Vacuum Switching Experiments
at California Institute of Technology

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Synopsis.—Successful experiments in switching or breaking a circuit in a high vacuum have been made at the California Institute of Technology. This paper is a report on three sets of these experiments which extended over a period of three years. The conclusions drawn from the experiments may be summed up in the statement that vacuum breakers of laboratory type have been successful in breaking circuits and offer a possible solution of the circuit-breaker problem.

The results show that switching in vacuum affords the advantages of no pitting of contacts, quick break, the arc always going out on the first half cycle, small voltage rise across the switch, and small distance of travel necessary for the switch blades.

Making the vacuum switch practical calls for a solution of the problem of making commercial apparatus with vacuum-tight joints, and the elimination of the use of liquid air with the vacuum pump.

EXPERIMENTS on breaking an electrical circuit in a high vacuum have been made during the last three years at the California Institute of Technology in connection with the study of switching high-voltage, high-power circuits. These experiments were undertaken as a result of the well-known limitations of oil circuit breakers. A large number of tests was made on high-vacuum breakers of laboratory type. Some very promising results were obtained in interrupting large currents.

When these experiments were suggested, the question immediately presenting itself was: Will the vacuum maintain itself at the time the arc is formed between the separating metallic parts of an opening switch?

This doubt was quite generally substantiated by the commonly recognized theory of the electric arc,[1] *viz.*, that the maintenance of an arc is dependent upon the giving out of thermions from hot spots on the electrodes between which the arc is formed, with the attendant vaporization of the metal. If this were true, a large current could not be interrupted in a vacuum because the formation of even a small amount of gas would reduce the vacuum and cause it to become a conducting vacuum rather than an insulating vacuum.

The fact of the matter, however, is that if the vacuum is sufficiently high and all adsorbed gases have been removed from the metal electrodes, very large currents can be broken without formation of enough vapor to maintain an arc.

Dr. R. A. Millikan has shown[2] that, with cold electrodes suitably prepared, millions of volts of potential gradient are required to obtain discharges of any kind between metal surfaces. He has also worked out with much care the conditions necessary for denuding metal surfaces of gases and preventing the impairment of the vacuum through the evolution of gases. A. Janitzky[3] also has reported experiments showing that currents will not flow across the space between cold electrodes in a vacuum provided the electrodes have been completely outgassed.

According to the older theory, it would seem that considerable vapor might be formed in the vacuum on breaking a circuit. P. Charpentier[4] has given the following equation:

$$W = 0.07\, E\, I\, t$$

as the equation for the energy to be dissipated in an oil switch at the time of opening. In this equation, E = voltage, I = current, and t = the time in seconds between the initial separation of the switch contacts and the complete extinguishing of the arc. Charpentier's experiments, and also those made by Swiss engineers in 1915 and 1916, indicate that this energy is used in vaporizing oil at the rate of 46.5 cu. cm. per kw-sec. Some of the tests made on oil switches show the vaporization of smaller amounts of oil per kw-sec. and also show power factors of less than 0.07 across the switch at the time of interruption. Applying Charpentier's equation to a single-pole switch opening a 15,000-volt, 100-ampere, 50-cycle circuit, we find that the switch must dissipate 1.05 kw-sec. if it opens on the first half cycle. Assuming as an extreme case, for the vacuum switch, all of this energy available to vaporize copper at the switch blades, we find that it would vaporize approximately one-fifth gram. This amount of copper turned into vapor would reduce an insulating vacuum in a container of considerable size to a vacuum which would be conducting for 15,000 volts applied between electrodes extending into the container.

However, the later theories to which reference has been made indicate that such an amount of vapor will not be formed provided the vacuum is high and the electrodes are free from gas.

Therefore, in making the experiments, the prime requisites were to have the electrodes entirely free of adsorbed gases and to obtain a good vacuum. Dr. Millikan was immediately interested in the proposal of the tests and placed at our disposition the facilities and high-vacuum experience of the Norman Bridge Laboratory; also he cooperated in the development of the switch by making many valuable suggestions and by assigning to the work two graduate students of the physics department, H. E. Mendenhall and Russell Otis.

Three switches were developed and tested. The first

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1. For references, see Bibliography.

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switch is shown in Fig. 1. It consists of a glass envelope with two fixed electrodes as shown, separated by one-half inch. These have crescent-shaped contact surfaces, *a* and *b*, as shown. The contact area of each of the fixed terminals is ⅛ sq. in. The circuit is closed by a flat circular copper disk resting upon them with no contact pressure other than the weight of the disk, to which is attached a light plunger. The switch is opened in operation by a solenoid which, when energized, raises the plunger. In interrupting the circuit, the bridging circuit contact is raised ½ in. by the solenoid. This type of construction gives two breaks in series when the switch is open.

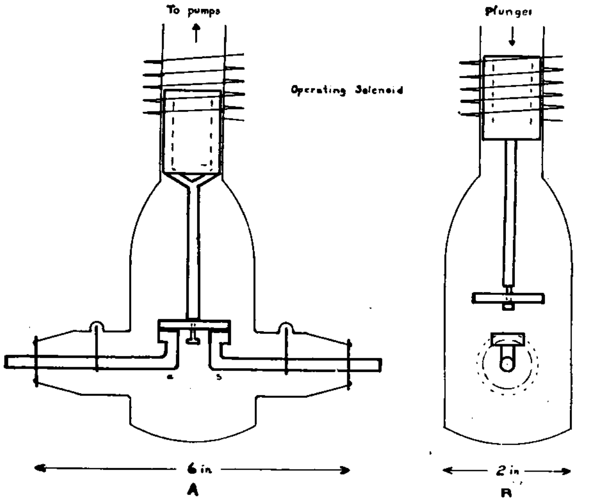

FIG. 1—CROSS-SECTION VIEWS OF SWITCH NO. 1

Vacuum-tight joints between the lead-in conductors and the glass envelope of the switch were easily obtained by means of W. G. Houskeeper's disk seals.[5] This switch was evacuated down to 10^{-6} centimeters of mercury pressure. An initial test was made by using this switch to interrupt currents up to 125 amperes at 110 volts d-c. The results were encouraging, and the switch was connected to an a-c. supply and the test repeated with very satisfactory results, the interruption of current being accomplished with less arcing than occurred when direct current was used.

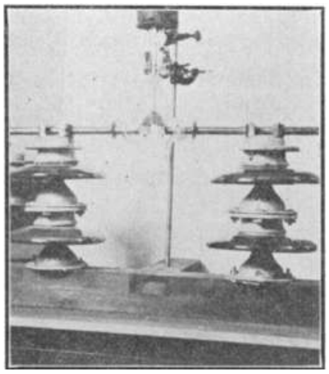

FIG. 2—VACUUM SWITCH NO. 2

The switch was then successively used on a-c. circuits for 220 volts, 2300 volts, and 15,000 volts. The load in every case was a single-phase load connected and disconnected by means of the switch used as a single-pole switch. There was no apparent difference in the operation of the switch at the different voltages with the exception that the switch was not properly designed to guard against arcing over the outside at 15,000 volts. This trouble was eliminated by immersing the switch in oil. When so immersed the switch was operated many times as a single-pole switch to interrupt 100 amperes at 15,000 volts. Every operation was successful.

The terminals of this switch, however, were very small and therefore a second switch having terminals with more contact surface and leads of greater carrying capacity was built. Fig. 2 shows switch No. 2. This switch was constructed in the same manner as switch No. 1, but is larger and has better contacts, the bridge being made of spring-copper laminations. When the switch is closed, the edges of the laminations are held against the fixed contacts by the weight of the bridge and its lifting solenoid, the total weight being two pounds. The contact area of each fixed terminal is ¾ sq. in., the distance between the fixed terminals being one inch. In interrupting circuit the bridge is raised one inch.

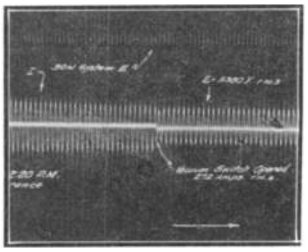

FIG. 3—VACUUM SWITCH INTERRUPTING 272 AMPERES AT 5380 VOLTS

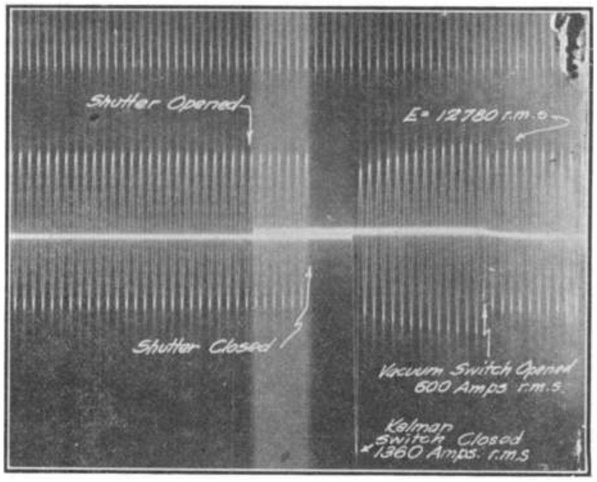

FIG. 4—VACUUM SWITCH INTERRUPTING 600 AMPERES AT 12,780 VOLTS

This switch was given laboratory tests on a 15,000-volt, single-phase circuit providing currents up to 120 amperes at this voltage. The switch was operated as a single-pole switch to open and close this circuit more than 500 times without showing any burning of the switch contacts. It was then sealed off from the vacuum pump and allowed to stand in the laboratory for three months, during which time it was tested occasionally to determine its condition. At the end of the three months the switch was taken to the Torrence substation of the Southern California Edison Company and used to open short circuits made on a synchronous condenser just as the condenser was disconnected from the Edison distribution system. The current was supplied to the switch from the condenser through step-up transformers. The switch repeatedly opened the single-phase short circuit thus provided without any failure to interrupt the circuit or any burning of the switch contacts. Figs. 3 and 4 show oscillograms of switch No. 2 opening 272 amperes at 5380 volts and 600 amperes at 12,780 volts, respectively.

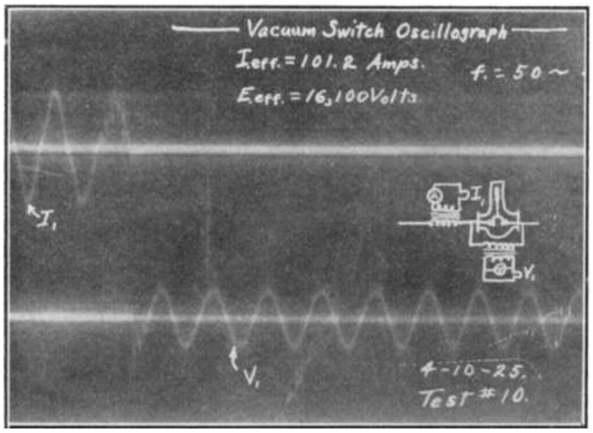

FIG. 5—OSCILLOGRAM SHOWING CURRENT OPENED BY VACUUM SWITCH AND VOLTAGE ACROSS SWITCH AT OPENING

I_{eff} = 101.2 amperes E_{eff} = 16,100 volts f = 50 cycles

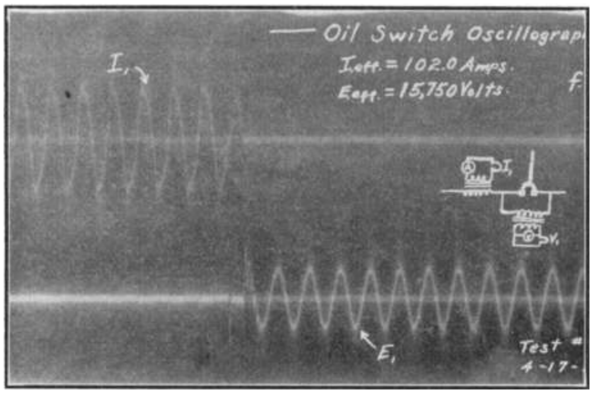

FIG. 6—OSCILLOGRAM SHOWING CURRENT OPENED BY OIL SWITCH AND VOLTAGE ACROSS SWITCH AT OPENING

Note that 12 cycles are between initial contact separation and extinguishing of arc

I_{eff} = 102 amperes E_{eff} = 15,750 volts f = 50 cycles

Figs. 5 and 6 show oscillographic records of vacuum switch No. 2 and a standard make of oil switch opening the same circuit on a load of 100 amperes at 15,000 volts. The tests were made under conditions as nearly identical as possible, and within a few minutes of each other. It will be noted from these graphs that the rise in voltage when the circuit is opened with the oil switch is greater than when the circuit is opened with the vacuum switch. The oil switch in a large number of tests failed to open the circuit on the first half cycle, while the vacuum switch always opened the circuit on the first half cycle. An examination of a number of oscillograph records for oil switches and for the vacuum switching showed that when the circuit was opened the rise in voltage above normal circuit voltage was higher for the oil switch than for the vacuum switch. The klydonograph[6] was used in some of the switching tests to record any high-frequency surges that might occur. In no case did the instrument indicate voltages much above normal.

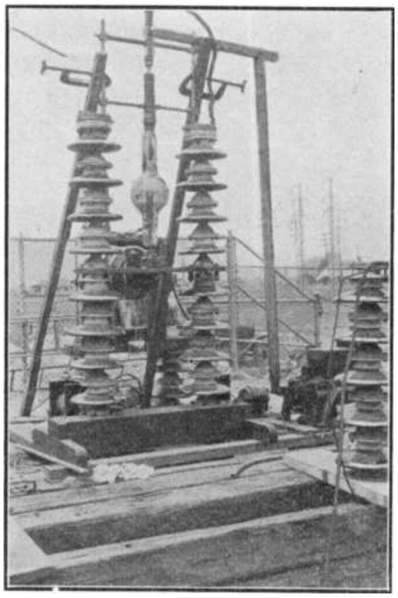

FIG. 7—VACUUM SWITCH NO. 3

Following these tests, switch No. 3 shown in Fig. 7 was constructed. The figure shows the switch in the closed position. Switch No. 3 was constructed primarily to overcome the disadvantage, in switches Nos. 1 and 2, of having all moving parts sealed inside the glass envelope of the switch, a condition requiring the operating solenoid to be kept energized when the switch is open, unless a rather intricate locking mechanism also be installed inside the switch to hold it open.

In switch No. 3, the moving contact is of the bayonet type, the bayonet sliding into a cylindrical socket. The bayonet is a ¾-in. copper rod projecting into the socket when closed so as to give a contact length of one in., the total contact surface obtained in this way being 2.3 sq. in. With this construction, there is only a single break, the contacts opening so as to separate them a distance of one in. when the switch is completely open.

The single break appeared to function as well as the double break used in switches 1 and 2. The switch was operated by a standard switch-operating mechanism borrowed from an oil switch. With such an arrangement, the switch can be left open or closed at will. Vacuum-tight joints for the lead-in conductors of this switch were made by cementing to the glass envelope metal caps attached to the leads and forming a part of the leads.

After some preliminary testing in the laboratory, this switch was taken to the Laguna-Bell substation of the Southern California Edison Company and used as a single-pole switch to open single-phase short circuits on a 30,000-kv-a., synchronous condenser. In performing the tests, the synchronous condenser was brought up to speed on the distribution system of the Edison Company, disconnected from the system and immediately short-circuited through the switch. The condenser used was a 6600-volt, three-phase, Westinghouse condenser which, for the purpose of testing the switch, was connected to the switch through step-up transformers by means of which voltages across the switch as high as 41,500 volts were reached. Fig. 8 shows an oscillogram for this switch interrupting 926 amperes at 41,500 volts.

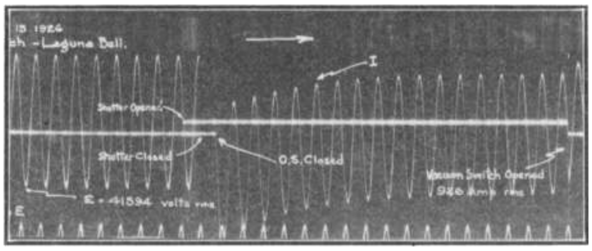

FIG. 8—VACUUM SWITCH OPENING 926 AMPERES AT 41,594 VOLTS

A noticeable feature of the vacuum-switch tests is that every oscillographic record shows that the arc produced at the opening of the switch is extinguished at the end of the first half cycle after the separation of the contacts. Only the very best oil-switch operations give this result.

The absence of any pitting of switch contacts and the fact that the vacuum is not reduced appreciably when the switch is in operation is evidence that very little of the energy dissipated when the switch is opened is used in vaporizing metal from the contacts.

When the contacts separate, there is a visible arc, just as when a switch is opened in air or oil. The magnitude of this arc, however, is much less than that of an arc made by like values of voltage and current in air or oil. This is to be expected because there is nothing in a vacuum switch to burn or to support combustion, as is the case when a switch is opened in oil or air.

The action of the arc in vacuum also indicates a doubt as to the soundness of the theory that an arc to be maintained must be supported by thermions emanating from hot spots on the electrodes between which the arc is formed. J. Slepian[7] has shown that an arc is probably formed near the surface of metal electrodes by very high temperatures caused by the concentration of electric current in the gas immediately surrounding the electrodes. The experiments at California Institute of Technology show that the vacuum switch, when opened, fails to interrupt an electric circuit if the metal forming the contacts has not been freed of the adsorbed gases; that is, gases adhering to the surface of the metal.

The results of these experiments cannot be taken as conclusive evidence that a new type of electric switch has been developed, because the limits of performance have not been determined and there are many problems relating to details that must be solved to make the switch practical. The switch, however, was never the limiting factor in any of the tests made. There is, therefore, certainly sufficient encouragement to warrant further investigation of the subject for the purpose of determining the fundamentals of switching phenomena, if for no other reason. Also, we have the encouraging fact that many practical devices in use today presented, in the early stages of their development, obstacles which appeared greater than those which these tests indicate.

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