, so that generally the original amount of energy of the oscillation decreases and disappears.

In a pure oscillation, e. i., where no losses occur, at a certain instant all the energy is electro-magnetic and equal to $\frac{1}{2}Li^2$. A little later all the energy is electro-static and equal to $\frac{1}{2}Ce^2$. Since the circuit does not dissipate energy, $\frac{1}{2}Li^2$ is equal to $\frac{1}{2}Ce^2$, and therefore $e = i\sqrt{\frac{L}{C}}$. $\sqrt{\frac{L}{C}}$ is in the nature of an impedance, because multiplied by a current, it gives a voltage. $\sqrt{\frac{L}{C}}$ is called"the natural impedance of a circuit". This natural impedance is of great impoRtance in the study of transient phenomena. So far as we know that it represents the ratio between the voltage and the current of the oscillation.

The frequency, f, at which the energy is transformed from magnetic to electric, and vice versa, is $\frac{1}{2\pi\sqrt{LC}}$, when both the inductance L and the capacity C are concentrated. This means that during the time $2\pi\sqrt{LC}$ a complete cycle of the oscillation occurs. So that, if we start at the instant when the voltage is maximum and the currnet zero, the voltage will again be maximum and in the same direction and the current will again be zero after a time $2\pi\sqrt{LC}$.

Since the electro-magnetic energy is equal to $\frac{1}{2}Li^2$ the change in this energy in a small interval of time dt will be $d(\frac{1}{2}Li^2)$, or $de_m = Lidi$. Likewise for the electro-static energy, the change $de_c = Cede$.

If the current does dissipate energy, as all circuits do, the energy lost as heat is equal to i^2R.

If the condenser is charged, and the energy is stored as electro-static energy, and then the condenser is discharged thru the resistance and inductance, the energy is transformed into heat energy and electro-magnetic energy. Therefore, in the interval of time dt, $Cede + Lidi + i^2Rdt = 0$

Since the current i is equal to the quantity of electricity dq set in motion in the time dt, we have $i = \frac{dq}{dt}$

and since $q = Ce$

we have $dq = Cde$

and $i = \frac{dq}{dt} = \frac{Cde}{dt}$

so that finally the equation may be written

$$\frac{d^2e}{dt^2} + \frac{Rde}{Ldt} + \frac{e}{LC} = 0$$

Letting $\frac{d}{dt}$ equal a, the equation becomes

$$e(a^2 + \frac{Ra}{L} - \frac{1}{LC}) = 0$$

If the values of a are real, that is, if $\frac{R^2}{4L^2} - \frac{1}{LC} = 0$ or $R^2 > \frac{4L}{C}$, the equations of e and i are not periodic functions of time. But if the values of a are imaginary, i.e., if $R^2 < \frac{4L}{C}$, the equations of e and i are periodic and exponential functions of time, and are therefore damped oscillations of frequency and decrement, the expressions of which are:

$$\text{Frequency } \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

$$\text{Logarithmic decrement } e^{-\frac{R}{4fL}}$$

If, however, $R^2 = \frac{4L}{C}$ the equation is just not periodic, or critically damped, and if the circuit contains constants of these relative values, upon discharging the condenser, the current reaches a maximum value in one direction and then decays to zero without reversing direction. The condenser in discharging uses up its energy in heat loss and in building up the magnetic field. At the time that the current reaches a maximum the magnetic field is at its maximum, and the condenser voltage is zero. The current then continues in the same direction due to the collapse of the magentic field, and the energy stored up in this field is totally consumed as heat energy. Therefore there is no energy left to charge the condenser; consequently no reversal of current.

As a verification of this analytical and mathematical analysis, we have set up series circuits of known constants, and then by means of the oscillograph, have recorded the transient in each circuit.

These circuits were arranged in three sets. One of constant resistance and capacity, and of variable inductance; another of constant resistance and inductance, and of variable capacity; and the third, of constant inductance and capacity, and of variable resistance. Included in the last set was a circuit in which R was of such value that $R^2 = \frac{4L}{C}$, which, theoretically, is the critical case.

The following are the oscillograms of the first set, in which the inductance was changed while the capacity and resistance were kept constant. Below each print is given the data for that curve, showing the constants that were in the circuit and the results, both computed and measured. At the end of the set is given a curve showing how the frequency and decrement vary with a change in inductance. All oscillograms show a 60-cycle timing wave.

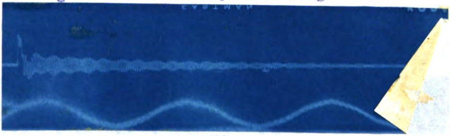

Fig. 2.

R 14.2 ohms. C 0.000,013,35 farads. L 0.006,24 henrys.

Frequency	Computed	521	Decrement	Computed	0.1126
	Measured	533		Measured	0.125

Fig. 3.

R 14.2 ohms. C 0.000,013,35 farads. L 0.0435 henrys.

Frequency	Computed	208.45	Decrement	Computed	0.457
	Measured	211.9		Measured	0.456

Fig. 4.

R 14.2 ohms. C 0.000,013,35 farads. L 0.1274 henrys.

Frequency	Computed	121.6	Decrement	Computed	0.632
	Measured	121.0		Measured	0.684

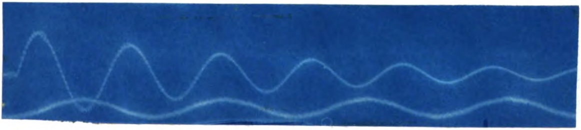

Fig. 5.

R 14.2 ohms. C 0.000,013,35 farads. L 0.227 henrys.

Frequency	Computed	91.3	Decrement	Computed	0.710
	Measured	91.0		Measured	0.701

Fig. 6.

R 14.2 ohms. C 0.000,013,35 farads. L 0.411 henrys.

Frequency	Computed	67.734	Decrement	Computed	0.775
	Measured	65.00		Measured	0.631

Fig. 7.

R 14.2 ohms. C 0.000,013,35 farads. L 1.01 henrys.

Frequency	Computed	43.28	Decrement	Computed	0.850
	Measured	44.00		Measured	0.700

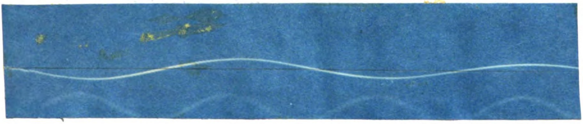

Fig. 8.

R 14.2 ohms. C 0.000,013,35 farads. L 1.574 henrys.

Frequency	Computed	34.63	Decrement	Computed	0.873
	Measured	30.8		Measured	0.831

It appears that the computed and measured values do not check very closely in some cases, but this is due to the fact that it is very hard to measure accurately the decrement when the amplitude is small, and the presence of the small vibrations makes the measurement of the frequency a difficult matter. However, the measured and computed values are near enough to verify the laws as set forth in the explanatory subject matter.

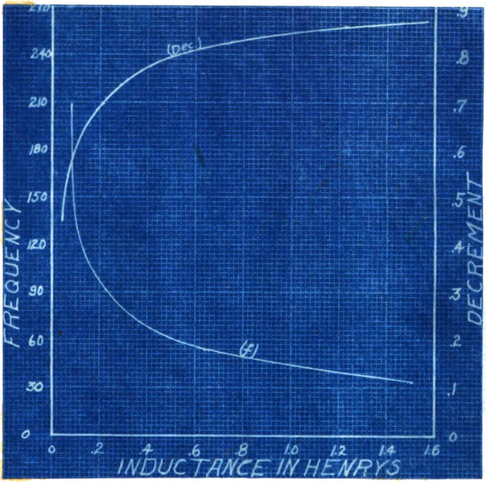

Fig.9.

This curve shows the variation of the frequency and decrement of the oscillatory discharge current in circuits containing resistance, capacity, and inductance in series, when the resistance and capacity are kept constant, and the inductance is varied.

Following is the second set of oscillograms, in which the capacity was changed while the resistance and induct nce were kept constant.

Fig. 10.

R 14.2 ohms. C 0.000,013,35 farads. L 0.0435 henrys.

Frequency	Computed	208.45	Decrement	Computed	0.457
	Measured	211.9		Measured	0.456

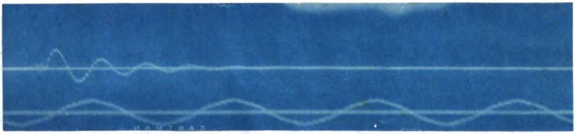

Fig. 11.

R 14.2 ohms. C 0.000,015,39 farads. L 0.0435 henrys.

Frequency	Computed	187.3	Decrement	Computed	0.4178
	Measured	192.0		Measured	0.46

Fig. 12.

R 14.2 ohms. C 0.000,017,46 farads. L 0.0435 henrys.

Frequency	Computed	180.59	Decrement	Computed	0.405
	Measured	180.00		Measured	0.383

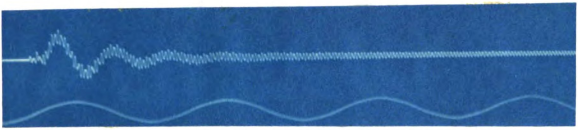

Fig. 13.

R 14.2 ohms. C 0.000,020.632 farads. L 0.0435 henrys.

Frequency	Computed	166.63	Decrement	Computed	0.375
	Measured	170.00		Measured	0.333

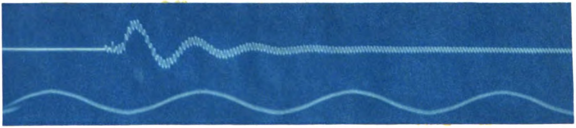

Fig. 14.

R 14.2 ohms. C 0.000,023,713 farads. L 0.0435 henrys.

Frequency	Computed	154.42	Decrement	Computed	0.347
	Measured	154.1		Measured	0.375

Fig. 15.

R 14.2 ohms. C 0.000,026,772 farads. L 0.0435 henrys.

Frequency	Computed	145.0	Decrement	Computed	0.325
	Measured	144.1		Measured	0.315

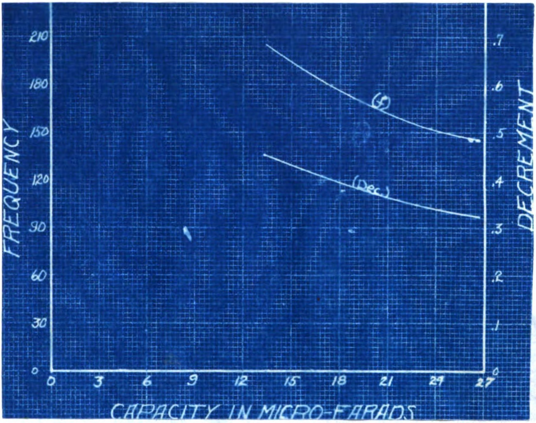

Fig. 16.

These curves show the variation of the frequency and decrement of the oscillatory discharge current in circuits containing resistance, inductance, and capacity in series, when the resistance and inductance are kept constant and the capacity is varied.

Following is the third set of oscillograms, in which the resistance was changed while the inductance and capacity were kept constant.

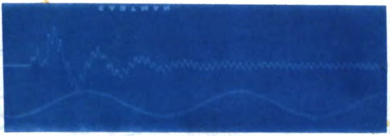

Fig. 17.

R 14.2 ohms. C 0.000,013,35 farads. L 0.0435 henrys.

Frequency	Computed	208.45	Decrement	Computed	0.457
	Measured	211.9		Measured	0.456

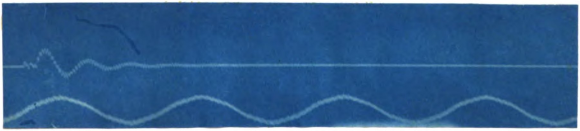

Fig. 18.

R 20 ohms. C 0.000,013,35 farads. L 0.0435 henrys.

Frequency	Computed	205.2	Decrement	Computed	0.327
	Measured	203.0		Measured	0.325

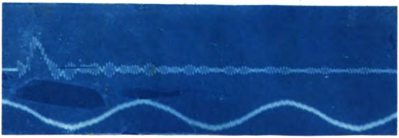

Fig. 19.

R 60 ohms. C 0.000,013,35 farads. L 0.0435 henrys.

Frequency	Computed	177.5	Decrement	Computed	0.0206
	Measured	175.0		Measured	? (very small)

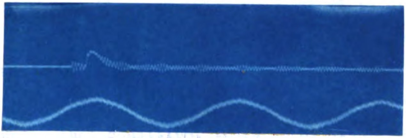

Fig. 20.

R 114 ohms. C 0.000,013,35 farads. L 0.0435 henrys.

This oscillogram represents the critical case where $R^2 \; \frac{4L}{C}$. Since the inductance and capacity were constant for this set of oscillograms, R was computed from the equation just given, and the computed resistance was placed in the circuit. Theoretically, this was the critical case, and the oscillogram verified this.

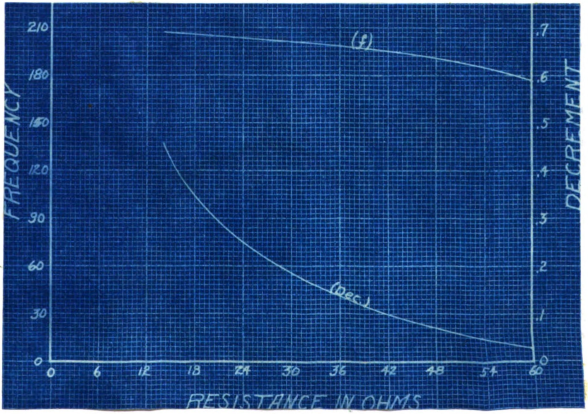

Fig. 21.

Fig. 21 shows the variation of the frequency and decrement of the oscillatory discharge current in circuits containing resistance, inductance, and capacity in series, when the inductance and capacity are kept constant, and the resistance is varied. The curve does not include the critical case, for under that condition, there is no frequency, since there is current in one direction only. It seems apparent from these curves that if the resistance in such a circuit were zero, there would be a definite frequency, and the decrement would be unity. In other words, the current would oscillate back and forth in the circuit at a definite rate, with no decrease in strength from cycle to cycle. It is impossible, however, to obtain such a circuit, for any circuit whatever has some resistance and the I^2R losses must be supplied. In the oscillatory discharges, these were supplied by the initial charge of electro-static energy in the condenser, and in the critical case, this charge was expended during the first flow of current in one direction. This also explains the possibility of maintaining an alternating current from a direct current source by supplying, during alternate half-cycles, enough energy from the direct current source to overcome the I^2R losses during that cycle.

Flux Distribution

The fundamental principle upon which the present day electric generator is based is that in a conductor cutting magnetic lines of force, an e.m.f. is induced which is proportional at every instant to the rate at which these lines are cut as expressed by the equation $e = \frac{d\phi}{dt}$.

Due to the increased hysteresis and eddy current losses in transformers, generators, and other electrical apparatus at increased frequencies, the voltage applied to this class of apparatus should be free from harmonics, and therefore the aim in the design of generators is to produce a pure sine wave of terminal voltage. In the analysis of flux distribution along the circumferential path thru which the conductors move, it is found that there are variations in the flux density. From $\frac{d\phi}{dt}$ it is seen that the induced voltage in an individual inductor will vary from instant to instant directly as the variations in the flux. These variations do not appear in the terminal voltage of the modern machine because the individual inductors are distributed around the periphery of the armature in such a manner that the vector sum of the instantaneous voltages of the inductors form, with respect to time, a pure sine wave.

If, then, the voltage from an individual inductor is represented on a time axis, the curve will also represent the flux distribution, one-half cycle of which will contain all the variations of the flux from one pole.

To obtain this voltage wave an inductor was placed in a slot of the armature of a generator, and its terminals connected to the oscillograph. Below is shown an oscillogram representing the voltage induced in an inductor placed in a slot of a 2300-volt alternator.

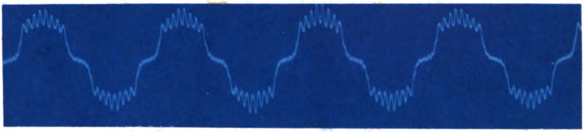

Fig. 22.

This oscillogram shows very plainly the variations in the flux. Two harmonics are represented, one of a frequency double that of the other. The lower harmonic which appears at the crest of each half-cycle of the main wave contains eight cycles for each pole-face passed under by the inductor. The number of these cycles is equal to the number of teeth under a pole-face. If the pole-face and teeth are so proportioned that there is at all times a constant tooth-area under the pole-face, th reluctance of the magnetic circuit would be a constant, and hence the flux through the pole would not vary, assuming a constant m.m.f.

But should the pole-face and teeth be so proportioned that there is not at all times a constant tooth-area under the pole-face, then there is at one instant, a maximum tooth-area, andat another instant, a minimum tooth-area under the pole-face, the change from maximum to minimum and back to maximum, or one cycle of flux variation, occuring each time there is a relative motion of one slot-pitch between the field and the armature. If there are N slot-pitches spanned by one pole-face, there will be N cycles of flux variation while an inductor, carried in an armature slot, moves from one edge of the pole-face to the other. And thus it is seen from the oscillogram that there are eight slot-pitches spanned by a pole-face in the machine from which the oscillogram was taken.

The higher harmonic, which appears at the axis of the main wave, and which is of double frequency of the harmonic at the crest of the main wave, is due to a different phenomenon, The wave form of the main flux shows that a periodic flux does not vary according to a simple sine function, but is flat at the points of maximum and minimum reluctance. Due to this wave form, a voltage induced by a periodic flux has a frequency double that of the flux, as seen from the equation, e $\frac{d}{dt}$.

As a tooth emerges from a pole-region, there is a variation in the reluctance between the pole and the tooth, and consequently, a change in the flux. Some of the flux which at one instant passes through a certain tooth will, as the tooth proceeds, snap back to the succeeding tooth, cutting across the inductor in the intervening slot. We have seen that the flux wave is flat at the points of maximum and minimum reluctance, and therefore the flux snapping across the slot will be of this form, and hence the voltage induced has a frequency double that of the flux, or double the number of teeth.

There is fringing of the flux in the space between the poles, and the same double-frequency voltages induced in this

region, added to the inertia of the oscillograph ribbon, maintains the amplitude of the vibration as shown on the oscillogram for this region.

There are 16 cycles of the lower frequency harmonic, and 16 cycles of the higher frequency harmonic, in each cycle of the main wave, or eight cycles of each harmonic per pole. Eight cycles of the higher frequency harmonic represent 4 teeth, and eight cycles of the lower harmonic represent 8 teeth, or a total of 12 teeth per pole, which is exactly the number of teeth per pole in the machine from which the oscillogram was taken, the machine being 6-pole, and having 72 teeth.

It can be seen from Fig. 22 that the flux is the strongest at the center of the pole, but this represents no-load conditions. When a load is applied to the machine, either mechanical load when used as a motor, or electrical load when used as a generator, there is a certain amount of cross-magnetization and demagnetization which distorts the field-flux, and weakens it. If the machine is operating as a motor, the flux is crowded to the leading pole-tip, and for a generator, the flux is crowded to the trailing pole-tip.

Fig. 23.

This oscillogram shows evidence of distortion as it can be seen that the lower frequency harmonics are longer on one side of the pole than the other, and the double frequency harmonics show up due to the fact that there is a change in flux-density between the two sides of the pole-face.

Below is a set of oscillograms showing the distortion effects of different loads on the flux distribution of a 2300-volt alternator, with constant source of excitation.

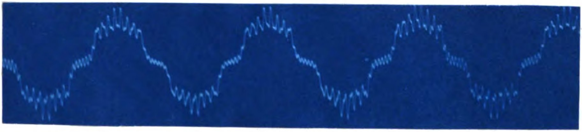

Fig. 24.

No load except a bank of 15 kv-a transformers.

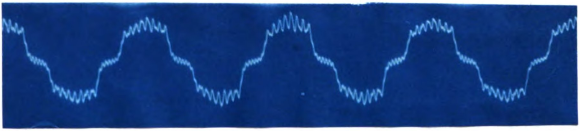

Fig. 25.

Forty ampere, unity power factor, load. Excitation unchanged.

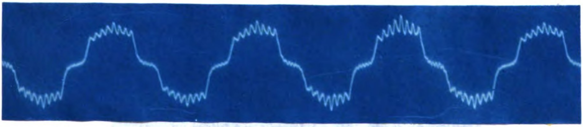

Fig. 26.

Sixty ampere, unity power factor load. Excitation unchanged.

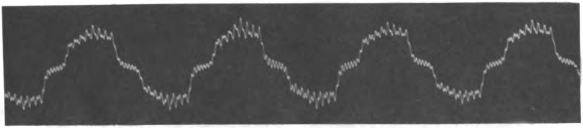

Fig. 27.

Eighty ampere, unity power factor load. Excitation unchanged.

It is seen that as the load increases, the voltage is decreased as shown by the amplitude of the main wave, and the flux is distorted, as shown by the shape of the main wave, and the lower and higher frequency harmonics.

Following is a similar set of oscillograms taken from a rotary convertor. It can be seen from the oscillograms that the flux is crowded to one tip of the pole due to the fact that the air-gap is narrower on that side, and when a load is applied, the flux is shifted ot the center of the pole as shown by figures 30 and 31. The higher frequency harmonic, however, is present because no matter how the pole-face and teeth are proportioned, fringing can not be prevented.

Fig. 28.

Separately excited as generator.

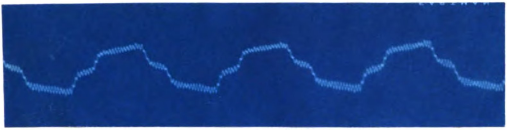

Fig. 29.

Running idle as direct current motor.

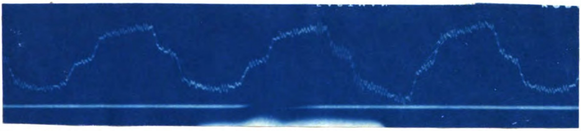

Fig. 30.

Running as direct cu rrent motor, drawing 15 amperes.

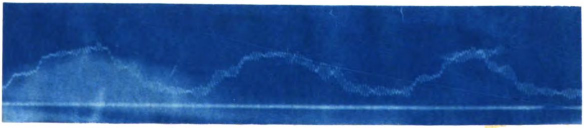

Fig. 31.

Running as direct current motor, drawing 20 amperes. The harmonics as shown in figure 29 and are not present in figure 28 are due to the effects of the armature current; there being no current flowing when figure 28 was taken.

Miscellaneous Transients

As an auxiliary study a few simple phenomena have been investigated. The ordinary door-bell is a common-place thing but the flow of current thru it it interesting. It consists of coils wound on an iron core and an armature which completes the magnetic circuit, and which carries the vibrating clapper and a circuit-interrupting device. When the circuit is closed thru a direct current source the current starts to flow, but due to the inductance of the coils wound upon the iron core, it does not reach its maximum value at once but increases gradually, building up the flux in the iron core at the same time. Soon after the current reaches its maximum value the armature is drawn by the magnets, striking the bell and interrupting the electrical circuit. If it were not for the inductance of the coils the current would cease instantly, but the inductance tends to prolong the current and an arc is established across the breaker points for a very small but a measurable length of time. After the circuit is broken the coils lose their magnetism and the clapper flies back to its original position, again closing the electrical circuit and the cycle is repeated.

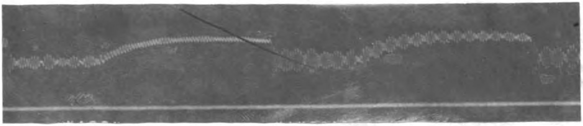

Fig. 32.

Figure 32 shows the current through an ordinary door-bell. Time is toward the right. It is evident that the growth of the current is gradual, arriving at a constant maximum value. Then the circuit is broken and the current drops to zero. The high frequency harmonic shown on the oscillogram is due to the natural vibration of the oscillograph ribbon, as is seen from the fact that it continually decreases in amplitude.

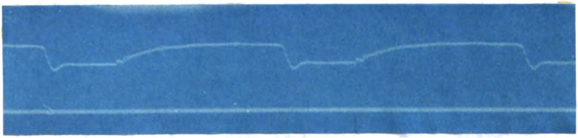

Fig. 33.

The above oscillogram shows the current through the same door-bell with a condenser connected across the breaker points. The building up of the current is very similar to that shown in figure 32, but when the current is broken, instead of an arc resulting from the energy stored in the coil, this energy is absorbed by the condenser. The stored energy in the condenser causes a reverse current to flow through the inductance, resistance, and the counter e.m.f. of the source, the combined impedence of which brings the current to zero. The absence of ripples is due to the fact that there is no abrupt change in current value and hence the oscillograph ribbons have no tendency to vibrate.

Another comparatively simple piece of apparatus which is used in the electrical industry is the magnetic circuit-breaker. It is connected inseries with the line, and its purpose is to protect apparatus by allowing only a certain amount of current to flow. It consists of one or more series turns of wire so interlinked with the magnetic curcuit that the armature will operate at different values of flux density corresponding to different values of current. The armature has a time lag depending on the air-gap, being greater for a greater air-gap. There is also a time element connected with th opening of the circuit-breaker contacts which is due to the inertia of the moving parts, For a short interval of time after the circuit starts to open, there is an arc maintained until t e resistance of this gap becomes so great that the current ceases to flow. During this interval the current dies down from its maximum value to zero. It was the purpose of this investigation to measure the time element of a circuit-breaker in the laboratory. The circuit was arranged so that when the shutter of the oscillograph opened, a relay closed t e circuit through the circuit-breaker and through the load which drew enough current to trip the circuit-breaker.

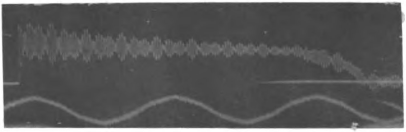

Fig. 34.

Set for 25 amperes, 120 V. d.c. supply.

This oscillogram represents the current from the time the relay closed until after the current ceased, due to the opening of the circuit-breaker. The high frequency harmonic is due to ribbon vibration caused by the large initial deflection. From A to B the flux is built up and the armature is drawn up closing the magnetic circuit and releasing the circuit-breaker. From B to C represents the decay of current from the time the circuit-breaker opens until the arc is extinguished. From the sixty cycle timing wave it is seen that it takes about one-twentyfourth of a second.

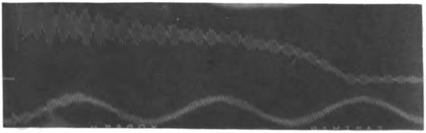

Fig. 35.

Same circuit-breaker, same setting, 220 V. d.c. supply.

From this oscillogram it is evident that there was more current flowing because the initial deflection was greater and the time of building up the flux less, as shown by the distance AB. It is also evident that it takes longer to extinguish the arc as shown by the distance BC; this being due to the higher voltage. But the total time taken for the breaker to open is practically the same for both cases.

There are many other interesting studies which could be made by means of the oscillograph, but which, due to insufficient time, were unable to be included in this report.

It would be worth while, in connection with rotating machinery, to take oscillograms of the simultaneous currents in the field, and in the armature, of either a direct or an alternating machine during short-circuit. It would also be instructive in this connection to record the change of field flux by winding a few turns of wire around the pole and connecting its terminals to one ribbon of the oscillograph, while the other ribbon could be connected so as to record the short-circuit current, or the field current.

Synchronous motors, while hunting, would afford another source of study. Some synchronous motors are equipped with damping rings mounted upon the poles. These prevent excessive hunting and carry considerable current. By means of the oscillograph, the current in such a ring might be recorded simultaneously with the armature current. This would show the exact relation between the hunting and the damping effect.