TOLERABLE LIMITS OF VOLTAGE FLUCTUATIONS PRODUCED BY MAGNETS PULSED DIRECTLY FROM ALTERNATING CURRENT POWER LINES*

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Summary

Switching magnets, for time sharing of beam lines, can be pulsed directly from the ac power line if it does not cause objectionable line voltage fluctuations (flicker). Switching circuits, which are less expensive and more reliable than conventional magnet power supplies are often all that are needed. Of particular interest for beam lines of the Zero Gradient Synchrotron (ZGS) was a test to determine the permissible attenuation of 1 cycle of the 60 Hz power line every 2 s. Other tests included multiple cycle attenuation at different repetition rates and square wave modulation of the ac power line. Thresholds of perception and the distribution of opinions on the flicker disturbance as functions of voltage attenuation were determined for viewing TV and reading by incandescent light. The results of these tests are reported and can be used to calculate the permissible magnitude of pulsed current in a given ac power system.

Introduction

Bubble chamber beam line magnets need to be energized for less than 1 ms. They can be pulsed from the power line if this does not cause objectionable line flicker. Figure 1 illustrates a typical circuit in its simplest form. A bending magnet is connected to two phases of the secondary of a 132 kV/12.5 kV three-phase substation transformer through an ignitron. With reference to Fig. 2, the magnet current is

$$i_m = \frac{E_m}{(R^2 + \omega^2 L^2)^{1/2}} \left[\sin(\omega t + \lambda - \theta) - \sin(\lambda - \theta) e^{-Rt/L} \right] \quad (1)$$

where

E_m = magnet voltage,

R = magnet resistance,

L = magnet inductance, and

θ = $\tan^{-1} \omega L/R$.

In order to compensate for slow line voltage fluctuations with a feedback loop, λ is about 10°. The distortion in the ac lines, as illustrated by Fig. 3, will limit the pulsed single-phase load that can be tolerated.

There will be five bending magnets in the beam line for the 500-Liter Bubble Chamber at the ZGS. It is desired to pulse these magnets for 1 cycle from the 60 Hz power line to obtain 920 kG-feet for a fraction of 1 cycle every 2 s. The public utility company could not advise whether such a load could be tolerated on its 138 kV line serving the ZGS. Therefore, experiments were made with critical loads to determine the thresholds of perception and the distribution of opinion rating on the severity of this flicker disturbance. In addition, the effects of multiple cycle attenuation at different repetition rates and of square wave modulation of the line voltage were determined in order to obtain data for other possible future loads and to tie the results in with published flicker curves.

Tests Performed

General

Published flicker[1] curves are based on the sensitivity of low-wattage incandescent light bulbs (25 to 60 W). Higher-wattage bulbs, fluorescent, mercury-vapor, and sodium lamps are less sensitive. There are no known flicker curves for TV sets.

For our special application, it was thought that 1 cycle out of 120 cycles could be attenuated quite severely before it would be detected or would cause irritation.

Test Circuit

The flicker test circuit is shown in Fig. 4. Voltage sensitive single-phase loads are connected to 120 V, 60 Hz through a fixed reactor, L_1. A series connection of a variable reactor (comprised of a 117 V variable autotransformer loaded by choke L_2) and a silicon controlled rectifier (SCR) are in parallel with the load. The variable reactor is switched into the circuit by means of the SCR, which is triggered from the 60 Hz line and controlled from preset counters. The reactor can be in the circuit for any preset

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number of cycles of the ac line and for any preset repetition rate. The amount of flicker is varied by changing the tap on the autotransformer. An oscilloscope is used to determine the voltage drop, ΔE, on reactor L_1 during a pulse. The ratio of ΔE to the line voltage without the pulsed load, E, is a measure of the amount of flicker.

Test Conditions

Incandescent Light Bulbs. At repetition rates of 0.133 s (8 cycles) and 2 s (120 cycles) 1, 2, 3, or 4 cycles were attenuated as illustrated by Fig. 5. Two types of tests were made with a number of observers. The first aimed to establish the threshold of perception of flicker disturbance as a function of bulb power rating. The second was to find the distribution of opinions on the disturbance caused by discrete flicker levels while reading.

For the first type of test, light bulbs were placed behind the flaps of cardboard boxes which had been lined with white paper. The lower flap of the box shielded the eyes of the observer from directly viewing the bulbs. The bulbs tested were 1.1, 6, and 11 W of simple-coil construction and 60 and 200 W of coiled-coil construction. A string of the low-wattage bulbs was put in its respective box, but only one bulb was used with the 60 and 200 W boxes. While an observer in a relaxed position viewed a box from a chair, the percentage of flicker was increased until it became noticeable. A total of 15 observers viewed one box at a time.

In the second test, the top of a table 60 in. x 34 in. x 31 in. high was illuminated to 20 fc by twelve 60 W bulbs having coiled-coil filaments. The bulbs were arranged as shown in Fig. 10. While four observers read, the flicker was increased in steps and the readers recorded their opinions of the disturbance. This procedure was continued until the last reader found the flicker "bad."

In the above tests, the flicker was increased in steps of 0.3% in irregular intervals. After running with a flicker for a while, the operator would call for an opinion rating, which will be explained later, before going to the next flicker level. A total of 20 persons in groups of four were tested.

TV Pictures. Visible impairments in TV pictures were assessed by two methods. In the first one, groups of three observers were seated 40 in. from the front of a 13-in. black-and-white TV set. A landscape consisting of a village situated on a lake with snow covered mountains as the background was permanently displayed on the screen. The pastel green room was illuminated to 5 fc by fluorescent light. As the flicker magnitude and rate applied to the TV ac supply changed, the observers recorded an opinion rating on the picture quality. A total of 21 observers in seven groups participated in this test.

The second test sought to establish the threshold magnitude at which an impairment would just become visible. The two observers chosen for the test had good color vision and had the median opinion ratings for the reading and TV viewing tests. The test was made by viewing TV sets in the laboratories of two TV manufacturers in the Chicago area. With an ambient of about 5 fc, TV test patterns and panel shows were viewed while line flicker was applied to the TV ac supply. Both black-and-white and color sets ranging from 13 to 25 in. were viewed. The distance between TV screen and viewer was approximately six times the picture height.

Discussion of Results

Thresholds of Perception

Incandescent Light Bulbs. When the voltage supplying a bulb is changed suddenly, the resulting change in brightness is delayed by the time constant of the bulb. In Fig. 6 the percentage of voltage change, ΔE, required to produce a detectable change in brightness is shown when 1, 2, 3, or 4 cycles of the line voltage, E, are attenuated at 0.133 s repetition rates. Figure 7 shows the results for a 2 s repetition rate. The time constants of bulbs below 10 W are so short that attenuating 1 cycle is nearly as easily detected as attenuating 4 cycles.

TV Test Patterns and Panel Shows. The results are shown in Fig. 8. With the exception of the 21 in. color set of Mfgr. B, there is little difference between the black-and-white sets and the color sets in the percentage of flicker required to produce a detectable change in the test patterns.

The relatively large spread of the curves when viewing panel shows is due to different amounts of motion in the shows. Even with very little action, e.g., an announcer introduces a contestant in the "Dating Game," the flicker usually had to be twice that of the test pattern before it was detected. With much activity, such as a chase in a western, the flicker had to be increased three to five times before it was noticed.

Distribution of Opinions

The observers of the tests described were secretaries, technicians, and staff members of the ZGS divisions. The ratio of male to female participants was 2 to 1; the observers were between 18 and 45 years of age. A single intentional impairment was presented at a time, the variable being the magnitude of line flicker applied to degrade otherwise perfect conditions while reading or viewing a TV picture. It also has to be borne in mind that these TV tests were made in the absence of sound and other influences, such as program interest, which normally divert a viewer's attention from flicker.

Since annoyance is a subjective phenomenon, wide variation is to be expected in the opinions expressed by different observers. A statistical method[2] was therefore employed to analyze the results. The quality scale

A = excellent (not perceptible)
B = good
C = fair
D = poor
E = bad (unusable)

was used to obtain the "opinion distribution" of the observers for a given disturbance. If p_A is the proportion of grade A opinions, etc., then

$$p_A + p_B + p_C + p_D + p_E = 1 \quad . \tag{2}$$

For each condition tested the average opinion, p, was obtained from the five grades of opinions expressed by the observers. It was found that the opinion grades A, B, C, D, and E follow the binomial distribution

$$(p+q)^4 = p^4 + 4p^3q + 6p^2q^2 + 4pq^3 + q^4 \tag{3}$$

where $p + q = 1$.

For any average opinion rating, p, between 0 and 1, the opinion distribution will be as shown in Fig. 9 where the vertical lengths are equal to the five individual terms of the expansion.

Reading Tests. The average opinion, p, as a function of percentage flicker, ΔE, is shown in Fig. 10 for 1, 2, or 4 cycles of the line voltage attenuated at 0.133 s repetition rates. For example, a 2% flicker once every 0.133 s causes a flicker disturbance with an average opinion value, p, of 0.35. From Fig. 9 we find for p = 0.35 the following opinion distribution among observers.

Opinion	A	B	C	D	E
%	1.5	11.1	31	38.4	18

Figure 11 shows the results for a 2 s repetition rate. A 2% flicker once every 2 s corresponds to p = 0.66, and from Fig. 9 we find an opinion distribution that is the reverse of the results of the previous example.

Opinion	A	B	C	D	E
%	18	38.5	31	11	1.5

TV Picture Tests. Figure 12 shows p as a function of percentage flicker for 1, 2, 5, and 10 cycles of the line voltage attenuated at 2 s repetition rates. The effects of modulating the ac supply voltage with square waves ranging from 0.1 to 15 Hz are shown in Fig. 13. As with other sources of light, the most sensitive flicker frequency to the human eye is around 8 Hz. However, the eye is much more sensitive to flicker when viewing a TV picture than when reading by incandescent light. This is illustrated by comparing Fig. 10 with Fig. 13 for 8 cycle flicker and Fig. 11 with Fig. 12 for flicker at 2 s repetition rates.

Conclusions

Incandescent lighting, TV test patterns, and relatively inactive TV programs, all impaired by line flicker at discrete repetition rates, were used to measure the thresholds of perception of observers. It was found that low-wattage bulbs (< 10 W) are about as sensitive to flicker as a TV set displaying a test pattern.

The reactions of observers to the flicker while reading by incandescent illumination or while viewing a standardized still TV picture were studied. It was found that the opinion distribution followed a simple binomial which could be expressed as a function of the average opinion, p. The human eye was found to be much more sensitive to flicker when viewing a TV landscape than when reading by incandescent light bulbs. However, as the activity in the TV picture increases, the sensitivity to line flicker decreases.

From the graphs presented, one can calculate for any source reactance the magnitude of pulsed, single-phase currents that will cause identical effects. For the 138 kV line which feeds the ZGS and two other large industrial loads it is assumed that a line flicker causing an average opinion rating of p = 0.7 can be tolerated. This corresponds to a ΔE of 1.9% for a 1 cycle flicker at a 2 s repetition rate and will permit pulsing a magnet load of $\int B dl \approx 400$ kG-feet.

The quantitative data presented are based on the reactions of observers placed under stringent viewing conditions. These reactions will most likely differ systematically from those stimulated by the same causes in everyday life. Customer reaction will also vary among utilities and with the type of territory served.

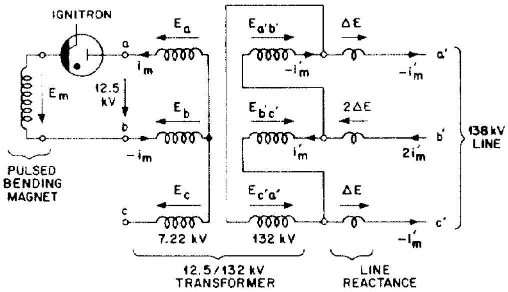

Fig. 1 - Bending magnet pulsed from 12.5 kV substation

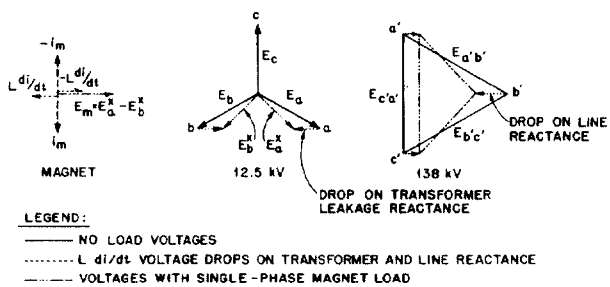

Fig. 3 - Distortion of line voltages due to single-phase magnet load

References

1. J. F. Watson, "How to Solve Problems of Power Supply to Critical Loads," Power Engineering (Nov. 1966).

2. R. D. Prosser, et al., "Quality Grating of Impaired Television Pictures," Proc. IRE, III, 3, 491 (1964).

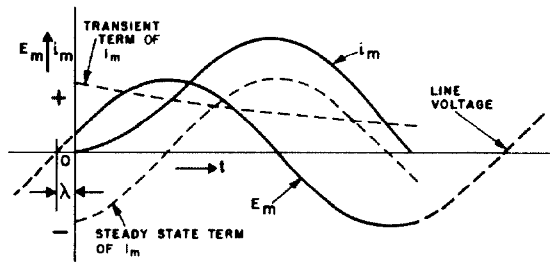

Fig. 2 - Magnet current and voltage

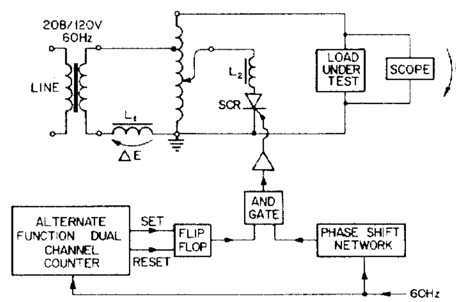

Fig. 4 - Line flicker test circuit

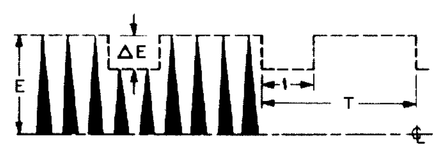

Fig. 5 - Type of line flicker investigated

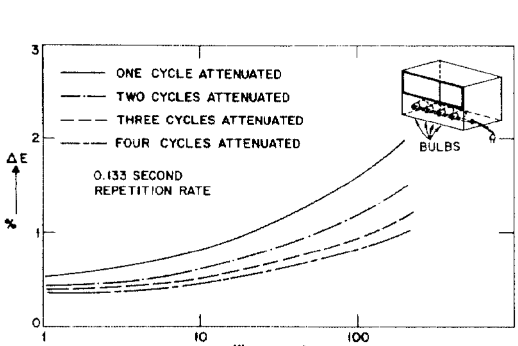

Fig. 6

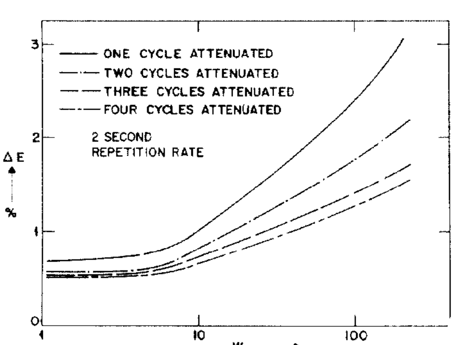

Fig. 7

Threshold of perception of flicker, ΔE, versus power rating of incandescent lamps

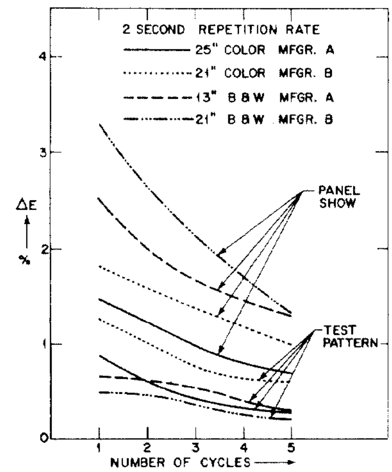

Fig. 8 - Threshold of perception of TV picture impairment, ΔE, versus number of cycles attenuated

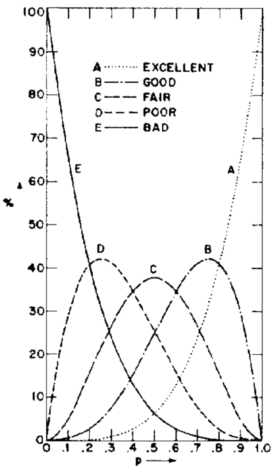

Fig. 9 - Distribution of opinions, %, versus average opinion, p

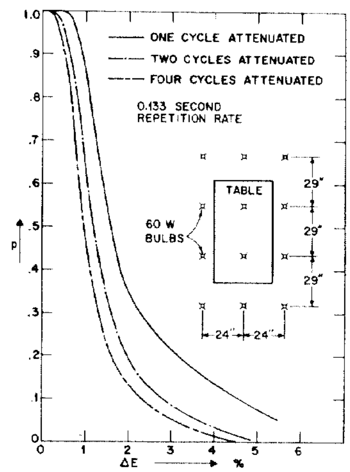

Fig. 10 - Average opinion, p, versus flicker, ΔE, when reading by incandescent light

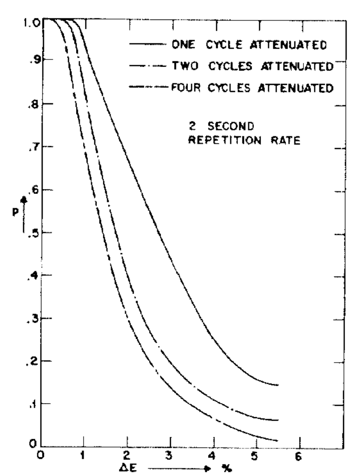

Fig. 11 - Average opinion, p, versus flicker, ΔE, when reading by incandescent light

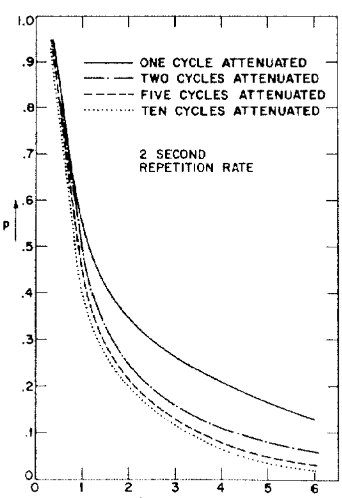

Fig. 12

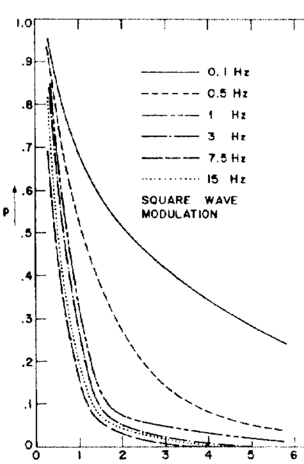

Fig. 13

Average opinion, p, versus flicker, ΔE, when viewing a landscape on a 13 in. black-and-white TV screen