

HIGH-POWER SURGES IN ELECTRIC DISTRIBUTION SYSTEMS OF GREAT MAGNITUDE.¹

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In the following, I intend to give a review, investigation, and discussion of a high-power surge, which occurred in the high-potential distribution system of the Manhattan Railway, in New York, during the early days of its electric operation. The very complete data on the phenomena occurring during the surge and the effects caused by it have been furnished by Mr. H. G. Stott, at that time superintendent of motive power of the Manhattan system. The surge resulted in a complete shut-down of the power station at 5.50 P. M., July 23, 1903, and again during the following night at 12.45 A. M.

At 5.50 P. M., July 23, the load on the generating station was 37,000 kilowatts and was being carried by six 5,000-kilowatt, 11,000-volt, three-phase, twenty-five-cycle generators, Nos. 1, 2, 4, 5, 6, and 7. This power was being transmitted to a substation No. 1, located in the generating station, and also to seven other substations by three-conductor, lead-covered underground cables.

The substation high-tension bus-bars were divided into as many sections as there were synchronous converters installed and at the time of the trouble they were being operated with these section-switches open.

All feeders to substations, except 4-C and 7-C, were protected with static dischargers at the power-station end of cable, but not at the substation end. The dischargers consisted of nine air-gaps in series with three carbon resistances, each of 0.003 megohm resistance. Feeders to substations are designated by a number and a letter; the number denoting the number of substation and the letter the number of the feeder. For example, feeder 8-F is feeder F of substation No. 8.

At about 5.45 P. M., substation No. 7 notified the power station that there was quite a lot of static discharge on cables in that station, but that it could not be located on any particular cable. Immediately after, substation No. 8 made a similar report and then the power station operator went to the cable gallery to examine static dischargers and try to locate the trouble. He had examined the dischargers on two cables when a loud explosion was heard; whereupon he ran up to the switchboard gallery, and as soon

as he arrived there No. 4 generator short-circuited. Two or three seconds before the generator short-circuited, a synchronous converter in the power station arced over, and its positive direct-current circuit-breaker opened. This circuit-breaker was arranged to operate on reverse current only. The explosion heard before the generator short-circuited came from a manhole just outside the power station, and was caused by a cable short-circuiting. When the generator short-circuited, the time-limit relays on generators Nos. 1, 2, 4, and 5 opened their respective oil-switches, and the oil-switches of generators 6 and 7 were opened by the switchboard attendant. As these relays were set to operate after three seconds, it is possible that the switchboard attendant opened switches 6 and 7 before the relays had time to act.

On the feeder system the following occurred: feeder 8-F short-circuited at a joint 243 feet from the power station, the three conductors being blown out for about twelve inches, and one leg of the feeder punctured a porcelain insulating tube and grounded in the power station between the oil-switch and cable bell. Feeder 8-B broke down in a section, and at a point 23,980 feet from power station. The breakdown showed two legs completely open and the other grounded. Feeder 2-E broke down at a joint 4,800 feet from the power station, the break showing one leg open and grounded.

At the power station the time limit overload relays on feeders 4-E, 4-F, 8-B, and 8-F opened their switches; the connections from the main leads to the static dischargers on feeder 4-A, 4-B, and 2-F burned off; the walls of the static discharger compartments of 4-B were cracked and sprung, and two small holes were burned in the end bell on the power station end of 2-F.

At the substations no damage was done, but most of the reverse-current relays and some overload relays operated, showing that the converters in the substation were feeding back into the cable system.

Careful investigation shows that the following damage was caused by the cables and generator short-circuiting: on generator No. 4, twenty-eight armature bars and eleven connectors at the terminals of machine were broken, bent, or badly burned. On generator No. 1, the insulation at the end of a bar in phase "A" and one in phase "C" was punctured, showing that the pressure had jumped across the intervening air-gap of four inches; the pressure also jumped from an end-connector of phase "A" to the frame,

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a distance of six inches, and a number of overhanging ends of armature bars of phase "C" were slightly bent. On generators 2, 5, 6, and 7, some of the armature bars of phase "C" were also slightly bent, showing excessive current.

In addition to the damage mentioned above, some harm was done to the transformers supplying power for lights in the passenger stations.

Step-down transformers—11,000 to 2,300 volts—for the lighting system are located at the substations. The current is transmitted to the passenger stations at 2,300 volts and is there transformed to 110 volts.

When the cables broke down and the generator short-circuited at the power station, the fuses blew on nine of the 2,300/110-volt lighting transformers, and on four of them several coils of the high-pressure winding short-circuited.

The damaged parts of the system were cut out, and the power station and substations again started. On the following night, July 24, at 12.45 A. M., a complete shutdown of the system again resulted from a surge.

The load on station at the time was about 3,500 kilowatts, being carried by generators 1 and 5. A short time previous (about midnight) the ground detectors on the 11,000-volt bus-bar indicated a 10,000-volt ground on one phase. Preparations were at once made to locate the ground by a process of elimination, by cutting out the feeders of each substation in turn. Some delay was caused by waiting for the adjacent substations to cut in enough synchronous converters to carry the load of the station cut out. Just as everything was ready to cut out substation No. 8, a synchronous converter in the power station blew its direct-current positive circuit-breaker. Immediately thereafter the following occurred:

Feeder 4-F short-circuited in a section 16,000 feet from the power station, burning one conductor completely open and grounding another conductor. The current transformer in one phase of feeder 3-D, and the relay on the transformer, burned out.

One main lead from the bell at the power-station end of feeder 3-B burned off for about two inches at a point seven inches from the copper sleeve of the joint. The static discharger lead was connected at this point of main lead. The copper sleeve was found to be loose when the cable was repaired. The static discharger leads from this cable were burned off, the discharger compartment division walls were badly cracked and sprung, and a

hole one inch in diameter and another four inches by two inches was burned in the bell at the power-station end. On feeder 3-A the static discharger leads were burned off, and the discharger compartment walls were slightly cracked. No damage was done elsewhere to the system.

Regarding this occurrence, Mr. H. G. Stott makes the following comments:

"A summary of the happenings of that night in their proper sequence is:

"First: a static discharge over the high-tension insulators and cables was observed in substations Nos. 7 and 8.

"Second: within a few minutes a feeder short-circuited in the manhole nearest to the power station, blowing out about twelve inches of three-conductor cable, and raising the manhole and pavement all around it with a loud report.

"Third: one of the six generators operating in multiple short-circuited near the terminals, conductors on two turns of the winding being driven out until they struck the iron of the frame of the generator; i. e., to say, the armature bars, which are two inches by one-eighth inch, three in each slot, were bent edgewise for over six inches, showing that the force bending them probably amounted to at least 3,000 or 4,000 pounds.

"Fourth: practically simultaneously several of the three-conductor feeders from substations 8, 4, 3, and 2 short-circuited, some of them in the manholes at a greater or less distance from the power station, and some of them on the static dischargers in the power station, and one across an end bell in the power station. No damage took place in the substation.

"Upon examination, one of the generators, which was apparently otherwise uninjured, showed that the current had jumped across between the end connectors near the end of one phase, a distance of four inches, through the air. At another point on another phase of the same machine marks showed that the current had jumped from one of the end bars to the iron through the air, a distance of six inches. Other arcing distances showed conclusively that the potential must have risen to not less than 70,000 volts.

"The above is a brief résumé of what happened.

"My own opinion is that the source of all the trouble was in the feeder in the manhole next to the power station breaking down the insulation to ground; this caused the static to show up at the substation; the large capacity current of the system burned the insulation of the neighboring conductors in the three-conductor cable, and formed a short-circuit which blew out the arc, due to the sudden expansion of air in the manhole from the heat generated by approximately 70,000 kilowatts (each machine being capable of giving out 12,000 kilowatts). The arc was probably reestablished several times, thus setting up an oscillating current, and

giving rise to the potential above mentioned."

The most characteristic feature was the enormous volume, and relatively very low frequency of the oscillating surge occurring in this system. This explains the severity of the destruction and its widespread extent. Any oscillation of very high frequency could be local only and could not extend over any considerable part of such a system, since the high capacity of the cables necessarily would act as a short-circuit to any very high-frequency oscillation.

The trouble was undoubtedly started in the manhole next to the power-house by a spark-discharge between one of the conductors of feeder 8-F and the cable armor, possibly due to the gradual breaking down of a weak spot in a cable joint.

This spark-discharge between conductor and cable armor, or ground, was oscillating in character, local in extent, and of moderate power and pressure, but of rather high frequency. It was the discharge of a condenser of a pressure equal to the pressure between conductor and ground; that is, the Y pressure of the system, or about 6,400 volts, and the capacity and inductance between the cable conductor and ground. The capacity and inductance, however, in this case were distributed.

The length of cable from the substation where the electrostatic displays were observed to the point of discharge in the manhole was 26,780 feet. The estimated capacity between conductor and ground was approximately 0.115 microfarad, and the inductance between conductor and ground 0.106 millihenry per 1,000 feet of cable, or a total of 3.07 microfarads and 2.83 millihenrys respectively.

The spark passing in the manhole from the conductor to the cable armor, that is, to the ground, connects the conductor to the ground by an arc. The potential difference E between conductor and ground, therefore, falls to zero, or practically zero, while a current I flows toward the break, which is the charging current of the system against ground, or about 200 to 300 amperes. With the potential difference E disappearing, the current in the short arc shunted by capacity blows out the arc explosively, and so disconnects the conductor from ground. At the moment when the grounding arc opens, $E = 0$, $I = i_0 = \text{constant}$, in the conductor, at least near the fault. The current i_0 still flowing toward the fault pro-

duces a potential difference in the conductor, so that as a result of this period we get zero current, but a potential difference $E = e_0$ in the conductor, at least at and near the fault. This potential difference e_0 again causes a spark to jump at the fault, and again grounds the conductor. In the moment when the spark jumps $I = 0$, $E = e_0$.

We have the two periods succeeding each other, the starting condition of each being the final condition of the preceding:

a. From the moment where the arc at the fault ruptures until a spark restarts it. During this period the conductor is not connected to ground at the fault.

b. From the moment where the arc starts at the fault until it ruptures itself again, or while the conductor is grounded at the fault.

This results in two oscillations of wave trains, originating at the fault and alternating with each other.

The two wave trains cause a successive series of impulses of high electromotive force but zero current, and of high current, but zero electromotive force to run along the circuit, starting from the fault and traveling toward the substation 8 with such a velocity that the distance, 26,780 feet, is traversed during one-fourth cycle of the fundamental frequency of oscillation, which in this case is found to be $N_1 = 2,670$. The velocity of wave propagation is therefore $4 \times 2,670 \times 26,780 = 285 \times 10^6$ feet per second = 54,000 miles per second, or about thirty per cent of the velocity of light.

The duration of the successive periods of current and of electromotive force depends on the conditions existing at the starting point of the wave; that is, at the fault in the manhole, but not directly on the constants of the rest of the circuit, and as a rule the duration of the period of high electromotive force and the period of high current are not equal. These successive wave-trains constitute a cyclic phenomenon with a frequency of 13,000 cycles.

These waves of current and electromotive force which travel along the circuit from the source of disturbance with high frequency are in their simplest form flat-topped with steep wave front and back. The steepness of wave front and back depends upon the rapidity with which the arc at the fault establishes itself and ruptures, and also upon the distance from the starting point.

Where these waves meet obstructions, as localized inductance, the steepness of

the wave front results in the induction of high electromotive forces of very limited extension, and gives the pyrotechnic displays observed at the switchboards of high-pressure stations when there is a disturbance on the line, which sometimes are called "static." Due to their very limited power, these phenomena are relatively harmless of themselves; their danger rather lies in producing or establishing a path for short-circuits or surges of high power, as happened in the case under discussion.

Localized inductance offers some protection to the system against these waves even if the inductance is very small. For instance, assuming 11,000 volts and 300 amperes as full load condition of the feeder cable and an inductance of 0.05 millihenry inserted, this inductance at the impressed frequency of twenty-five cycles would give a reactance $x_0 = 0.008$ ohm; hence 300 amperes consume 2.4 volts or about one-fiftieth of one per cent.

Assuming the maximum current of the traveling wave as 300 amperes and at the steepest part of the wave to change in strength 250 amperes during $\phi = 1^\circ$; that is, $t = 1/360 \times 2,670 = 1.04 \times 10^{-6}$ seconds. This gives $di/dt = 240 \times 10^{-6}$, and the counter-electromotive force which this wave front would meet in such a reactive coil would be:

$$L di/dt = 12,000 \text{ volts.}$$

I have dwelt somewhat fully on this system of wave-trains and the frequency of propagation along the circuit, since I believe this phenomenon of a third frequency, besides the impressed frequency and the frequency of circuit oscillation, has not before been fully recognized. It seems, therefore, that in an electric circuit containing distributed capacity and inductance, as in an underground cable, a long-distance transmission line, or in the high-pressure winding of a transformer or high pressure generator, three distinct frequencies must be recognized that are essentially independent of one another.

1. The impressed frequency supplied by the generating system, of twenty-five, forty, or sixty cycles as fundamental, and their odd multiples as higher harmonics or wave-shape distortion, which higher harmonics are usually of small or even negligible magnitude.

2. The frequency of oscillation of the system, or natural period of the circuit, depending on the constants of the circuit, mainly the capacity and the inductance, and consisting of a fundamental frequency

$N_1 = \frac{1}{4 \sqrt{L_0 C_0}}$, where L_0 and C_0 are the inductance and capacity respectively

of the total circuit, and all the odd multiples thereof as higher harmonics. The relative magnitude of fundamental and higher harmonics depends on the distribution of pressure and current in the circuit at the moment where the oscillation starts. As a rule the higher harmonics are not negligible, but usually rather predominate.

3. The frequency of circuit disturbance which has no direct relation to impressed frequency or to the natural period, but depends upon the character of the disturbance. It appears as a system of waves traveling along the line, and results in the static displays at the end of the line; that is, at the station switchboards. In its simplest form, as a single wave or impulse traveling along the circuit (frequently visible to the eye as a luminous streak), it probably appears when a moderate lightning flash or side discharge strikes a transmission line, and from there to the ground, giving at a point of impact a sudden rise of pressure against ground, immediately relieved by the discharge to ground.

This phenomenon, so far as I know, has never been investigated from the theoretical point of view. While of itself rather harmless, its danger consists in the self-destructive forces that it may set into play. In the circuit under discussion here the impressed frequency is twenty-five cycles, the natural period 2,670 cycles. The frequency of the static display is 13,000 cycles, but of such steep wave front as to correspond to a far higher frequency, possibly of the magnitude of 200,000 cycles per second.

In the breakdown in the Manhattan system, starting with a spark discharge between conductor and cable armor in a faulty joint in the manhole near the power station, attention was called to the disturbance by the arrival of the wave trains and the resultant static displays on the cables and switchboards of the next substations. No direct harm was done by this "static," but before the fault could be located and cut out, the spark discharge had reached the next conductor of the cable and started a short-circuit between two conductors. With six generators of 5,000-kilowatt rating and a momentary maximum of 12,000 kilowatts each, and the synchronous converters feeding back into the short-circuit as evidenced by the opening of the reverse-current relays in the substations—it probably is a conservative estimate to assume that for a short period a power of 100,000 kilowatts was concentrated in the short-circuiting arc

in the manhole. The energy of 100,000 kilowatts applied during only one-tenth second equals the explosion of about half a pound of dynamite.

The explosion tore off the insulation and protection of the conductor, and a flaring arc started in the manhole, and being oscillating or self-rupturing in character, created a surge of low frequency and enormous power in the whole system, beyond the disruptive strength of any part of the system or any protective device. This short-circuit oscillation was a surge of the whole system throughout, and almost instantaneously caused all the breakdowns in feeders, cables, cable-bells, transformers, generators, etc. The static protectors apparently discharged and somewhat lowered the pressure, but could not be expected to take care of the enormous volume of the surge. Some burned up explosively due to the excessive pressure imposed upon them.

From the data available I estimate the capacity of the system between two conductors as $C = 76$ microfarads. In series with this capacity is the self-inductance of the generating system. Extensive tests which I made some years ago on a long-distance system at high pressures with aid of the oscillograph, proved that the electric oscillations due to changes of circuit conditions, when occurring in a high-pressure line, are not limited to the line but extend back into the generating system even if the generators are separated by transformers from the oscillating line, as was the case in my experiments. That is, the whole system, including generators, oscillates electrically. This has since been corroborated by observing that a breakdown in one feeder causes breakdowns in other feeders issuing from the same generator bus-bars, and therefore that the oscillation passes into and over the main generator bus-bars.

Assuming that the short-circuit current or synchronous impedance current of these generators at full pressure and no-load excitation is about three times full-load current or approximately 800 amperes, gives a synchronous impedance of eight ohms Y . We may probably assume that somewhat less than one-half of this is self-inductive reactance participating in the oscillation, and that the rest is armature reaction.

With the understanding that there is some reactance in the station wiring, current transformers, etc., we may assume the self-inductive reactance per generator as about four ohms, corresponding to an

inductance of 25.5 millihenrys. The self-inductance of the six generators in circuit during the accident then is: 4.25 millihenrys. Allowing 0.25 millihenry for effective resultant inductance of the cable system gives a total inductance of 4.5 millihenrys.

The fundamental frequency of the surge of the whole system would be

$$N_0 = \frac{1}{2\pi\sqrt{LC}} = 270 \text{ cycles, or quite low.}$$

$$\text{With } C = 76 \text{ microfarads, } L = 4.5 \text{ millihenrys, and } e = \frac{11,000}{\sqrt{3}} = 6,340$$

volts per phase, the instantaneous short-circuit current or the volume of the surge would be:

$$i_0 = e/2\pi N L = 9,000 \text{ amperes.}$$

Where N = impressed frequency, and the pressure of oscillation:

$$e_0 = 2\pi N_0 L i_0 = 68,800 \text{ volts per phase, or } 119,000 \text{ volts between lines, where } N_0 = \text{frequency of oscillation.}$$

With such a volume of surge all breakdowns that occurred would also be oscillating and therefore would not relieve the system by discharging the oscillation, but set up secondary oscillations. I observed this same feature in the experimental tests referred to above, where in one instance I had three oscillating circuits simultaneously in existence, and still enormous electrostatic displays.

Thirty-two static protectors of 0.003 megohm, each, hence of a total delta resistance of 282 ohms, and a "Y" resistance of ninety-four ohms, would, at 100,000 volts delta or 58,000 volts Y , carry off about 630 amperes or seven per cent, and therefore lower the pressure of oscillation by seven per cent, that is, to about 110,000 volts between lines, but they would be loaded far beyond their capacity, as evidenced.

As seen, the most prominent features of the surge seem to have been its enormous volume and relatively low frequency, which account for its wide extent and destructiveness.

From another phenomenon we can also estimate the approximate frequency of the surge. The burning out of the fuses of some 2,300-volt transformers without destruction of these transformers is explained by assuming that the high-pressure oscillation penetrated to these transformers and that their primary pressure rose so as to bring the iron of the transformers beyond magnetic saturation and blow the fuses by the excessive

exciting current, due to magnetic saturation. This did not occur in the 11,000-volt transformers, which were operating at lower magnetic density; while the 2,300-volt transformers, built originally for higher frequency, were operating normally at fairly high density on the twenty-five-cycle circuit.

From this we may estimate the frequency of the surge. Twenty-five-cycle transformers are necessarily operated at fairly high magnetic density, so that increasing the normal magnetic density two or threefold results in such high saturation as to blow the fuses by the exciting current. The magnetic cycle of the surge is superimposed upon the normal magnetic cycle of the transformer. It then depends at what point of the normal cycle the abnormal cycle started. If at the maximum point, an abnormal cycle of one-half the amplitude of the normal cycle would double the density and so saturate. If at the negative maximum point, an abnormal cycle would have two times the amplitude of the normal to treble the density. The most probable is that the abnormal cycle or the surge started near the zero point of the normal cycle or near the maximum point of the circuit pressure and then at 1.25 times the amplitude of the normal cycle, the abnormal cycle would increase the density 2.5 times.

Assuming from the striking distance a pressure of 80,000 for the oscillation, or 7.2 times normal pressure, to give an abnormal cycle of 1.25 times the amplitude of the normal cycle would require a frequency of nine times the normal frequency or 225 cycles respectively. The frequency of oscillation therefore would probably be in the neighborhood of 225 cycles.

The shutdown of the generating station ultimately stopped the surge. I should believe it quite possible, however, that besides the breakdowns which have been observed by their destructive effect, some more breakdowns have occurred lasting so short a time before the taking off of the generating system as not to cause any noticeable destruction, and merely weakening and partly breaking down the insulation. The breakdown occurring again toward midnight I attribute to such a partial breakdown, which was completed by some small oscillation as the opening of a converter circuit-breaker.

Two years have passed now, and I believe no further surge of this magnitude has occurred, and a protection of the system has been devised.