Surge Voltages in Residential Power Circuits

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IEEE Conference paper 31 CP 67-430[1]

Significance:
Part 3 – Recorded occurrences

One of the first papers reporting surge recording in low-voltage ac power circuits.
Both waveform information and frequency of occurrence marked the beginning of the IEEE effort toward characterizing surge voltages in low-voltage ac power circuits, a departure from the traditional unidirectional and separate 1.2/50 and 8/20 waveforms in use for high-voltage equipment testing.

In the mid-sixties, when these recordings took place, there were very few, if any, surge-protective devices (SPDs) installed in residential power circuits. After the emergence of ubiquitous consumer-type SPDs, the results of subsequent monitoring campaigns were drastically changed (See "Galore" in Part 2) but the information is still valid for the frequency of occurrences to the extent that the origins of surges have not changed, only the observed levels are now considerably reduced by the proliferation of SPDs.

[1] *1967 IEEE Conference papers were available at the meeting for $0.75 and later for $1.00. However, they became no longer available some time thereafter.*

Conference Paper

SURGE VOLTAGES IN RESIDENTIAL POWER CIRCUITS

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A paper recommended by the IEEE Protective Devices Committee of the IEEE Power Group for presentation at the IEEE Summer Power Meeting, Portland, Ore., July 9-14, 1967. Manuscript submitted April 3, 1967; made available for printing May 3, 1967.

Price: $1.00
(75¢ at meeting)

(15¢ per copy additional if first class mailing desired)

(25¢ per copy additional if air mail is desired)

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Paper No.
31 CP 67-430

SURGE VOLTAGES IN RESIDENTIAL POWER CIRCUITS

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Abstract

Special instrumentation was developed for monitoring the magnitude and frequency of occurrence of surge voltages in residential circuits.

Over a period of two years, more than 400 locations in 20 cities were surveyed. Monitoring was accomplished by automatic recording cathode ray oscilloscopes and simple surge counters.

Two significant sources of surge voltages were identified: load switching within the house, and external surges, most likely associated with lightning, coming through the service drop.

Internally generated surges as high as 2500 volts were recorded during this test program, and six of the 250 households (i.e., 2.4 percent) in the sample experienced surges of this type in excess of 1200 volts once or more per day. A statistical evaluation indicated that a 90 percent confidence interval for the true proportion of homes with such surge voltages is between 1.0 and 4.7 percent.

Surges due to lightning reaching 5600 volts have been recorded on a 120-volt overhead distribution line. Independent evidence shows the occurrence of a number of surges in excess of 2000 volts.

In this study, a total of 8 surges in excess of 1200 volts were caused by lightning and recorded on 39 counters at room outlets in 14 localities over the summer months.

Introduction

The successful operation of semiconductors and new insulation systems in appliances and consumer electronic devices may be adversely affected by transient overvoltages occurring on the 120-volt power supply. Detection and measurement of these transient surges permits a designer to provide suitable built-in tolerance, or at least to recognize that there is a need for appropriate suppression or protection.

Special instrumentation has been developed for detection and measurement of surge voltages. In the first phase of testing automatic recording cathode ray oscilloscopes provided complete information on wave shape, and on magnitude and frequency of occurrence at a small number of arbitrarily chosen locations. These data, though statistically restricted, were adequate to demonstrate the existence of the problem, define some sources, and indicate typical wave shapes. It also became clear that there was a need for a larger sample that would be more statistically valid.

In the second phase of testing, one hundred surge counters, simple in design and easy to install, were developed especially for this program. These counters were installed in several hundred homes in various cities located in the East and middle West of the United States.

The purpose of this paper is to discuss recordings obtained during the two phases of this program and the statistical aspects of the results. It is hoped that publication of this paper will encourage other investigators to publish their findings. This would provide a broader statistical base for verification of the frequency and magnitude of surge voltages.

Instrumentation

Recording surge voltages in the field poses special problems. For example, the instruments cannot be continually attended and the signals to be recorded are unpredictable in magnitude, polarity, and frequency of occurrence.

In cooperation with Tektronix, Incorporated, a type 515 cathode ray oscilloscope was modified to record transients on film, with automatic advance of the film after a recording.

The modifications involved a change in the trigger and sweep circuits, as well as removal of all knobs (an important detail for an instrument to be left in all types of locations).

Most oscilloscope trigger circuits are polarized. This often causes a loss of recording when the polarity of the initial signal is not known. For surge recording, the trigger circuit was modified by feeding to the time base trigger through two OR logic diodes the push-pull signal that is applied to the input of the oscilloscope delay line. With this modification, the sweep is started for either polarity, while the signal is delayed before reaching the deflection plate of the CRT. In addition, the conventional blanking circuit holds the beam in low intensity before the sweep starts.

A second modification changed the sweep from a constant speed to a logarithmic speed, fast at the start and slow toward the end. This allows the recording of an impulse front with good resolution, while providing sufficient duration of the sweep to record a long tail.

Finally, a relay was added with its coil energized whenever the beam sweep is triggered. Through a set of contacts on this relay, the film advance sequence in the camera is activated.

The camera, attached to the scope bezel, is a Beattie-Coleman system, accommodating 100 feet of 35 mm film, with no shutter, and recording on a 24 x 36 mm frame the trace displayed on the CRT. Following the sweep, the contact mentioned above closes the motor circuit, advancing the film to the next frame in a few seconds. This film transport duration is matched in the oscilloscope trigger circuit by a hold-off so that no sweep will occur during film advance.

In order to prevent the film from being fogged by extended exposure to the faint glow on the phosphor (caused by imperfect blanking of the beam, cathode glow or light leaks) a built-in timer in the oscilloscope advances the film by one frame every hour. This provides an approximate method for timing the occurrence of surges. Since the surge-voltage tests were conducted, an automatic time recording feature has been added to give a more precise recording of time at each event.

Figure 1 is a photograph of this oscilloscope camera system. The relatively high cost of this system, its conspicuous presence (e.g., size, camera noise, etc.) in a home, and the amount of film to be scrutinized frame by frame limit the number of locations at which recordings can be made. However, for conclusions to rest on a sound statistical basis, it is necessary to investigate a large number of locations. To be acceptable to cooperative home owners, a transient detector should therefore lend itself to inconspicuous installation and simple data handling. Thus, a device which can merely be plugged into a wall receptacle, and that has a digital counter indicating the number of surges occurring above a specified threshold is satisfactory for widespread recording.

The circuit shown in Figure 2 was developed for the purpose, and packaged as shown in Figure 3. This device is connected to a wall receptacle by a conventional appliance cord, not a special probe. This connection is simple, establishes a typical final path for a surge impinging upon any appliance connected to this particular wall receptacle, and provides power for the high impedance rectifier circuit and a signal input to the trigger-sensor circuit.

A crudely compensated divider (R1C1/R2C2) attenuates the incoming surge before application to the Silicon Symmetrical Switch (SSS). This device has the characteristic of turning on abruptly whenever the voltage across it reaches a threshold, such as 250 volts. This threshold remains constant for durations as short as 0.1 μs. When the SSS turns on, the attenuated surge is applied to the gate of the very sensitive, fast switching Silicon Controlled Switch (SCS). If the polarity of this surge is positive, the SCS turns on, allowing the capacitor C to discharge through the coil of the solenoid-actuated counter S. A high impedance (50,000 ohm) divider and half-wave rectifier provide a trickle charge 15-volt supply for the capacitor C. The resistance of this divider represents a negligible load for the house wiring system, yet is sufficiently low to allow some leakage in the electrolytic capacitor C. The long charging time (several seconds) of the capacitor is not objectionable, since the transients to be detected do not have a high repetition rate.

Calibration of the circuit is obtained by adjusting the value of the divider (R1C1/R2C2). In these tests, the threshold level was set at 1200 volts for one group of counters and at 2000 volts for another group. A bench circuit was set up, whereby a surge with adjustable level and duration could be superimposed on a 60 Hz, 120-volt power supply. Some consideration was given to the need to segregate, or filter out, the surge from the 60 Hz power voltage; in this case, however, with the minimum level at 1200 volts, the base 170-volt crest represented a small contribution and was included in the signal detected by the circuit. Surges with approximately flat top and durations from several microseconds to 0.2 microsecond were applied to determine the variation of the threshold voltage as a function of surge duration. A typical response curve is shown in Figure 4. The response of this crest-indicating counter can be considered satisfactory, since the oscilloscope recordings in homes, as will be discussed later, have indicated that the shortest half-period of oscillatory surges is in the order of 2 microseconds.

Recording Procedure

In the first phase, oscilloscopes were installed at the basement service entrance of homes in the Schenectady, New York area. These locations do not represent a statistician's ideal sampling, but, during the initial phase of the program, the nature of transients rather than statistical accuracy was the major subject of interest. Later in the program, the range of locations was broadened to include homes in other urban and rural areas, particularly in Florida and South Carolina.

In the second phase, surge counters were installed at unspecified outlets in the homes of engineers in 20 cities in the northeast and midwest. Two distinct recording periods were scheduled: winter, because there is usually a minimum of lightning activity at that time of year, and summer, which ordinarily includes a maximum of lightning activity.

Since the oscilloscope input circuit operates at a level of a few volts, it is somewhat sensitive to direct radiation of electromagnetic noise in the preamplifier, even if there is no signal from the probe. In order to discriminate against this type of spurious indication, the recording procedure included a period during which the oscilloscope probe was shorted with the ground terminal remaining connected, so that spurious signals due

to ground loops would be detected. In this manner, any noise entering the system could be recorded and later recognized for what it was in the analysis of the recordings made with the short circuit removed from the probe.

The surge counters record only one polarity; in order to minimize record keeping by the homeowner, the connection of the cord was not polarized. In the event of an oscillatory surge (which is always quickly damped in these systems) two cases of counting can occur. For instance, the high side of the divider can be connected to the "hot" terminal of the receptacle (Figure 5). If the first half-cycle is positive and exceeds 1200 volts, a count is registered. If the first half-cycle is negative, and the second, positive half is highly damped, no count is registered. If the first half-cycle is well above 1200 volts causing the second half, in spite of some damping, to exceed 1200 volts, a count is registered. For the reverse connection, the same would occur for reverse polarity. Thus, the actual number of surge occurrences of both polarities in excess of 1200 volts is between 1 and 2 times the number indicated by the counter. The objective of the recording in this test series was only to determine whether or not surges occurred rather than their exact number. Consequently, the value of the multiplying factor is not very significant.

Results Of The Recordings - Oscilloscopes

The first recording analysis revealed that some homes were subject to frequent surge voltages, some experienced only a few isolated surges, and others did not experience any surges in excess of the trigger level (300 to 400 volts). Furthermore, among those installations where surge voltages frequently occurred, the surges at some houses were relatively low (rarely in excess of 800 volts), while other houses had surges in the range of 1200 to 2500 volts.

Rates of surge occurrence ranged from zero (no surge in one to two weeks) to 0.5 per hour, with peak values from 400 volts (trigger threshold) to 5600 volts.

At the conclusion of the recording program, a total of 16 homes and two overhead distribution poles had been monitored for a total of 7000 hours. The peak of the surges was distributed as shown in Figure 6a; the most frequent and severe surges were distributed as shown in Figure 6b.

Further analysis of some recordings was made by deliberate switching of loads in the houses where frequent surges had been observed. In some cases, the operation of a specific device (e.g., oil burner, fluorescent lamp, pump motor, refrigerator, food mixer, etc.) was found to be the cause of the surges. In other cases, no amount of deliberate load switching could reproduce surges such as those recorded during unattended monitoring. The home owner was occasionally able to correlate surge recordings with lightning or power system disturbances.

A pattern emerged from all this information, showing two definite causes of surge voltages in the homes:

1. Load switching in the house occasionally produced transient surges; these affected only that particular house. For any particular house, these transient surges had a wave shape which was consistently repeated with variations in amplitude along the entire film recording. This probably resulted from combination of switch characteristics and the impedance of the house wiring system; the variations in amplitude were probably caused by variations of the switching angle and/or connected loads. Typical wave shapes of the recorded surges are shown in Figures 7a, 7b, and 7c.

   In one case, it was possible to install an oscilloscope in a house adjacent to that where repetitive surges up to 1700 volts were being recorded. The service drops were connected to the same pole, yet no surges occurring simultaneously were recorded in the second house.

2. Surge voltages not associated with load switching within the house were associated with lightning storms. In some cases, the home owner was able to correlate the film advance counts with the storm. Although recorded during lightning storms at two different locations, the surges shown in Figures 8a and 8b present the interesting characteristic of being oscillatory at a frequency in the range of 300 kHz. The surge shown in Figure 8a was recorded at the overhead distribution line (oscilloscope mounted on the pole), while the surge of Figure 8b was recorded at the service entrance in a home. The first exhibits far less damping than the second; this might be explained by the lower damping due to lower resistance of the system at the pole than at the end of a service drop.

Both of these surges, as well as most of the other surges recorded during lightning storms, exhibit this oscillatory characteristic at a frequency which is nearly constant for a particular locality. This constancy suggests that the oscillation of the system followed an excitation caused by the lightning stroke. A number of surges in the range of 800 to 1200 volts were observed during several storms. The maximum surge voltage recorded was 5600 volts; several other surges recorded during the same period were in excess of 4000 volts.[1]

Results of The Recordings - Counters

With the two causes of transients identified by the oscilloscope measurements, the surge counters were applied in two separate programs. First, during the winter months, the counters were installed in a large number of houses for periods of one or two weeks; the objective was to

determine how many houses sustained repetitive surges. Second, during spring, summer, and fall, each counter was left at one or two locations for periods of 9 to 48 weeks; it was known from the first test that these homes were not subject to load switching surges. The objective was to determine the frequency and characteristics of externally generated surges, presumably caused by lightning.

The first period produced the data shown in Table 1, and the results obtained during the second period are shown in Table 2.

Statistical Analysis of The Recordings

Internally Generated Surges

The data in Table 1 show that 6 houses, or 2.4 percent, were subjected to repetitive surges from among a total of 250 homes sampled. The true percentage doubtless differs somewhat from 2.4 percent due to statistical variations. However, one may be 90 percent confident that the true percentage is between 1.0 percent and 4.7 percent.* This band could be narrowed by taking additional samples. However, it should be noted that the precision is proportional to the square root of the sample size. Thus, four times the number sampled, or 1000 homes, would be necessary to cut the size of the statistical error band by approximately one-half. Since the above results refer to statistical variations only, they do not take into account possible biases due to such factors as restrictions in selecting members of the sample (principally engineers in a number of designated locations) or the time of year (winter months).

The probability of internally generated surges undoubtedly varies among economic groupings (i.e., the devices in use in homes probably vary with the economic status of the resident); however, devices found to generate surges (i.e., furnaces, refrigerators, etc.) exist in most homes.

Externally Generated Surges

Results from the second testing period that was concerned with externally generated surges are shown in Table 2. From 39 counters installed in a total of 91 homes in 14 localities, a total of 8 occurrences in 6 separate localities were observed during an equivalent exposure time of 846 weeks. A ninth occurrence was disregarded in this analysis because it occurred in the same home during the same storm. Of the two pairs of occurrences which took place in the same location, one pair occurred during the same storm and the second involved two occurrences at different times.

*This result is obtained by the well-known method of setting confidence intervals for a sample percentage. Further details may be found in statistical texts.[2,3,4]

Analyses could be conducted based on the following alternative assumptions:

1. Voltage surges above 1200 volts occur only during the period of the year that the counters were installed in the homes. Thus, although the counters were in homes for only part of the year, the time involved (i.e., the summer months) was so chosen that no further surges would have been noted even if each counter had been run for 52 consecutive weeks. The average number of surges per year would then be 8/39, or 0.205.

2. Voltage surges occur randomly at a constant rate throughout the year. Thus, a counter which was in use 9 weeks, on the average, would be subject to a third as many surges as a counter in use for a period of 27 weeks. Under this assumption, a total of 8 surges observed in a total time equivalent to 16 years (846 weeks) yields an average of 0.5 surges per year.

Using these two extreme assumptions, a range could be established for the estimated number of surges per year in a larger sample, based on this specific sample. The above calculations refer only to single polarity surges. If all surges are being considered, the given values must be multiplied by a value corresponding to the additional proportion of opposite polarity surges above 1200 volts which do not also result in positive surges above 1200 volts. This multiplying factor is probably about 1.6; it accounts for the damping between the first and second 1/2 cycle of an oscillatory surge.

Lightning-induced surges are likely to affect more than one house when they occur. Local geographical and meteorological conditions are critical influences on these surges; however, these factors could not be considered in this preliminary investigation.

To relate the above data to risk of appliance failure, the given values must be modified by the probability that a surge above 1200 volts would cause failure of operating appliances. Failure effects would vary with different appliances.

Possible Further Analysis

A more refined analysis for a probability measurement of voltage surges per lightning storm is possible if the geographical location of the homes, the occurrence rate of lightning storms during the testing period, and exact dates at which voltage surges occur is considered. The resulting values can then be used in conjunction with information given in Reference 5 to calculate the probability of a voltage surge in any specified geographic area, during a particular part of the year. Such an analysis would remove the need for making one of the two alternative assumptions stated above and lead to a single set of estimates. However, this would require more detailed data than could be collected in this program.

Finally, it is noted that if one has knowledge of the actual voltage surges, rather than merely the information concerning whether or not a surge above 1200 volts occurred, a more sensitive analysis is possible. In this case, for example, probability plotting and other techniques based upon the statistical theory of extreme values[4,6] might well be applicable.

Effects of Surge-Voltages On Connected Electrical Devices

The surges which have been recorded in this program occurred during normal operation of the household, with no knowledge of the connected load situation at the time of occurrence.

The question of energy involved in the surge is related to the impedance of the system, since these recordings provide voltage data only. Surge impedance measurements of house wiring cable indicate a value of 100 to 300 ohms for a typical branch circuit, so that the surge impedance at the service entrance could be in the order of 5 to 10 ohms. However, this low value exists only for the travel time (i.e., a fraction of a microsecond). Connected loads will have a lower impedance than that of the branch circuit. This value will be dependent upon frequency whenever inductive components are present. These loads will absorb part of the energy of the surges and thus lower their peak.

Devices such as motors and transformers have solid insulation and such a long history of successful application that their performance is not in question. Perhaps unusual failures can be explained by extreme values of surges as indicated by the data.

Defective wiring practices (e.g., pinched insulation, reduced air clearances in wall boxes, etc.) will cause air flashover with or without 60 Hz power follow. In fact, one house was brought to our attention because of complaints of sparking in a light fixture. With the switch in the ground wire and the frame attached to a grounded pipe, flashover at 1700 volts was observed in correlation with the start of an oil burner in the house. This defective light fixture was acting as a voltage limiting gap for the house.

Appliances containing semiconductors and directly exposed to the line transients may be more vulnerable. Actually, the 1200-volt threshold level was selected as the result of this consideration. It is interesting to note that, although a number of surges above 2000 volts were recorded by the oscilloscopes, the few surge counters calibrated for 2000 rather than 1200 volts did not produce any recording above 2000 volts.

An independent study of clock motor failures produced information on failure rates versus withstand levels. This study was very pertinent to the surge counter program, since thousands of clocks are connected at all times to the power system. Over a period of three years, failure rates were correlated with insulation level of the coils. A very significant 100 to 1 drop in failure rate resulted from an increase in withstand voltage from approximately 2000 to approximately 6000 volts. This shows that, even though no surges over 2000 volts were recorded by the 2000-volt counters, surges in excess of 2000 volts do indeed occur.

Conclusions

1. Residential power circuits are subjected to surge voltages due to two distinct causes: load switching within the house, and externally generated surges that are most likely associated with lightning.

2. Internally generated surges caused by load switching are likely to be repetitive. They can generally be associated with a specific device, probably operating erratically or exciting some natural frequency of the wiring system. They are not related to lightning or disturbances from the utility. Peaks as high as 2500 volts have been observed. The best single statistical estimate is that 2.4 percent of households of the type sampled experience these internally generated repetitive surges in excess of 1200 volts. However, because of the statistical variability in the sample, this value may be as low as 1 percent or as high as 4.7 percent. Surges may be repeated several times a day.

3. The frequency of surges caused by lightning is not affected by household electrical devices, but rather by local geographical and meteorological conditions. The limited data in this program reveal several lightning-caused surge occurrences above 3000 volts with one reaching 5600 volts.

4. Independent evidence shows that a significant number of surges above 2000 volts do occur periodically in residential power lines.

Acknowledgments

The contribution of the hundreds of individuals involved in the data collection and the contribution of J.E. Lenz for the data on overhead distribution lines are gratefully acknowledged.

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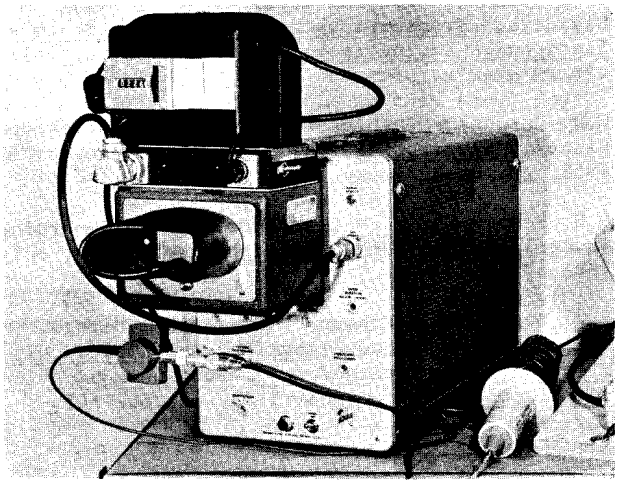

Figure 1. Oscilloscope and Camera

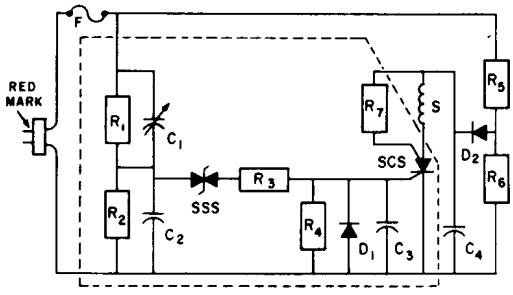

Figure 2. Surge Counter Circuit

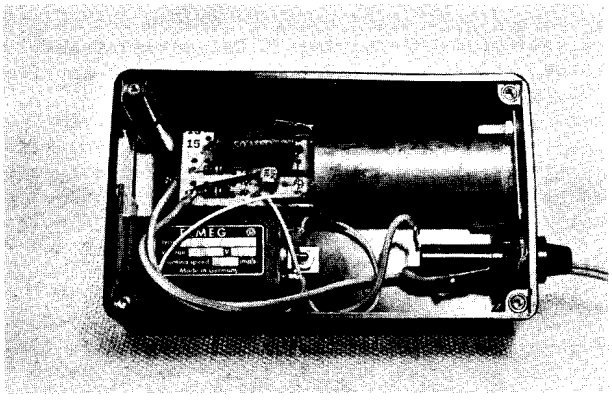

Figure 3a. Surge Counter--Cover Removed

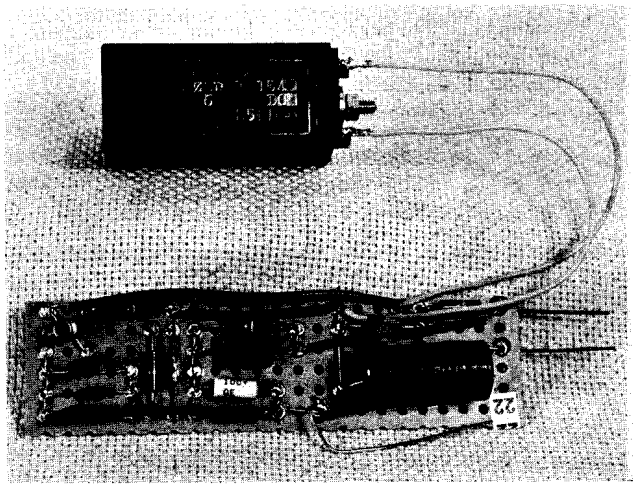

Figure 3b. Surge Counter Elements--Removed from Shield

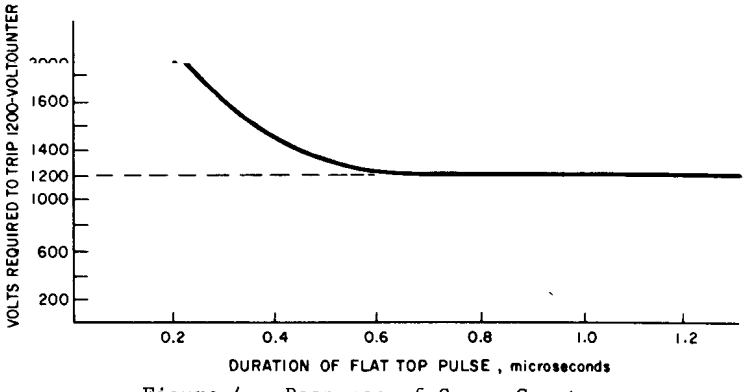

Figure 4. Response of Surge Counter

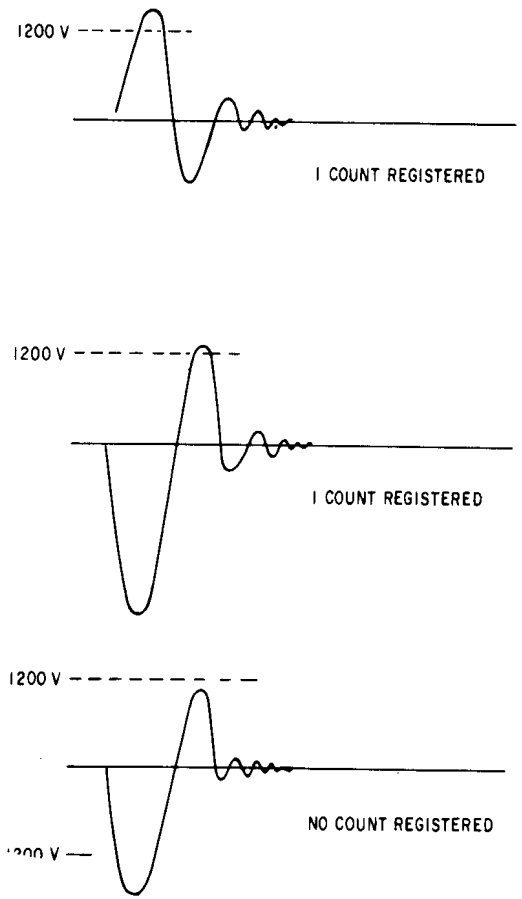

Figure 5. Recording of Surge with Single Polarity Counter

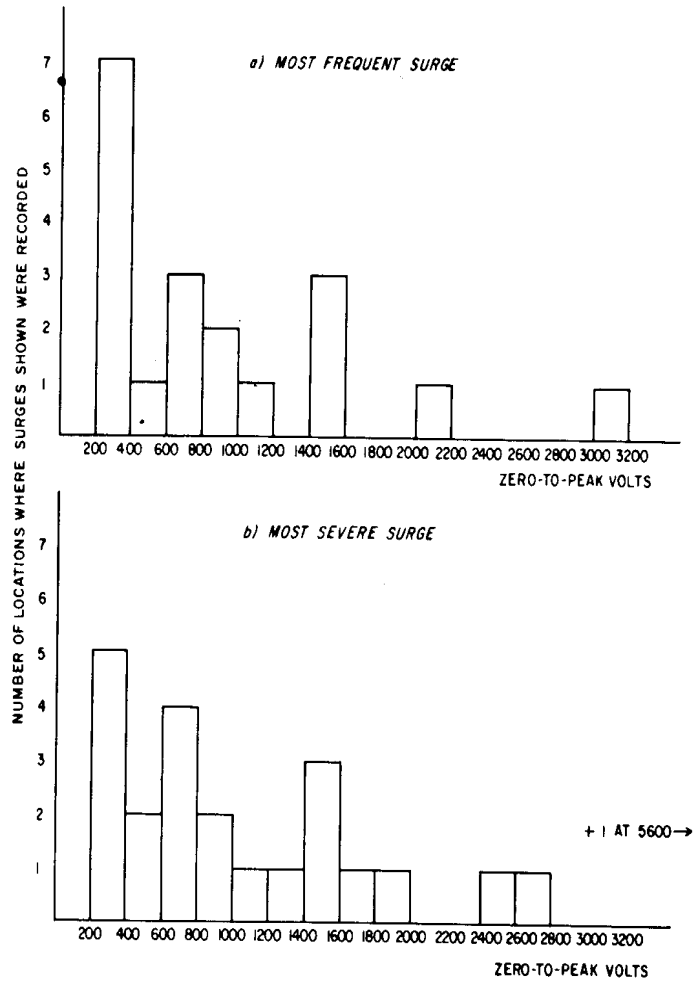

Figure 6a. Distribution of Surges--Most Frequent Surge

Figure 6b. Distribution of Surges--Most Severe Surge

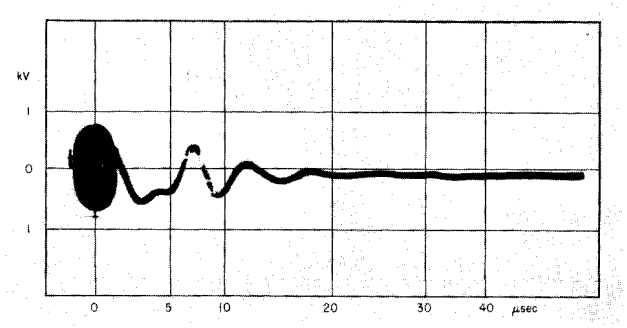

Figure 7a. Internal Switching Transient Recorded at a Farmhouse (15 such transient surges in 1500 hours)

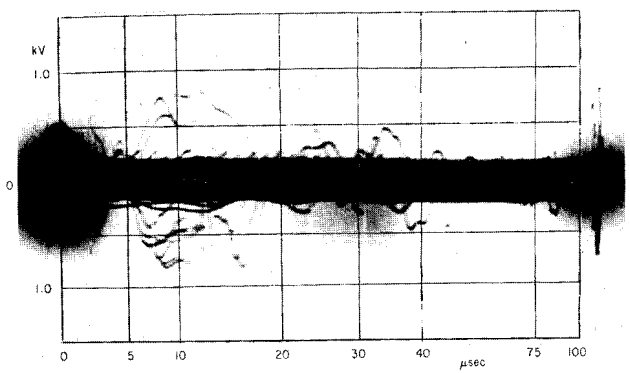

Figure 7b. Composite Record Showing Surges for a 24-hour Period at a Suburban Home. (Oscilloscope is triggered for each surge, plus once every hour, resulting in ± 165-volt band of steady state 60 Hz voltage. Recordings above 1800 volts are blanked out by the oscilloscope.)

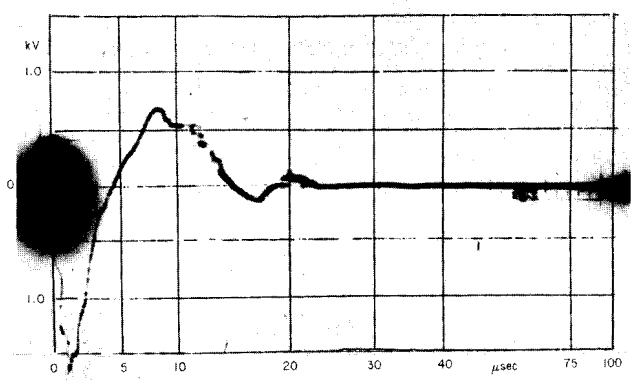

Figure 7c. Single Surge with 1700-volt Peak, Recorded at the Same Location as Figure 7b. (In a 5-day period surges of this wave shape were recorded as follows: 13 above 1000 volts, 18 above 1500 volts, 21 above 2000 volts, and 1 above 2500 volts. Source was determined to be interruption of a high-voltage transformer for an oil furnace.)

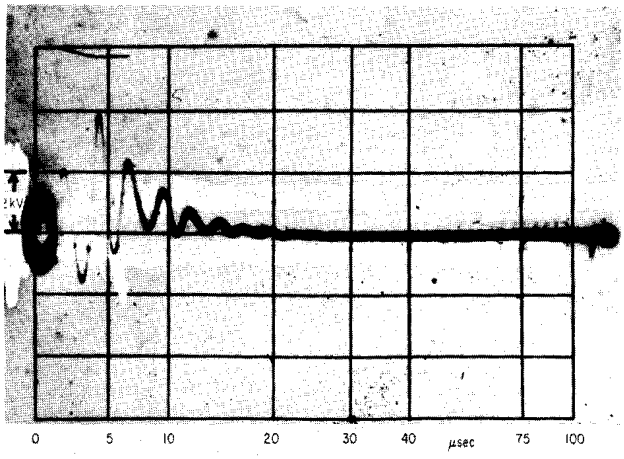

Figure 8a. Transient Surges Recorded on Overhead Distribution Systems in Charleston, South Carolina (3800-volt crest, 300 kHz oscillation.)

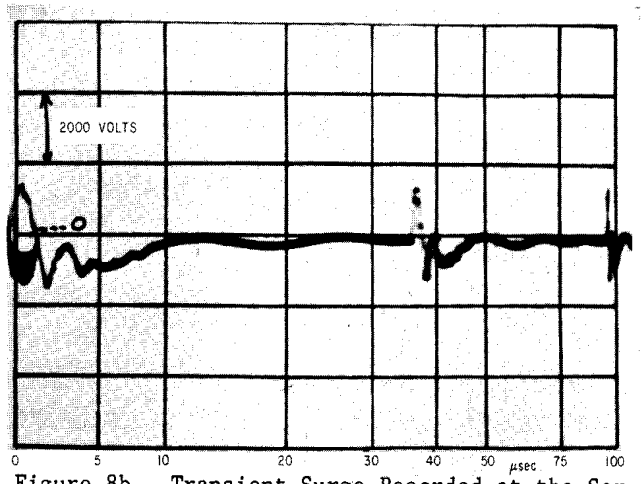

Figure 8b. Transient Surge Recorded at the Service Entrance of a Home in Florida