STUDIES IN THE OPERATING CHARACTERISTICS OF PRE-HEAT HOT CATHODE FLUORESCENT TUBE CIRCUITS

(Part—II)*

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Abstract

This paper discusses the various types of noise generated by fluorescent tube circuits and some of the results of wave analyses conducted in this laboratory—the percentage of harmonics in the range 50 c/s to 16 kc/s and the experimental determination of the circuit characteristics at high supply frequency. A range of supply frequencies from 50 c/s to 3 kc/s only has been considered for analysis. The advantages of high frequency operation have been discussed and some of the attendant problems briefly considered.

Introduction

It is known that fluorescent tube circuits give rise to harmonics which result in certain disadvantages such as radio-interference, etc. It has been now established by experiments that higher frequencies are better for the operation and performance of the tube. High frequency operation is not peculiar or new to the electrical engineer because he has already realised that high frequencies are better for several applications such as induction heating, power equipments in aircraft ships and railway coacnes, and so on.

Harmonics in Fluorescent Tube Circuits

Any of the usual types of fluorescent tube circuits generates harmonics to an appreciable extent. This results in distorted tube voltage and current wave-forms with the consequent lowering of the power factor and reduced life of the tube. Also, it can be seen from analysis that there are harmonic components in the low as well as high frequency regions capable of interfering with radio reception. The worst affected region is the medium frequency band.

The high frequency oscillations in the tube voltage wave (Fig. 11 *a*) can be detected by suitably filtering out the low frequency components and amplifying

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the higher ones. The latter, being non-sinusoidal, can be subjected to analysis for components. Steele[1] used three noise-meters of different ranges to measure the noise strength in the range 15 kc/s to 100 Mc/s. In this laboratory wave analysis has been carried out by a different method in the lower range, *viz.*, 50 c/s to 16 kc/s.

In the AC arc discharge inside the fluorescent tube it is found that various types of oscillations occur giving rise to various types of noise. The mechanism of this generation is discussed, in the light of the valuable study made by Culp.[2]

By an examination of Maxwell's wave equation in a conducting medium it can be shown that the different types of oscillations can be visualised as originating from rapid variations in the space charge distribution in the AC arc. Starting from Maxwell's fundamental electromagnetic equations the wave equation can be derived as follows:

We have†

$$\text{div } \underset{\cdot}{H} = 0 \tag{1}$$

$$\text{curl } \underset{\cdot}{H} = \frac{1}{c}\left(\frac{\partial \underset{\cdot}{F}}{\partial t} + 4\pi\rho \underset{\cdot}{V}\right) \tag{2}$$

$$\text{curl } \underset{\cdot}{F} = -\frac{1}{c}\left(\frac{\partial \underset{\cdot}{H}}{\partial t}\right) \tag{3}$$

and

$$\text{div } \underset{\cdot}{F} = 4\pi\rho \tag{4}$$

$$\text{Also } \rho \underset{\cdot}{V} = \underset{\cdot}{j} \tag{5}$$

where $\underset{\cdot}{H}$ and $\underset{\cdot}{F}$ are the magnetic and electric field strengths (and the permeability and the permittivity of the medium are both assumed to be unity), ρ the space charge density, $\underset{\cdot}{V}$ the velocity of charge, $\underset{\cdot}{j}$ the current density, *i.e.*, rate of flow of electricity and c the velocity of light.

Now

$$\text{curl}(\text{curl } \underset{\cdot}{F}) = \text{curl}\left(-\frac{1}{c}\frac{\partial \underset{\cdot}{H}}{\partial t}\right) = -\frac{1}{c}\left(\frac{\partial}{\partial t}\text{curl } \underset{\cdot}{H}\right)$$

and from equations (2) and (5)

† The lower dots represent vectorial quantities.

$$\nabla\nabla\cdot\underset{\cdot}{F}-\nabla^2\underset{\cdot}{F}=-\frac{1}{c}\frac{\partial}{\partial t}\left\{\frac{1}{c}\left(\frac{\partial \underset{\cdot}{F}}{\partial t}+4\pi \underset{\cdot}{j}\right)\right\}$$

$$=-\frac{1}{c^2}\frac{\partial^2 \underset{\cdot}{F}}{\partial t^2}-\frac{4\pi}{c^2}\frac{\partial \underset{\cdot}{j}}{\partial t}$$

$$\therefore\quad \nabla^2\underset{\cdot}{F}-\frac{1}{c^2}\frac{\partial^2 \underset{\cdot}{F}}{\partial t^2}=\nabla\nabla\cdot\underset{\cdot}{F}+\frac{4\pi}{c^2}\frac{\partial \underset{\cdot}{j}}{\partial t}$$

$$\therefore\quad \nabla^2\underset{\cdot}{F}-\frac{1}{c^2}\frac{\partial^2 \underset{\cdot}{F}}{\partial t^2}=4\pi\left\{\frac{1}{c^2}\frac{\partial \underset{\cdot}{j}}{\partial t}+\nabla\rho\right\},\ \text{using equation (4)} \qquad (6)$$

This is the wave equation in a conducting medium. In the absence of a knowledge of the boundary conditions this can only be of help to us in forming a picture of the internal phenomena. Thus we know that radio frequency oscillations are generated and radiated owing to the existence of an electric field $\underset{\cdot}{F}$ which varies in time. Such a variation in field strength must be due to a space charge whose density is varying in time. Such a phenomenon involving rapid changes in space charge distribution can well be visualised as the mechanism of noise radiation, and the different types of noise can be interpreted.

One of the types of noise known as the *re-ignition noise* comes in a pulse at the beginning of each half-cycle. While it is most conspicuous by its effect, the mechanism of its generation is difficult to explain. Without any definite frequency it spreads over a certain band-width below 2 Mc/s as an oscillating wave whose frequency changes sporadically throughout the duration of the pulse. Culp's experiments[2] indicate that the cathode is the true source of re-ignition noise and the noisy period occurs during the building up of the discharge at the beginning of the cycle. The noise-pulse is affected by a magnet held near the cathode. An auxiliary heating current through the filament also shows the same effect and occasionally the noise gets almost quenched. According to Culp[2] the metastable mercury atoms filling the space in the gas play an important role in re-ignition. The noise probably starts when an ion sheath is forming in front of the cathode.

A second type of noise, *the hollow-cathode noise*, is generally perceptible with aged tubes. It is due to the formation of a small cavity at some point on the coiled-coil filament due to the cathode hot spot and is evidenced by a punctuation of the noise oscillogram with sporadic radio-frequency pulses of smooth appearance. At a certain point in the voltage cycle there is a transitory negative glow in the cavity. The sudden appearance and disappearance of this glow gives rise to two separate pulses. This phenomenon can occur even on DC operation of the tube. The sudden appearance of the negative glow in the cavity results in the sudden formation of a positive ion sheath, and this redistribution of the space charge is the cause of hollow-cathode noise. Culp points out that there is the possibility of a frequency-modulated oscillation of the space-charge as it builds up or decays.

These two types of noise cause a pronounced buzz in the loud-speaker of a radio receiver if tuned.

The third type of noise, the *anode noise*, is noticed as low frequency pulses in the range 1 kc/s to several Mc/s in the middle of the voltage half-cycle. They are sporadic and random in character and may not always appear in both halves of the wave, and are affected by a magnet held near the anode. This noise is due to a pulsating anode glow which gives rise to abrupt changes in the space charge at the anode.

The mechanism of this phenomenon according to Culp[2] is as follows:

There is negative space-charge near the anode from where positive ions have been swept off by electrons drifting towards the anode. This creates a small potential difference across the region. As this drop increases the electrons drifting into that region are accelerated and they ionize some more atoms there. The sluggish positive ions so produced neutralise the electrons and the voltage drop disappears till the ions have moved away from that region. This gives rise to periods of alternate anode-glow and darkness.

To avoid anode noise large cylindrical anodes have to be designed. The addition of a series resistance to the circuit helps to quench these oscillations.

Starting and *extinction* oscillations are two more types of oscillations, of comparatively little practical significance as they are infrequent and transitory. During the time when the critical current is falling the ion sheath near the cathode breaks up, and the consequent sudden space-charge variations give rise to extinction oscillations. Starting oscillations occur when the tube is in the process of starting. They resemble the re-ignition oscillations as both have the same causes and characteristics, but the latter type is self-sustained.

Thus it is found that various types of oscillations are engendered by time variations in space-charge distribution. Any method adopted to reduce these variations would result in minimising the noise generated in the fluorescent tube. Proper design of the cathodes in the present type of hot-cathode tubes would result in eliminating some types of noise, but for better results more advances in manufacturing designs are necessary. Thus by using neon instead of argon as carrier or by reducing the argon pressure in the tube, the noise can be reduced. But neon, as a carrier gas, introduces other problems such as short tube life and changed tube voltage, and these have to be overcome first. For the present commercial tubes the only remedy is therefore to modify the external circuit as best as possible.

In the external circuit the method usually adopted to reduce the radio-interference is to shunt the tube with a capacitor ($\cdot 01 - \cdot 05\,\mu f$) which can suppress the interference appreciably (Fig. 1). In extreme cases where the tube and the receiver are very closely located special precautions are necessary. Various acceptor or rejector filter circuits have been designed to reduce the interference

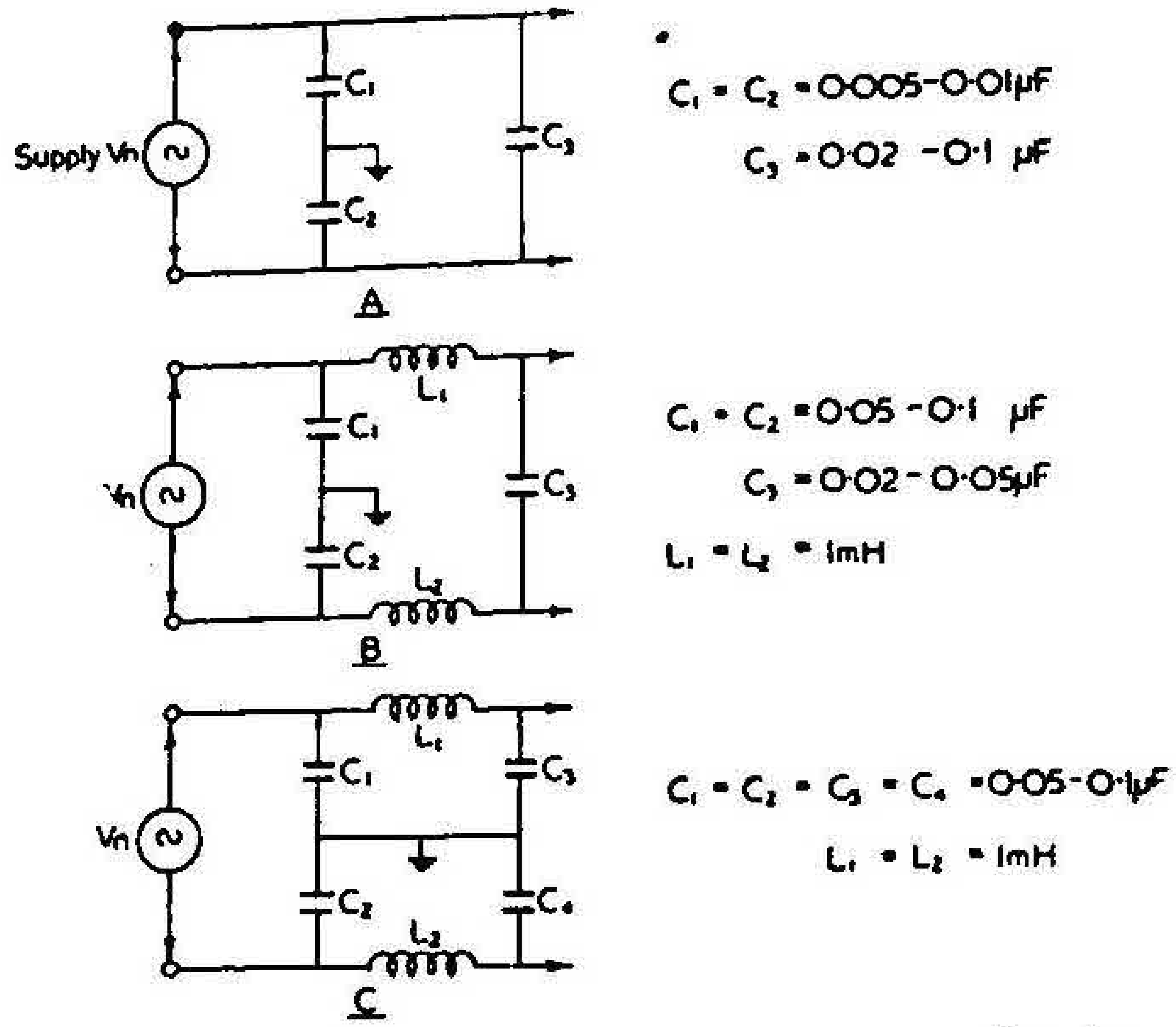

FIG. 1. Radio-interference suppressor circuits.

by feedback through the supply leads. A delta filter or a multiple filter may be used in the closest proximity to the tube (Fig. 1).

The radio-interference suppressor capacitor across the tube plays, in addition, an important part in starting the tube. It prolongs the pre-heating period, especially with a glow-starter, and is a valuable addition to start tubes employing glow-starter in avoiding cold-starting. A high value of this shunt capacitor is unadvisable as it has the undesirable effect of boosting up the initial peaks in the voltage waveforms

Wave Analysis (*Range* 50 *c/s to* 16 *kc/s*).—In this investigation a range of supply frequencies from 50 c/s to 3 kc/s has been considered for analysis. It is found, in general, that the magnitudes of harmonics decrease with higher supply frequencies and the waveforms progressively improve (Table IV). Most of the oscillations described above are non-sinusoidal, *i.e.*, they contain higher harmonics. If we aim at eliminating these non-sinusoidal oscillations we can expect as a corollary, a reduction of the higher harmonics too, and in effect lesser radio interference. An improved current waveform is in itself an advantage to the tube as it increases its life, and any step taken in this direction will, therefore, be useful. The analysis of the tube waveforms can be helpful to us in the appraisal of any particular type of ballast.

Of the harmonics present the odd ones are preponderant. But even harmonics are also often observed and they must be due to a slight asymmetry between the cathodes. They are generally of very small magnitudes, so that the waveforms are essentially symmetric, and an analysis can be carried out graphically. But a different approach has been made in this investigation. The necessary fluorescent tube circuits are set up and the wave to be analysed is applied to an electronic wave analyser in which the different harmonics are separated and individually fed into an amplifier through tuned circuits, and their magnitudes are read off on a calibrated vacuum tube voltmeter.

The tube voltage nas been analysed on choke and resistor ballasts for operation on 50 c/s supply, and on choke, resistor and capacitor ballasts for operation at high supply frequencies. To analyse the current, the voltage drop across a small series resistor was taken to represent the respective harmonic current. In the case of the resistor ballast the ballast voltage itself was analysed to obtain the current harmonics (Table IV).

In a choke circuit it is usually expected that the choke impedance z progressively increases with the order of the harmonic. Thus for the n-th harmonic we must have:

$z = n \cdot \omega \cdot L$ (neglecting the resistance of the choke which is comparatively very small).

In the case of an ordinary resistor ballast, however, the impedance must remain constant for all frequencies. Now the impedance can be computed for any harmonic from the harmonic voltage drop and the corresponding harmonic current obtained from analysis. On the basis of such calculation it has been observed that while the resistance remains the same (within limits of experimental error) for the resistor circuit (Table I), the impedance of the choke pulsates with frequency (Tables II and III, Figs. 2 and 3).

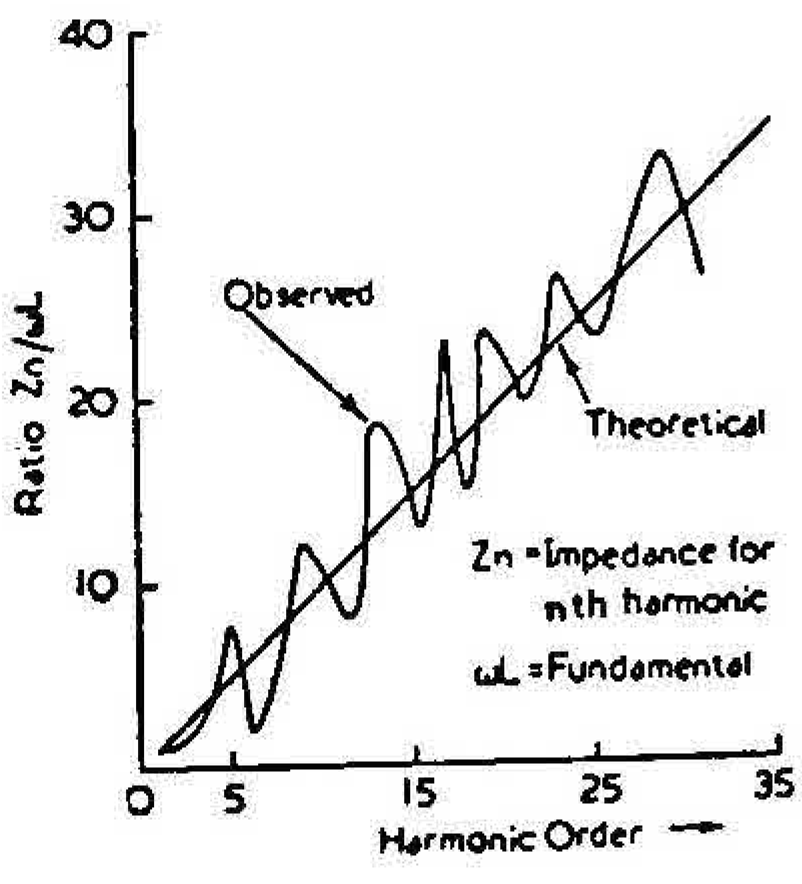

FIG. 2.

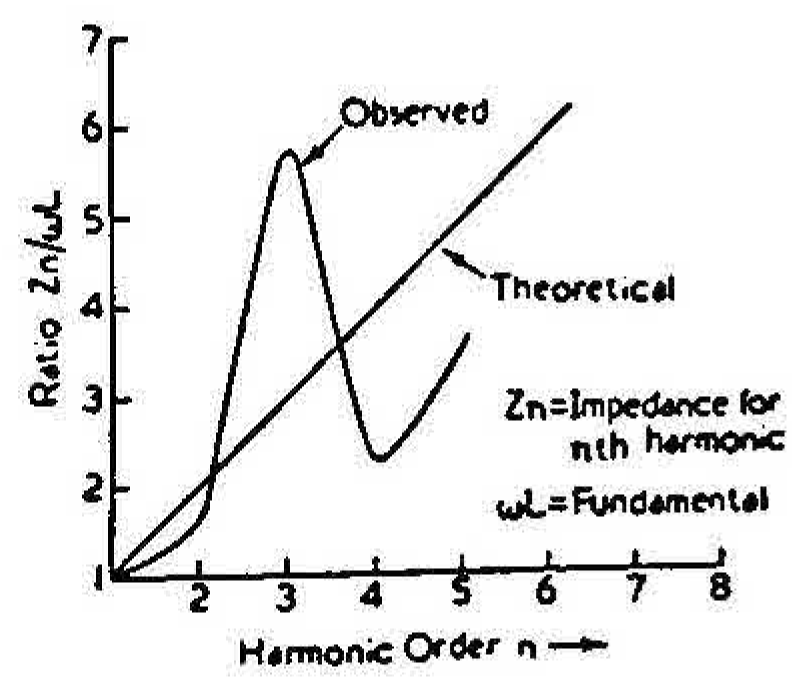

FIG. 3.

FIG. 2. Impedance-Frequency characteristic for a choke. Fundamental = 50 c/s.

FIG. 3. Impedance-Frequency characteristic for a choke. Fundamental = 3·2 kc/s.

A similar anomaly has been observed in tne case of the capacitor circuit. The impedance, instead of progressively decreasing with increasing frequency [since $z_n = (1/n\omega c)$, where c = capacity] suddenly increases (Table III). It may be pointed out that this has nothing to do with resonance as we are considering only the impedance of the capacitor and not that of the total circuit. This departure from normal exepcted behaviour is interesting.

TABLE I

Harmonic impedances of resistor ballast

Harmonic order	Resistance on 50 c/s supply (Ordinary resistor)
1	354 Ohms
2	340 ,,
3	354 ,,
4	334 ,,
5	327 ,,
6	340 ,,
7	347 ,,
8	334 ,,
9	350 ,,
10	334 ,,
11	343 ,,
13	367 ,,
15	354 ,,
17	334 ,,
19	340 ,,
21	340 ,,
23	334 ,,
25	350 ,,
	Resistance on 3·2 kc/s supply (Filament Lamp 130 V, 60 W as ballast, supply volts 190)
1	272 Ohms
2	280 ,,
3	274 ,,
5	267 ,,

Operation of the fluorescent tube on high frequency supply.—Though the most usual frequency of power supply is 50 — 60 c/s everywhere, higher frequencies are finding many applications in recent times. The advantages are reduced size and weight of the equipments as well as better overall efficiency. The performance of fluorescent tubes is also better as the frequency is increased.

The analogy between the incandescent lamp and the fluorescent tube[3] is helpful in understanding the dependence of the tube volt-ampere characteristics on the supply frequency. Figures 4 and 5[3] show the dynamic voltampere characteristics of the incandescent lamp and the fluorescent tube. In the former case, the filament resistance depends on its instantaneous temperature, as also on its previous thermal history. At low supply frequencies such as 25 c/s, the filament is cooler

TABLE II

Harmonic impedances on choke ballast

Harmonic order	$Z_n = \frac{(V_b)_n}{I_n}$ Ohms	Ratio $\frac{Z_n}{Z_1}$ Theoretical	Ratio $\frac{Z_n}{Z_1}$ Experimental
	On 50 c/s supply		
1	470	1	1
2	480	2	1
3	845	3	1·87
4	2000	4	4·3
5	3540	5	7·85
6	880	6	1·95
7	2200	7	4·9
8	3500	8	7·8
9	5560	9	12·3
10	5000	10	11·1
11	3800	11	8·4
12	3750	12	8·4
13	8400	13	18·7
14	8000	14	17·8
15	6000	15	13·3
16	7500	16	16·7
17	10350	17	23
18	6660	18	14·7
19	10700	19	23·6
21	8940	21	19·8
23	12000	23	26·7
25	10500	25	23·3
27	12600	27	28
29	15000	29	33·4
31	12000	31	26·7
	On 3·2 kc/s supply		
1	418	1	1
2	637	2	1·52
3	2400	3	5·75
4	933	4	2·27
5	1500	5	3·67

Note.—(1) Z_n denotes impedance for the *n*th harmonic. (2) The resistance of these chokes was so small, compared to the impedance, that the impedance was essentially inductive.

when the current is increasing than when it is decreasing—thus the resistance is more when the current is waning and the light produced during this part of the cycle is reduced, resulting in flicker. If the frequency is increased to 50 c/s, the current variation becomes too fast for the filament to cool off during one cycle so

TABLE III

Harmonic impedances on capacitor ballast

Harmonic order	$Z_n = (V_b)_n/I_n$ Ohms		Ratio Z_n/Z_1	
	Theoretical	Experimental	Theoretical	Experimental
		On 480 c/s supply		
1	450	460	1	1
2	225	175	0·5	0·39
3	150	89·5	0·33	0·24
4	113	180	0·25	0·4
5	90	32	0·2	0·071
6	75	42	0·17	0·093
7	64	70	0·14	0·16
8	56	120	0·125	0·26
9	50	120	0·11	0·26
10	45	115	0·1	0·25
11	40	143	0·09	0·32
12	38	148	0·083	0·33
13	35	150	0·078	0·33
14	32	170	0·071	0·38
15	30	183	0·067	0·4
17	27	170	0·06	0·38
21	21	285	0·05	0·63
25	18	340	0·04	0·75
27	16·6	360	0·037	0·8
29	15·5	380	0·0345	0·85
31	14·5	350	0·032	0·78
		On 3·2 kc/s supply		
1	545	545	1	1
2	273	440	0·5	0·81
3	182	216	0·33	0·4
4	136	..	0·25	..
5	109	850	0·2	1·56

that the resistance remains practically constant. There is a thermal equilibrium resulting in an almost straight line dynamic voltampere characteristic (Fig. 4).

The case of the fluorescent tube is similar except that the frequency has to be very much higher in order to realize a similar straight line characteristic because the time constant for the deionization of the discharge is very small compared to the time required for the thermal cooling off in the incandescent lamp filament. The conductance in fluorescent tube, however, depends on the state of ionization of the vapour in it. At any given value of the current, the resistance of the tube is higher when the current is increasing than when it is decreasing (Fig. 5), since at a given value of the current the ionization is less for a rising current than for a

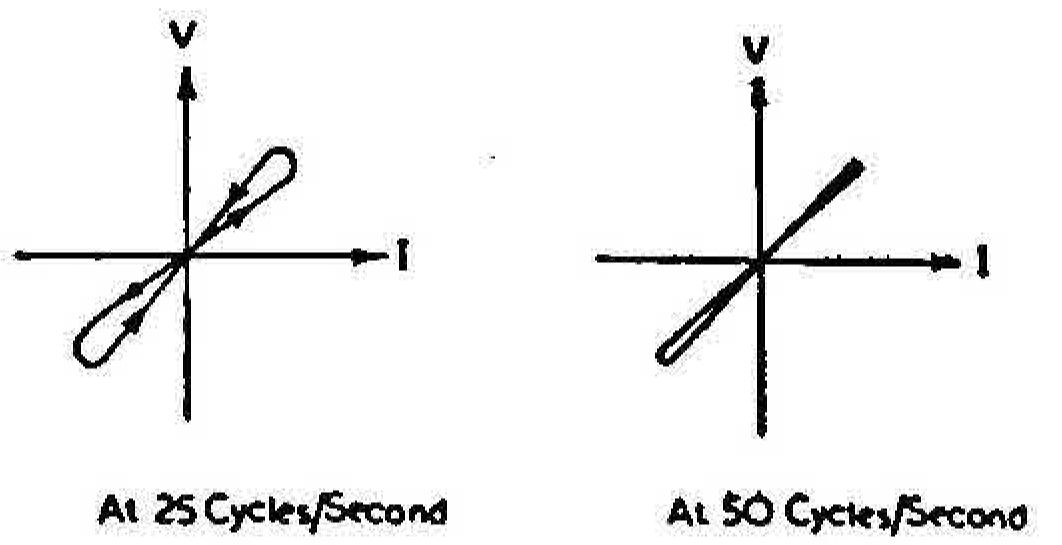

FIG. 4.

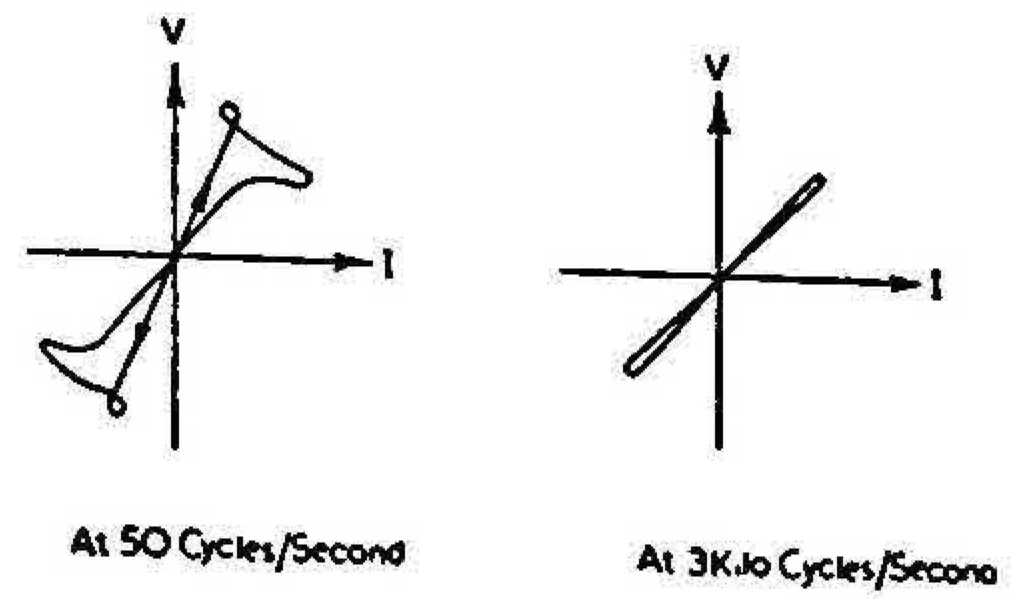

FIG. 5.

FIG. 4. Dynamic volt-ampere characteristic for an incandescen lamp at 25 c/s and 50 c/s.

FIG. 5. Dynamic volt-ampere characteristic for a fluorescent tube at 50 c/s and 3 kc/s.

falling current. Because of this property the voltampere loop is reversed in this case as compared with the loop for the incandescent lamp. At a high frequency of the order of 3 kc/s the loop develops almost into a straight line. The operation of the tube *is optimum under* such conditions because at a high supply frequency the state of ionization in the arc discharge inside the tube reaches a dynamic equilibrium as the deionization period is shorter and the residual ionization is large. Consequently the voltage peak necessary for re-ignition of the arc each half-cycle is reduced, and this results in an improved waveform, regardless of the type of ballast used. This implies in itself increased scope in circuit design (Figs. 9–17).

Further, owing to the greater residual ionization at high frequencies, the various voltage drops such as cathode and anode drops familiar at 50 c/s and the end losses are reduced. Hence the necessary voltage drop across the tube gets reduced with an increased probability of excitation of the resonance radiation of the mercury vapour. Also due to reduced deionization and increased inelastic collisions the amount of radiation produced is increased, resulting in improved luminous efficiency of the tube. If the end losses could be totaly eliminated the efficiency could be raised by 20 per cent.[4] But, in practice, this is not possible even at frequencies of the order of 20 kc/s. The maximum gain observed by Campbell, Schultz and Kershaw[4] is only 12 per cent.: but according to Spencer[5] the possible increase is 6–15 per cent. excluding ballast losses which can be further reduced by employing capacitors as ballasts, resulting in a still further saving in power consumption.

Tests conducted by Spencer and Coradeschi[5] at 3 kc/s show an increase in the life of the tube of at least 12 per cent. over that at 60 c/s, if not higher. This increase in life is due to easier and quicker starting at high frequencies and the minimising of ionic bombardment of the electrodes due to the dynamic equilibrium.

Further, the improved waveforms result in reduced radio interference and reduced harmonic voltage drops in cables (Table IV) and the tube power factor becomes almost unity. Flicker and stroboscopic effects will be totally absent. There is less audible noise from the auxiliaries and less masking of the audio

TABLE IV

Percentage of the magnitudes of current Harmonics in fluorescent tube circuits with different ballasts at different supply frequencies

Harmonic order	Magnitude of current harmonics in per cent.						
	50 c/s supply		480 c/s supply		3·2 kc/s supply		
	Choke Ballast	Ordinary resistor Ballast	Filament lamp Ballast	Capacitor Ballast	Filament lamp Ballast	Capacitor Ballast	Choke Ballast
1	100	100	100	100	100	100	100
2	0·67	0·35	0·14	0·5	0·53	0·65	0·73
3	9·5	23	5	14	2·24	6·5	1·31
4	0·09	0·33	0·15	0·19	0·021	..	0·2
5	1·1	8·1	1·75	1·4	2·4	0·26	1·85
6	0·07	0·22	..	0·06			
7	1·13	4·1	0·4	0·9			
8	0·03	0·16	..	0·05			
9	0·24	2·7	0·13	0·4			
10	0·03	0·08	..	0·065			
11	0·26	1·03	0·13	0·35			
12	0·02	..	..	0·06			
13	0·12	0·81	0·09	0·25			
14	0·01	..	..	0·04			
15	0·13	0·6	0·04	0·15			
16	0·005	..	..	..			
17	0·08	0·41	0·0[illegible]	0·075			
19	0·07	0·22	..	..			
21	0·07	0·14	0·06	0·09			
23	0·05	0·24	0·087	..			
25	0·05	0·16	0·087	0·125			
27	0·04	..	0·087	0·125			
29	0·03	..	0·075	0·11			
31	0·03	..	0·06	0·1			

(3·2 kc/s supply:) The values in this particular case are intended to give a qualitative idea of the actual harmonic magnitudes in a typical commercial high frequency supply-system which contains harmonics itself.

Note.—(1) Comparison should be made between the readings for the same type of ballast at a time. (2) Still higher harmonics do exist but their magnitudes are very small and varying, and hence they are not included in this table.

frequencies. There is also saving in weight and bulk of the auxiliary equipment of the order of 98 per cent. (at 3 kc/s, with capacitor ballast), and saving in ballast losses—about 28 per cent. with the motor-generator losses included, or 90 per cent. if power is generated at 3 kc/s, as estimated by Spencer.[5]

While high frequency operation looks attractive in these respects there are certain other aspects to be examined such as the economics of high frequency power generation or conversion from 50 c/s and the problem of efficient transmission. Regarding the latter, Spencer[5] has shown on the basis of a 'quarter wave-length criterion' that even at 10 kc/s there is no problem of fluctuating voltage up to 5 miles length, and at 3 kc/s up to 16 miles. This range can be further extended by employing compensating capacitors.

Among different devices for generating high frequency power, though rotary convertors are available in a variety of sizes and frequencies (medium) there are certain limitations. The overall power factor of the load should not be leading and circuits will have to be accordingly modified. Lead-lag circuits will have to be adopted or a reactor will have to be used. In places where only DC power is available these convertors prove very useful.

Motor-alternators and mercury-pool cathode rectifiers are available for converting DC or low frequency AC to high frequency AC. For industrial areas, big office buildings and departmental stores, and in transportation, equipped with their own power plants, it is profitable to design the generators for high frequencies like 3 kc/s. With little extra costs this will make for better overall economy.

With the mercury-pool cathode rectifier it is possible to get AC power at any desired frequency (up to a few kc/s) and of any number of phases by means of the control grid alone or in combination with ignitors.[6] With electronic convertors it is possible either to have a fixed ratio of the input to the output frequency, or to vary them over wide limits.

Magnetic frequency convertors can be used to obtain medium frequencies. The square wave produced by them presents many advantages[4] such as better efficiency (than with sine waves) of the order of 75 per cent., absence of deionization time and reduced end losses, and cheap maintenance owing to the absence of moving parts.

Thus it is possible to generate or convert power and transmit it at high frequency (the optimum being 3 kc/s, as already stated). A study of the economics of the problem shows that in spite of the extra costs involved the high frequency system results in an overall saving, and is a definitely attractive proposition to the modern illuminating engineer.

Experimental Determination of Circuit Characteristics at High Frequencies.— A Mazda 4 ft.–40 watt Daylight tube was operated on supplies of various high frequencies ranging from 480 c/s to 10 kc/s, employing choke, capacitor, resistor and specially-rated incandescent lamps as ballasts. The circuit characteristics were studied under varying supply voltage conditions. The relative changes in the illumination at a definite point near the tube were measured with a photo-electric light meter (the extraneous light being cut off), in order to get an idea of the variation in the luminous output of the tube.

A few typical results are shown in Figs. 6–8 incorporating $I - V_n$, $I - V_t$, $I - V_b$ and Illumination V_n curves, where I is the current, V_n the supply voltage, V_t the tube voltage and V_b the ballast voltage.

These curves may be compared with one another as also with the corresponding curves for operation at 50 c/s.[7] In particular it may be noted that the gradient of the Illumination $- V_n$ curve somewhat decreases at supply frequencies of the order of 9 kc/s; but it is experimentally found that this curve is actually steeper

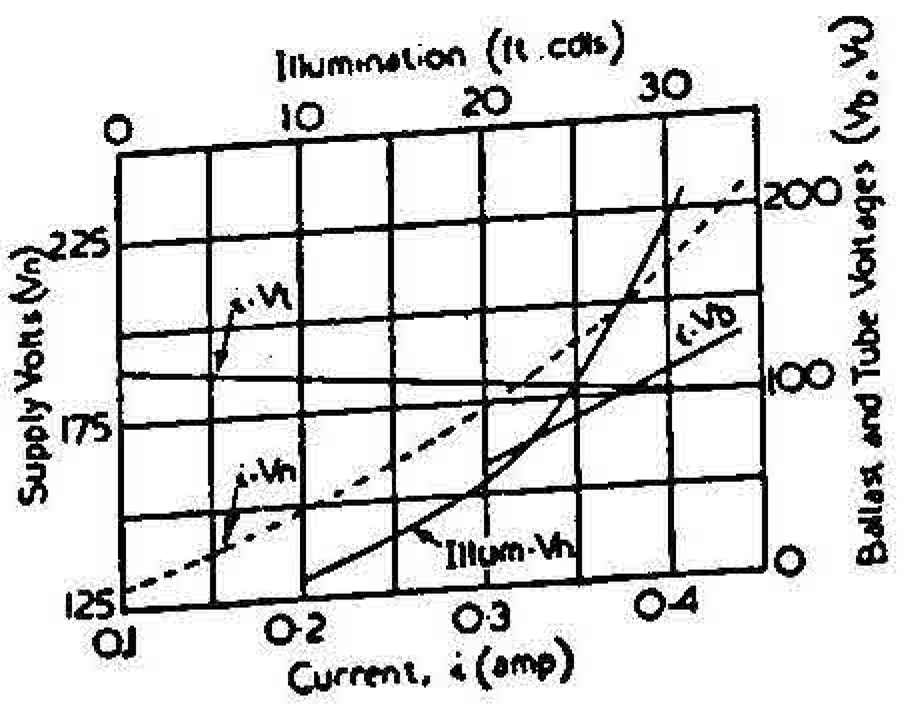

FIG. 6.

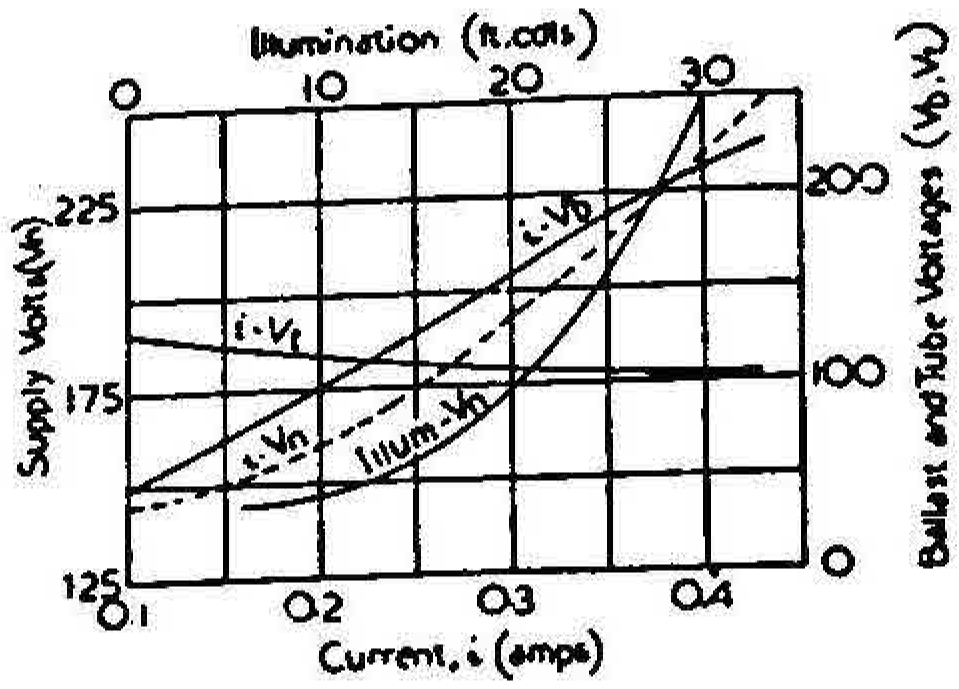

FIG. 7.

FIG. 6. Circuit characteristics on 150 V.–15 W incandescent lamp ballast (at 8·8 kc/s).

FIG. 7. Circuit characteristics on capacitor ballast (at 8·8 kc/s).

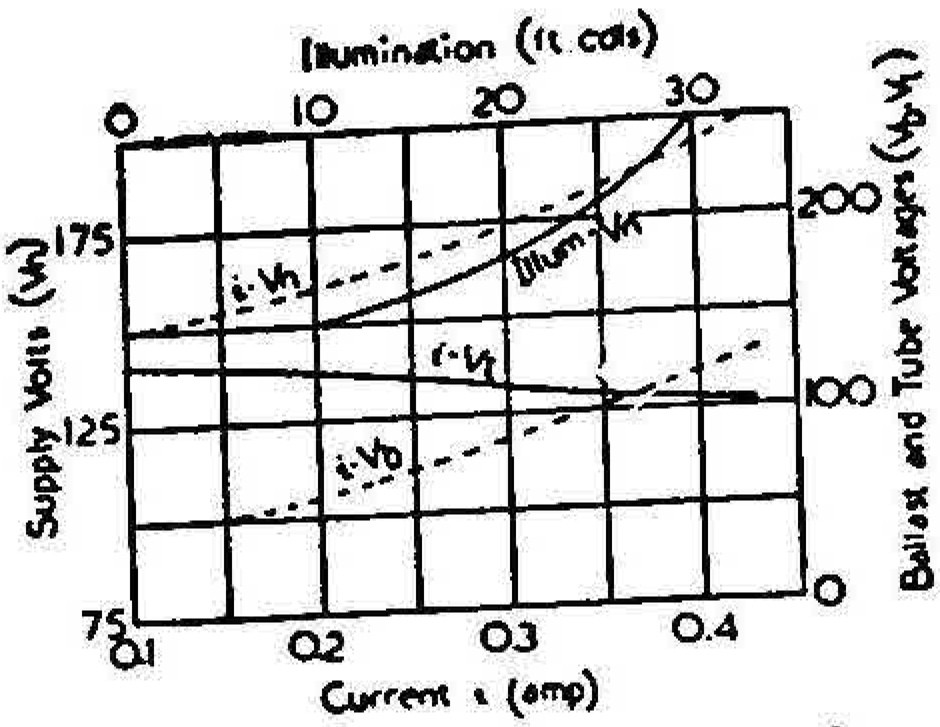

FIG. 8. Circuit characteristics on choke ballast (at 8·8 kc/s).

at 3·2 kc/s and 480 c/s showing that the regulation of the light output is even better at these frequencies. It may also be observed that there is a good deal of similarity amongst the characteristic curves for different ballasts irrespective of the type of ballast employed at high supply frequencies, and this fact is also borne out by the two groups of photographs—Figs. 12, 13, 14 and Figs. 15, 16, 17, in contrast with the group—Figs. 9, 10, 11.

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Waveforms of Current (top)

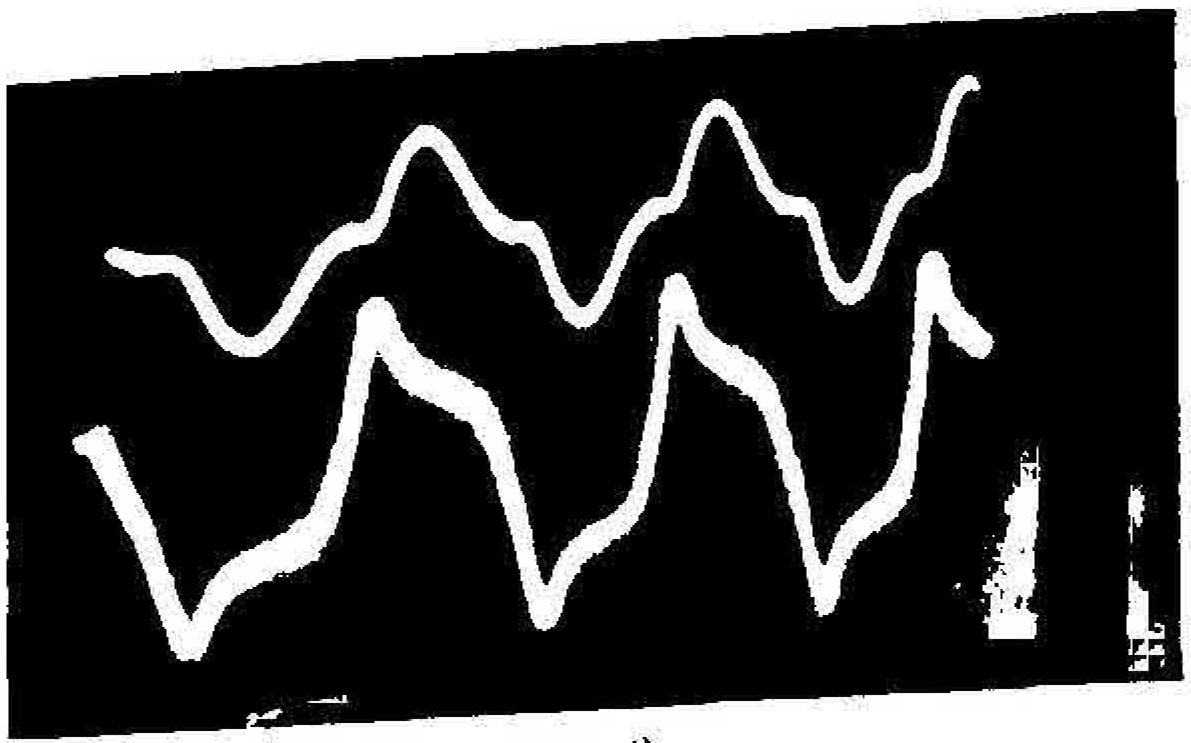

FIG. 9

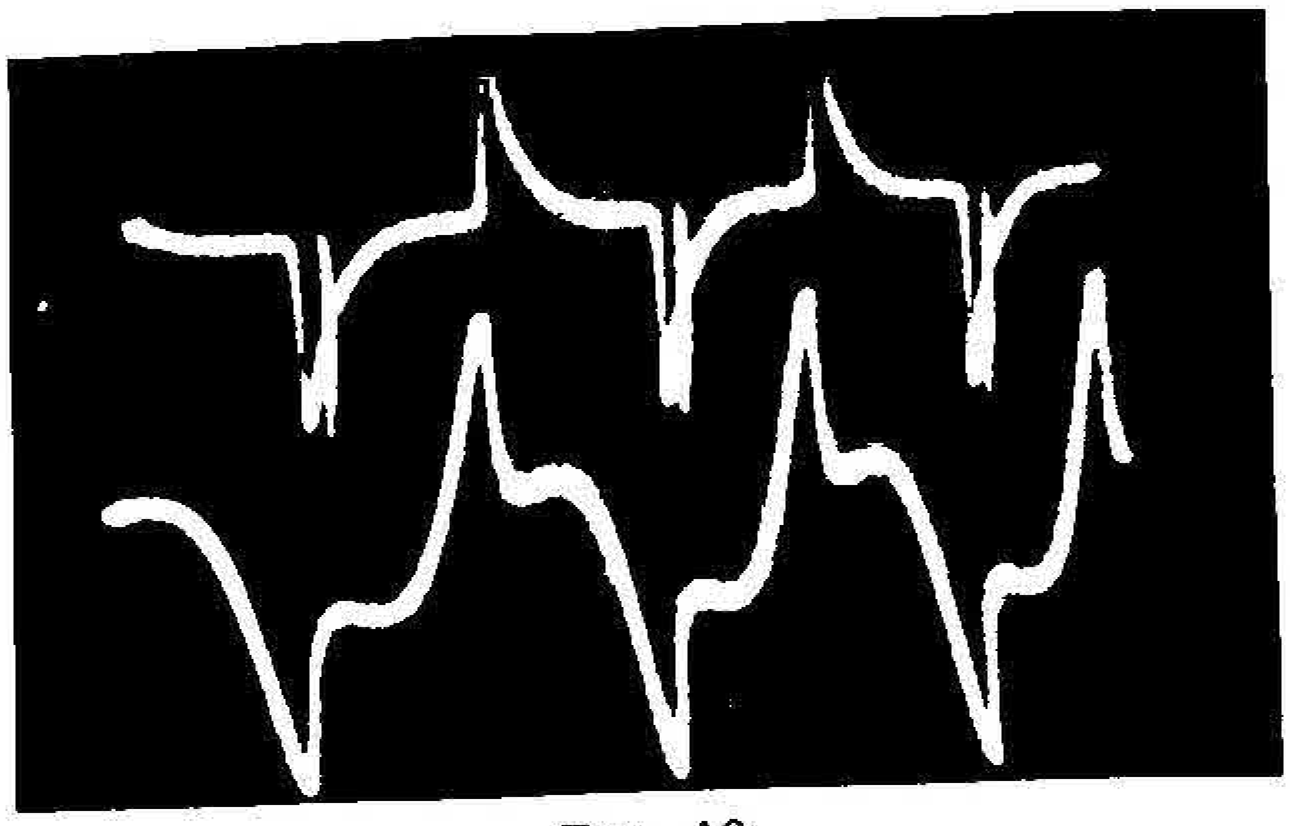

FIG. 10

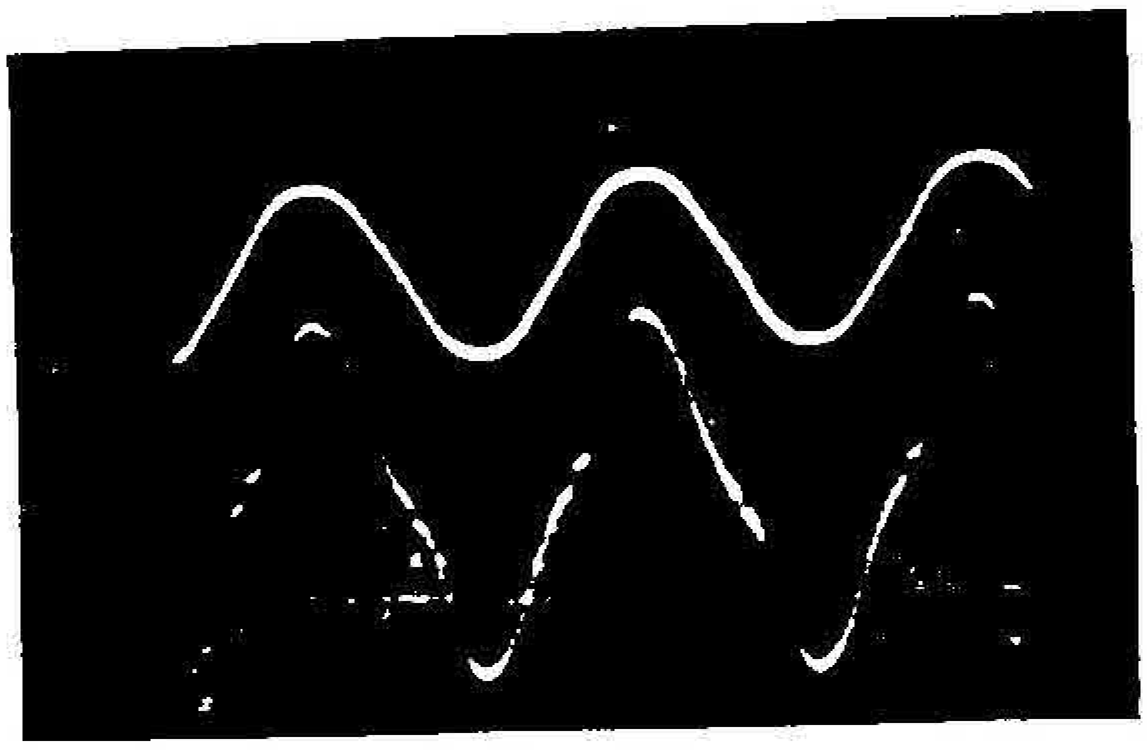

FIG. 12

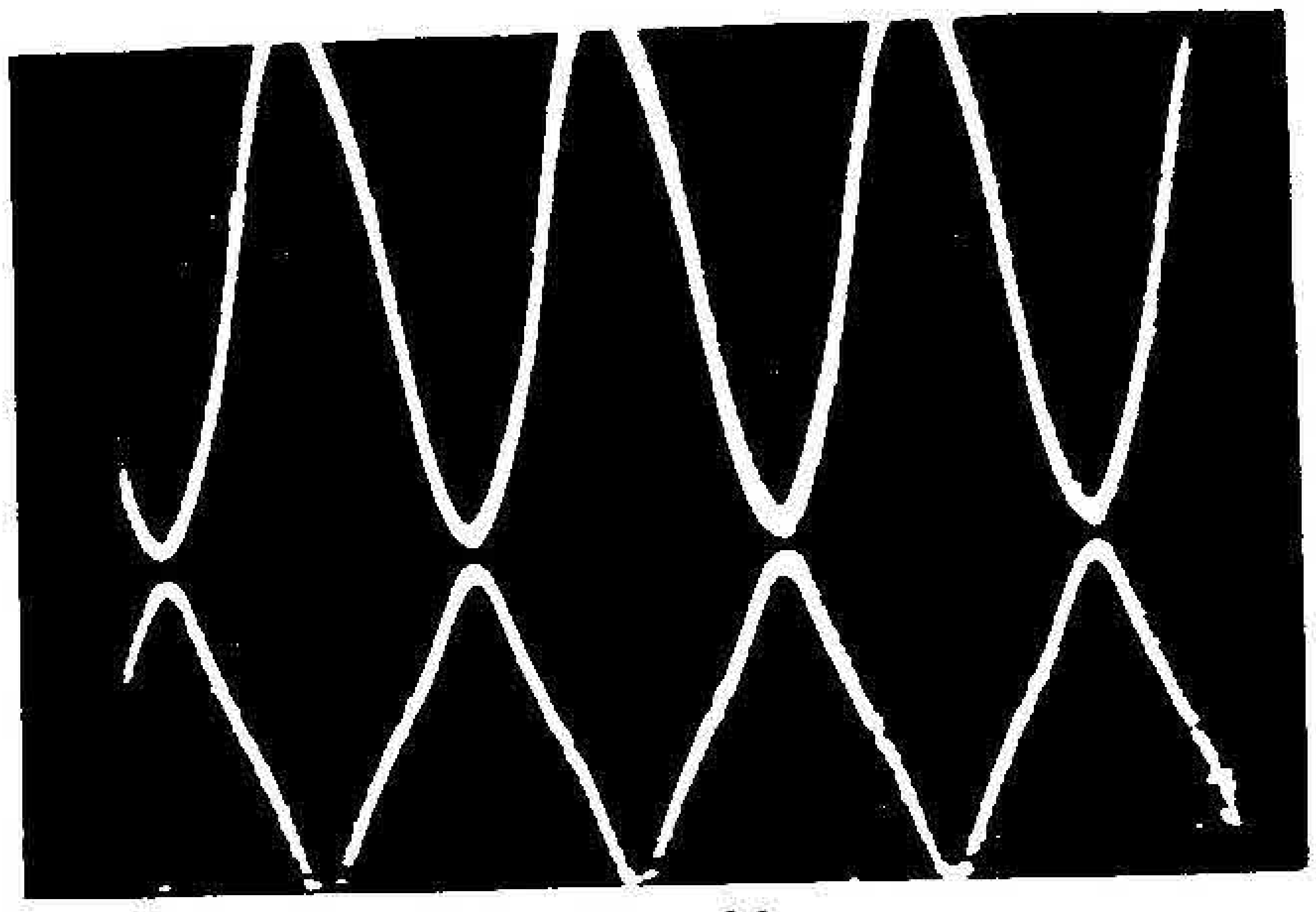

FIG. 13

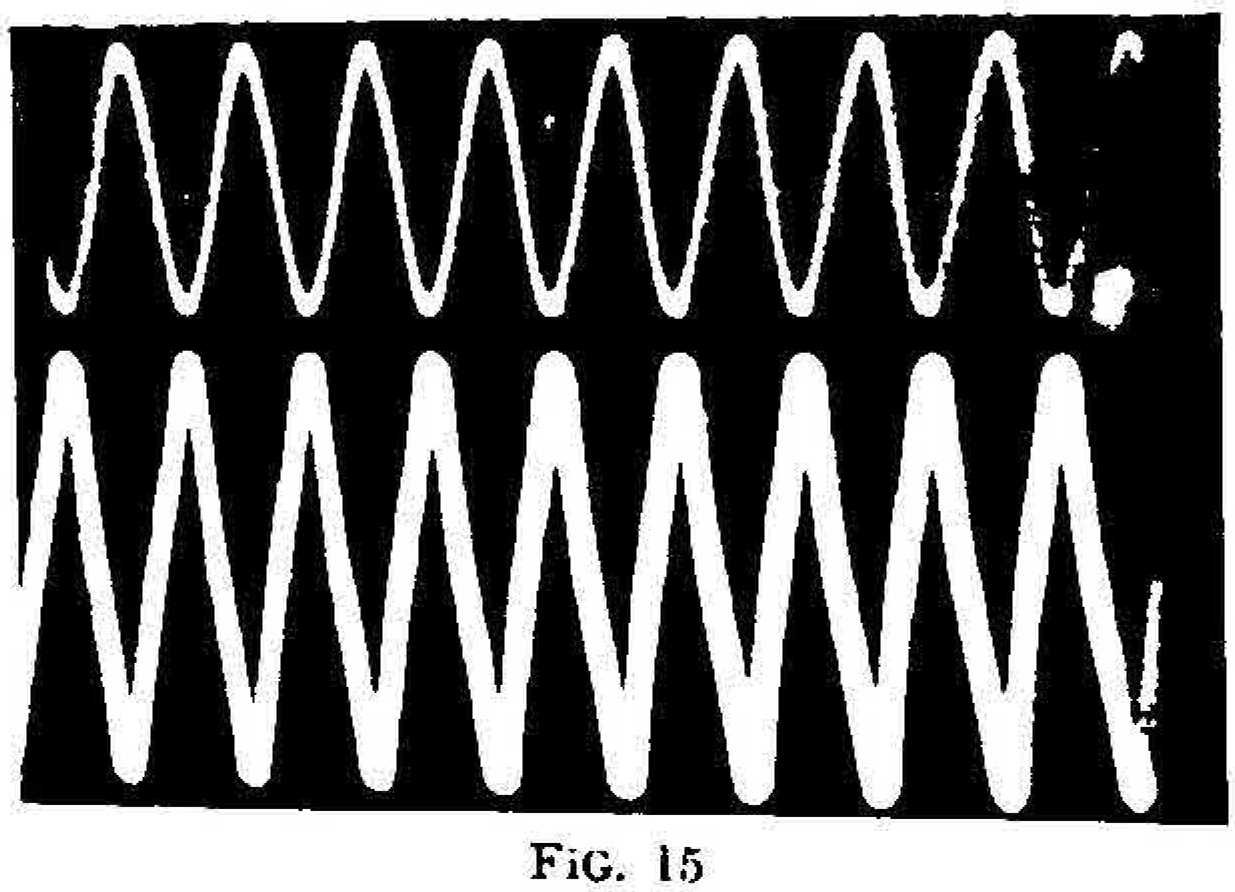

FIG. 15

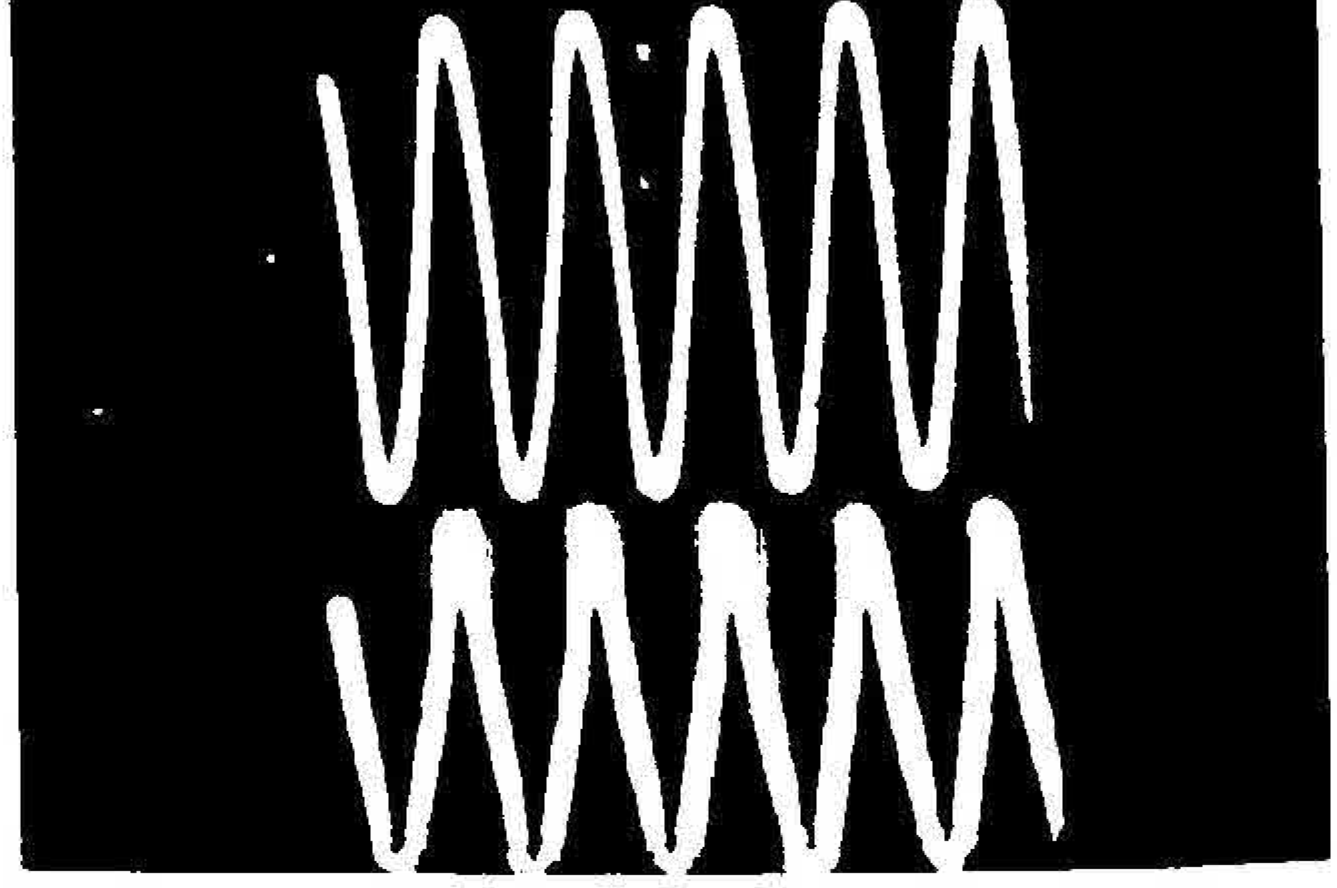

FIG. 16

FIG. 9. Resistor Ballast (50 c/s.).
FIG. 12. Incandescent-lamp Ballast (3·2 kc/s.).
FIG. 15. Resistor Ballast (9·76 kc/s.).

FIG. 10. Capacitor Ballast (50 c/s.).
FIG. 13. Capacitor Ballast (3 kc/s.).
FIG. 16. Capacitor Ballast (7 kc/s.).

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