BONNEVILLE POWER ADMINISTRATION 1400–MW BRAKING RESISTOR

M. L. Shelton
W. A. Mittelstadt

P. F. Winkelman
W. J. Bellerby

Bonneville Power Administration
Portland, Oregon

ABSTRACT

A 1400-MW dynamic braking resistor installed at the Bonneville Power Administration's (BPA) Chief Joseph Substation enhances system stability in the Pacific Northwest (PNW). The capacity of the Pacific Northwest–Southwest (PNW-SW) Intertie is increased by the use of resistor braking for faults in the PNW. The need of and benefits from the use of the brake are discussed. The physical and electrical characteristics of the brake are described as well as the control system for its operation.

INTRODUCTION

The Bonneville Power Administration has designed, constructed, and tested a 1400-MW resistor brake. The brake is located at the BPA Chief Joseph Substation in north central Washington. The resistor is designed to dissipate 1400 MW of power when energized at 240 kV and is capable of withstanding a three-second application between cooling periods. If applied for three seconds, the power output will decrease to 1000 MW as a result of temperature rise in the conductor. The resistor is strung on three towers (one per phase) with approximately 15,000 ft of 1/2-inch stainless steel wire per tower. The conductor in each tower is grounded to a common terminal which in turn is tied to the substation ground. A photograph of the braking resistor is shown in Figure 1.

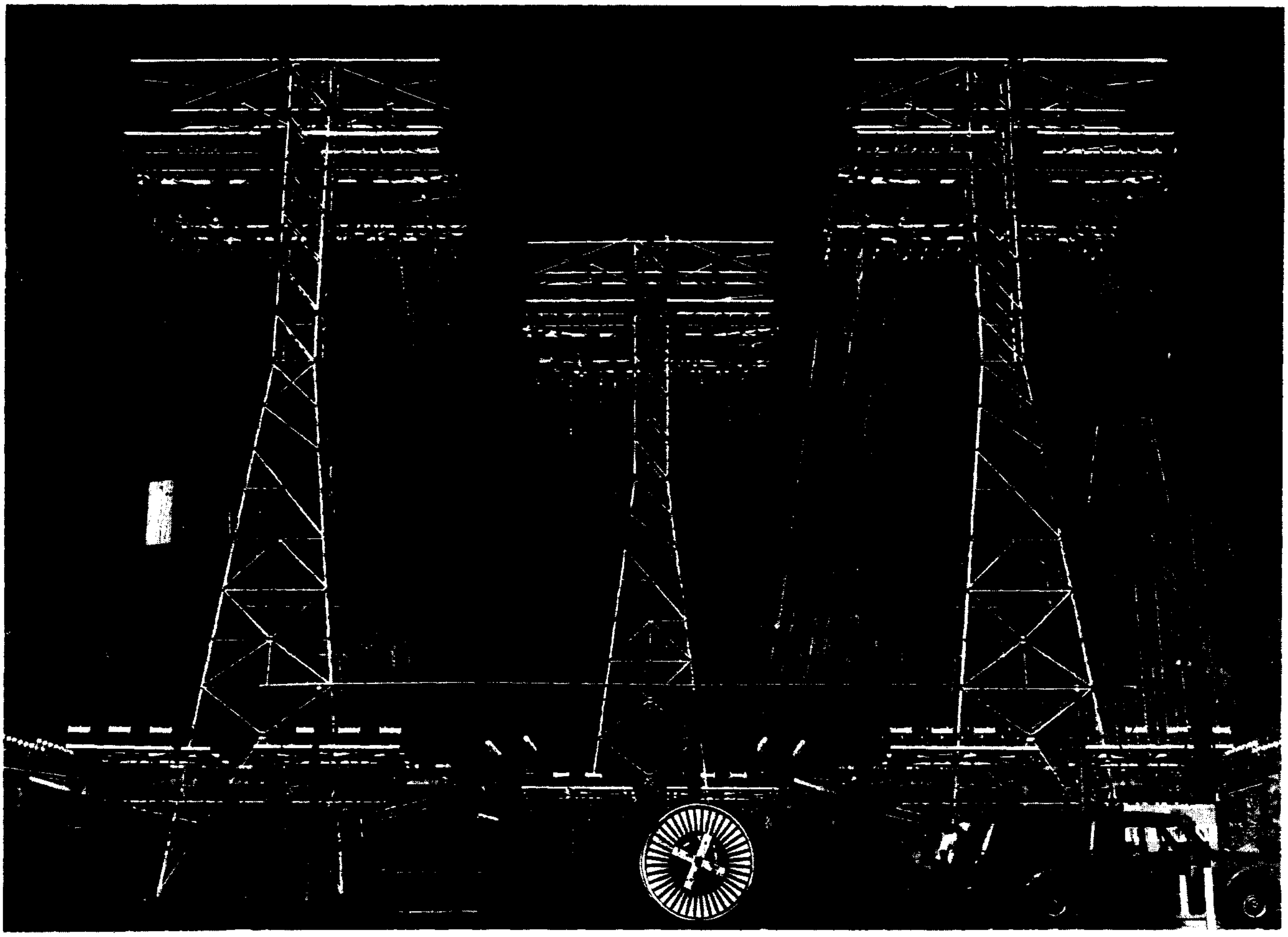

Fig. 1. Photograph of Chief Joseph dynamic braking resistor.

The brake is applied by closing a vacuum circuit breaker. Fault protection is provided by a standard power circuit breaker. The brake was energized for the first time on June 20, 1973, for 1/2 second. The current was approximately 3500 A initially

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decreasing to approximately 3200 A after 1/2 second. This corresponds to 1450 MW and 1330 MW respectively and agrees with the design values. The system behavior following the brake application agreed with the performance predicted from computer studies. No system problems were noted. A number of papers have been written on the subject of dynamic braking as indicated by references 1 through 9. Although the concept of dynamic braking is not new, it is one which probably has not been exploited to the best advantage of large power systems.

NEED FOR A BRAKE

The Bonneville Power Administration operates the major power transmission system in the PNW. This system is closely coupled and as such has a high degree of internal transient stability. As shown in Figure 2, the PNW transmission system is interconnected to many other systems in the Western United States and Canada.

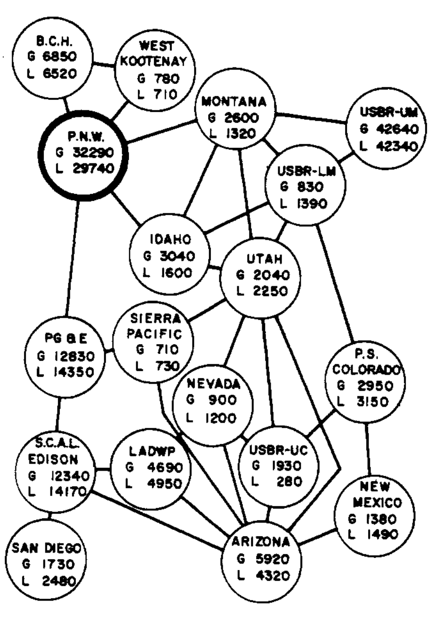

Fig. 2. Western United States power interconnections.

This figure is representative of the interconnections as planned by 1981. Large concentrations of generation exist in the Grand Coulee and Lower Columbia areas which is transmitted over the 500-kV main grid to load centers in Western Washington and Oregon as well as across interties to adjacent areas. Power purchased under the Canadian Treaty is also transmitted across the BPA system. The amount of power that can be transmitted over the interties is limited to a level which will not lead to instability for first-contingency faults on the BPA system in accordance with Western System Coordinating Council (WSCC) reliability criteria.

Faults near the large concentrations of BPA generation tend to accelerate the entire PNW. This produces severe angular swings between the PNW and the interconnected systems and can cause separation at the interconnection points although each area remains intact. When the PNW experiences a severe fault, a post-fault speed deviation between that area and its neighbors will result, which is proportional to the product of the fault accelerating power and the fault duration. If this speed deviation is great enough, the tie-line synchronizing power may be insufficient to maintain transient stability. When the loading of the tie lines is low relative to their maximum capacity, the synchronizing power is usually adequate to maintain stability with no extra control. It is when the tie lines are heavily loaded that some form of transient control is most needed.

The first line of protection is, of course, fast fault clearing.[12] Large-scale transient stability simulations indicate, however, that this is not sufficient to maintain intertie stability for peak load conditions. Transient stability simulations also show that appropriate application of a braking resistor at the Chief Joseph switchyard immediately after a fault in the PNW will retard the PNW area sufficiently to prevent tripping of the PNW-SW intertie and the subsequent islanding at high levels of tie-line flow.

Not all disturbances can be stabilized by use of a braking resistor alone. Any disturbance which demands a steady-state tie-line flow in excess of the available tie-line capacity must be controlled by some form of sustained countermeasure. For example, loss of the fully loaded dc line between the PNW and Southern California will require a net increase in flow on the parallel ac intertie of approximately 1400 MW. If the ac power flow is near full capacity at the time, one or more sustained countermeasures would be required to maintain stability, for example, dropping generation in the sending area and increasing tie-line capacity by switched series capacitors.

SELECTION OF SIZE

Although a braking resistor could be located at each major generating plant in the PNW, it was found by stability simulations that the closely coupled BPA system would react properly with a single strategically located brake for the first swing following a fault. The cost of a single brake would be less than that of many small brakes. Simulations showed further that the larger the brake, the more rapidly overspeed in the PNW could be reduced. With increased brake size also comes an increase in the voltage depression at the point of application and a more severe dynamic shock to nearby generators. Based on simulations of the expected system conditions, it was determined that a 1400-MW brake would be adequate to meet the needs for stability control of the interconnected area for several years to come. It was also found in preliminary designs that 1400 MW is about the maximum that should be carried on three towers for a single installation.

The brake duty time per switching application should be in the vicinity of one-fourth of the period of natural oscillation observed on the critical intertie for faults in the PNW. In this case the critical intertie is the PNW-SW tie-line which, when taken with the associated areas, has a natural frequency of about 20 cpm. The normal brake duty per application was determined by simulation to be one-half second. To permit multiple applications at a later date and to provide an adequate safety margin, a total duty time of three seconds for the brake was chosen.

EXAMPLES OF BENEFITS

The primary benefit from dynamic braking is the increased capacity which can be allotted to ties between the PNW and other areas without loss of stability for PNW faults. Compared to other methods of increasing tie-line capacity, use of a braking resistor was found to be least costly because the transient stability power limit was well below the steady-state power limit. Figure 3 illustrates the increased capacity of the PNW-SW intertie that can be realized by the use of dynamic braking.

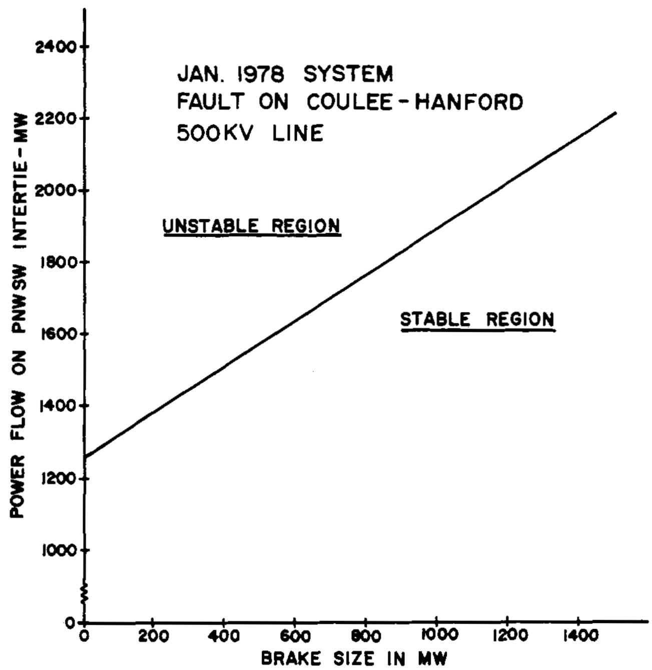

Fig. 3. Influence of brake size on PNW-SW intertie capacity.

It can be seen from this figure that the amount of firm power that can be transmitted from the PNW to California may be increased by 900 MW using a 1400-MW brake. This figure and the two which follow are from studies using 4-cycle clearing which assume 2-cycle power circuit breakers, 1-cycle relay time and 1-cycle margin. More recent studies with 2-cycle clearing (1-cycle fault clearing plus 1-cycle margin) would effectively raise the curve in figure 3 by approximately 600 MW.

Figures 4 and 5 illustrate the effect of the brake on two other system parameters for a specific loading condition.

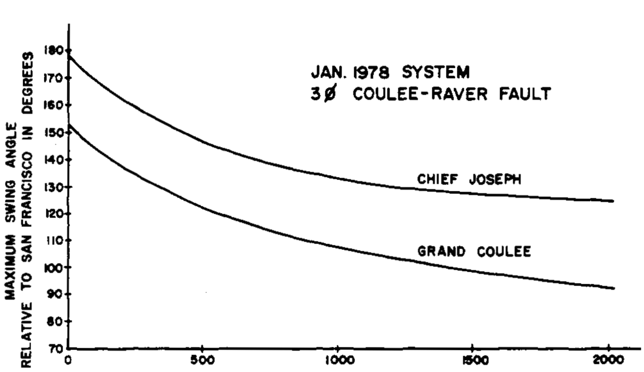

Fig. 4. Influence of brake size on maximum swing angle between BPA and PG & E.

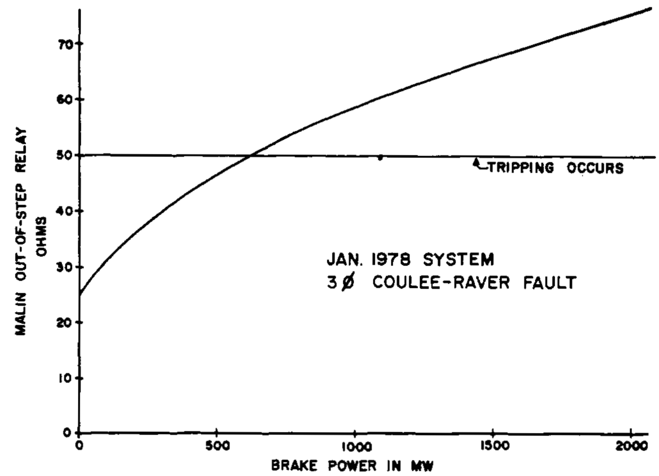

Fig. 5. Influence of brake size on PNW-SW relay impedance at Malin.

Figure 4 is a plot of brake power vs. the maximum angular swing between the BPA system and that of the Pacific Gas and Electric (PG & E) in California. It is observed that the larger the brake the lower the maximum swing angle that results on the first swing. Figure 5 shows the effect of brake size on the minimum first-swing impedance seen by the out-of-step tie-line relay at Malin near the Oregon—California border. When the magnitude of this impedance swings below a preset value, it is assumed that the system is about to lose synchronism, and the tie-line is automatically opened. As the brake size is increased, the first-swing relay impedance shows a higher minimum value.

BRAKE CONTROL SCHEME

A number of interesting procedures for the control of power system switching based on modern control-theory techniques have been reported in the literature and followed with interest by engineers at BPA. These procedures were generally ruled out for the initial control implementation because of the complex on-line computation and measurement problems presented. Fortunately, the behavior of the interconnected system is reasonably predictable, making it possible to design a relatively simple brake controller.

As mentioned, the primary purpose of the Chief Joseph braking resistor is to temporarily restrain the Pacific Northwest generating area when it is accelerated by a severe fault in that area to prevent loss of synchronism across one or more tie-lines to the external areas shown in Figure 2. Since the brake is switched on only for a short time, the system is expected to have a viable post-fault steady-state load flow to which the system state can converge as the transient swings die away. The control strategy following a disturbance can therefore be viewed as:

(1) To guarantee that a reasonable post-fault steady-state operating point will exist by switching generation, load, tie-line capacitors or other sustained control devices and

(2) To guarantee that the system state is brought within the region of attraction of the above operating point by use of appropriately controlled braking.

The region of attraction of the post-fault steady-state operating point is enlarged by good system damping resulting from wide-spread use of properly adjusted power system stabilizers for generator excitation systems. The role of the braking resistor applies to Item 2 above, to which the discussion that follows will be limited.

Figure 6 illustrates the brake control problem for a simple one-machine infinite-bus example.

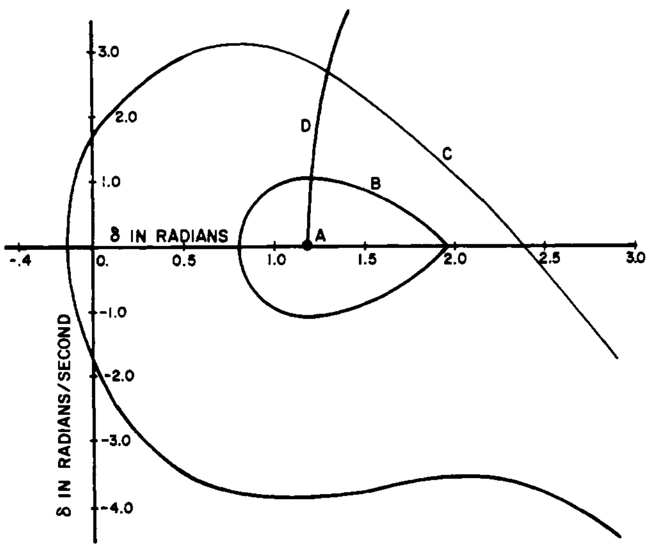

Fig. 6. Stability regions for a one-machine infinite-bus system.

This figure is a two-state phase-plane with coordinates of rotor angle (relative to the infinite bus) and time rate of change of rotor angle (speed). This figure applies only to a specific post-fault loading condition having an equilibrium angle of 68 degrees identified by point A. The stable region of attraction of this operating point with no control is enclosed by the tear-drop-shaped curve labelled B. The outer curve labelled C encloses the entire region which can be stabilized by proper application of a braking resistor rated at 42% of the maximum tie-line flow, assuming zero damping. A typical response path of the system state for a fault at the generator is shown as curve D. If the fault is cleared before passing outside boundary B, no braking is required. If the fault is cleared between boundaries B and C, the brake is needed to maintain stability. And last, if the fault is not cleared until the system state passes beyond curve C, stability cannot be maintained with the specified brake, assuming all other parameters to be unchanged. Clearly, the larger the normally stable region enclosed by curve B, the easier it is to control the brake to bring the state within that region. This emphasizes the importance of establishing a post-fault operating point having a sufficiently large stable region of attraction. While the region enclosed by curve C can be stabilized by the brake, it depends on properly controlled timing. Figure 7 shows a possible control law for this hypothetical system. The zone in which the brake is switched on corresponds to the two shaded areas labelled A and B.

The zone in which the brake is switched off corresponds to the unshaded region C. A system state originating in region B will require two brake operations to return the state to the normally stable region. A system state originating in zone A will require

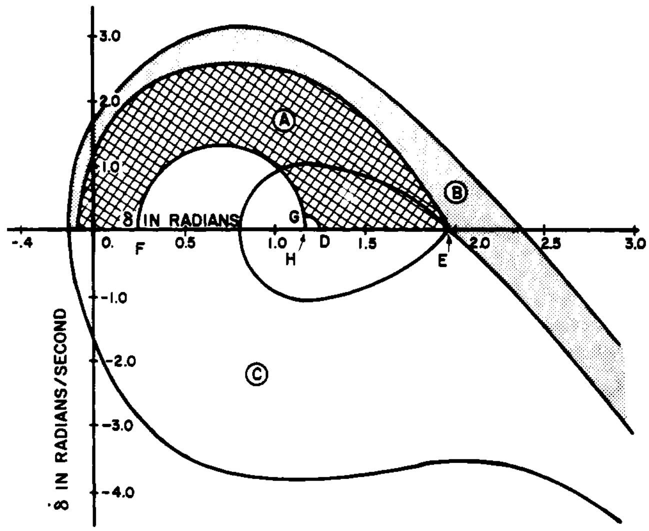

Fig. 7. Comprehensive brake control law for the one-machine infinite-bus system.

only one brake application. While the brake may be disconnected after the system state has entered the normally stable region, the ensuing transient will be less oscillatory if the brake is not disconnected until the rotor speed passes downward through zero across the switching boundary D-E. If the system state passes across switching boundary F-G, the brake-on trajectory will bring the state very close to the steady-state post-fault equilibrium point. The switching boundary G-D is somewhat removed from the equilibrium point H to prevent unnecessary brake switching resulting from minor perturbations about H.

The one-machine infinite-bus switching law can be applied to the actual multi-area problem only in a conceptual way. The ideal switching boundary of Figure 7 changes with loading condition and would be quite difficult to achieve in practice. The initial role

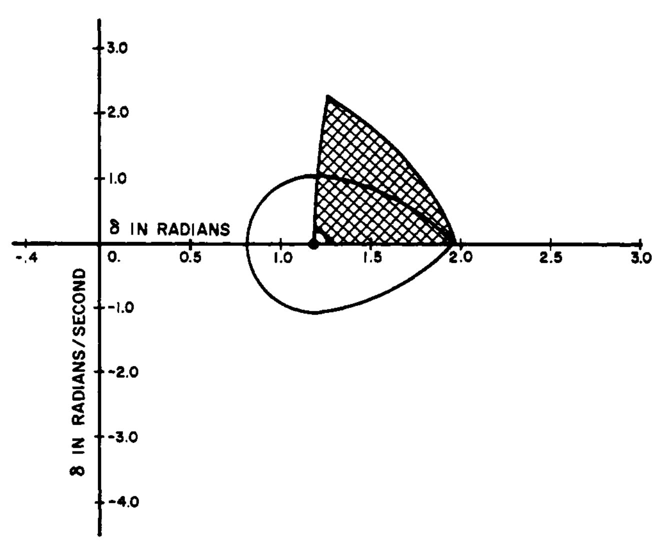

Fig. 8. Simplified control law for the one-machine infinite-bus system.

of the Chief Joseph braking resistor is primarily intended to be for faults in the PNW area when that area is in a heavy generation mode. First-swing application for faults only would reduce the brake on area for the one-machine infinite-bus system to that shown in Figure 8.

The resulting control law is bounded by the typical fault trajectory of Figure 6 on the left, by the zero-speed switching boundary D-E of Figure 7 on the bottom, and by the boundary between zones A and B of Figure 7 on the top.

Consideration is being given to the use of first and second swing brake switching, which can be shown to be quite beneficial in the one-machine infinite-bus representation. The benefit is not as easily demonstrated for the multi-area case unless each area is equipped with a brake or some other powerful form of transient control. This is because several inter-area swing frequencies may be present. Discussion of brake control in this paper is limited to first-swing brake switching only.

The initial control strategy chosen for the Chief Joseph brake is similar in concept to the control law shown in Figure 8. It involves switching the brake on when a severe fault is detected in the PNW, and switching it off when the average rotor speed of the PNW relative to the adjacent connected area passes through zero. Ordinarily when a fault occurs in the PNW area, this area is sure to be accelerating relative to the adjacent areas, and a brake operation is the correct control action.

In view of the relatively large size of the PNW area, it is expedient that the number of telemetered quantities be held to a minimum to prevent unnecessary expense. Based on large-scale simulation studies, it was found that a fault within the BPA system could be reliably detected by power measurements at two carefully chosen powerplants. It was also found that the required brake application interval was relatively constant and that an electronic timer could be used to control brake disconnection rather than making a speed-related measurement. The details of the initially installed brake controller form the remainder of this section.

The braking resistor located at the BPA Chief Joseph Substation, is connected to the 230-kV bus through a normally closed 230-kV oil circuit breaker and normally open 230-kV vacuum switch. Control devices (controllers) which insert the braking resistor are located at Chief Joseph and John Day Substations. These controllers detect a sudden decrease of power in the plant output with a simultaneous decrease in bus voltage. This is an indication of a disturbance in the power network. Loss of generation would cause a rise in bus voltage. When the controller at John Day or Chief Joseph detects a sudden power drop of more than 300 MW and a simultaneous decrease in bus voltage greater than 10 percent of normal bus voltage, an output is produced. This output closes the 230-kV vacuum switch which applies the brake to the system for a pre-set time of about one-half second.

The generating plant power output is measured by power transducers in each of the powerhouse lines. The output of the transducers is summed and applied to the detector portion of the controller. A negative change in power produces an output from the controller which is combined with the output from the undervoltage detector. The output of the controller circuit at John Day keys a frequency-shift audio-tone which is transmitted, via microwave, to Chief Joseph. The output of the audio tone receiver at Chief Joseph, or the output of the controller and undervoltage detector at Chief Joseph, produces a signal to close the vacuum switch and apply the brake. Overcurrent protection is installed on the backup power circuit breaker which is set to trip instantaneously for a brake failure. If the control scheme fails to trip the vacuum switch after a normal one-half second application, the overcurrent-relay time-delay element will trip the power circuit breaker in about one second.

The controller design and operating characteristics were verified by digital simulation. The essential characteristics of the brake insertion controller simulated are shown in Figure 9.

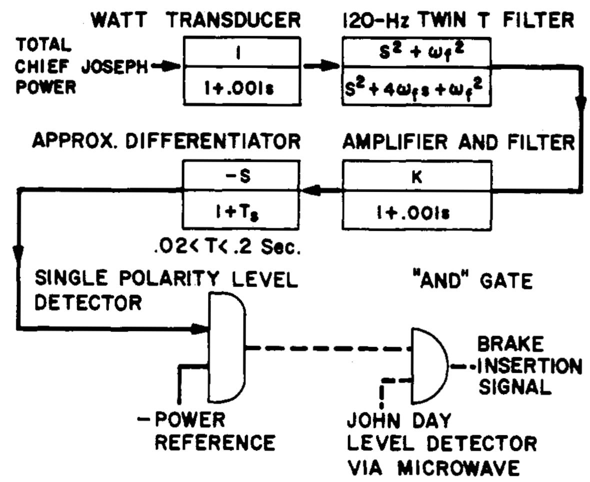

Fig. 9. Power portion of the brake insertion controller.

The instantaneous electromagnetic response imposed on the controller through an extensive 3-phase network was simulated using the BPA transients program.[13] Instantaneous 3-phase power at the sensor location was computed for each time step and used as input to a separate digital simulation of the controller shown in Figure 9. Using these two computer programs, a number of simulations representing different faults and operating conditions were made. A typical simulation result is shown in Figure 10.

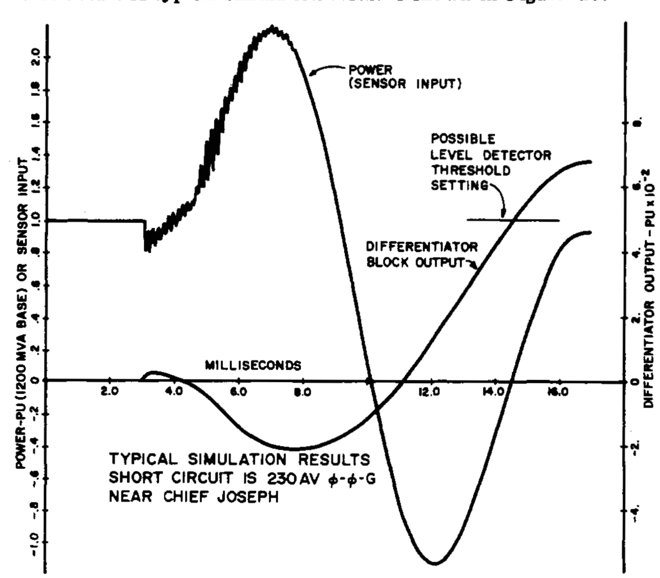

Fig. 10. Controller simulation results for an unsymmetrical fault near Chief Joseph.

For this unsymmetrical fault a trip signal is generated by the controller 11.5 milliseconds after the short-circuit.

DESIGN OF BRAKING RESISTOR

The Chief Joseph braking resistor was designed by BPA transmission design engineers. It was found that this design, which follows, resulted in a significant savings over other types which have been proposed of comparable rating.

Each phase of the braking resistor is supported on a modified double-circuit 115-kV suspension tower body approximately 90 ft high. The towers also serve as a dead-end support for the 795-MCM ACSR Drake conductor that energizes the resistor from the main substation 230-kV bus. The grid resistor for each phase is formed by 14,700 ft of 1/2-inch, 19-strand stainless-steel wire zig-zagged around the tower in 60-ft vertical loops as shown in Figures 1 and 11.

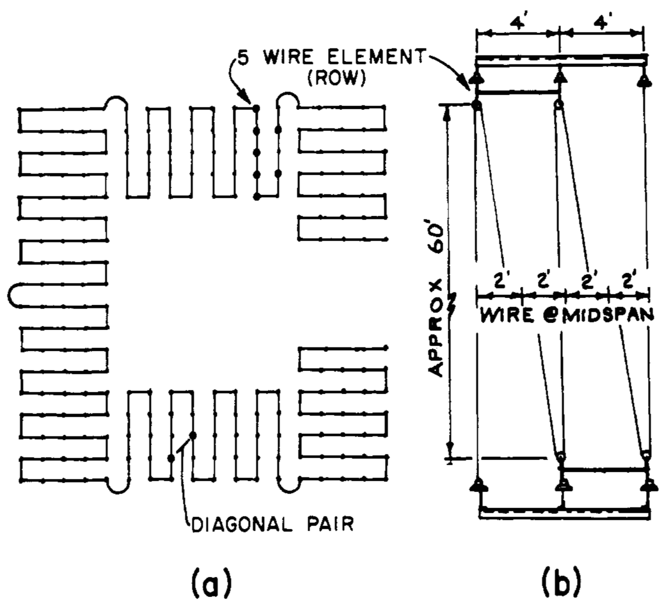

Fig. 11. Top view of resistor (a), and five-wire element (b).

The current flows in opposite directions through adjacent wires within each row and in the same direction on diagonally adjacent wires. With wires in the normal position, this results in a repulsive force acting between adjacent wires in each row and a lesser attractive force acting between the diagonally adjacent wires which have greater separation. The forces are inversely proportional to the separation of the wires. This conductor configuration effectively neutralizes the grid inductance.

The resistor grid is made up of 5-wire elements independently fabricated with compression jumper terminals at each end. This permits easy replacement of damaged wire by maintenance personnel. Groups of 7 to 9 of the 5-wire elements are connected in series and vertically supported through insulated sheaves and clevis insulators between an upper rack (Figure 12) and a lower rack (Figure 13).

The lower rack is held out from the tower legs by vertically hinged insulated struts and is weighted to maintain tension in the grid wires. The elongation of the grid wires from the 1200 degrees

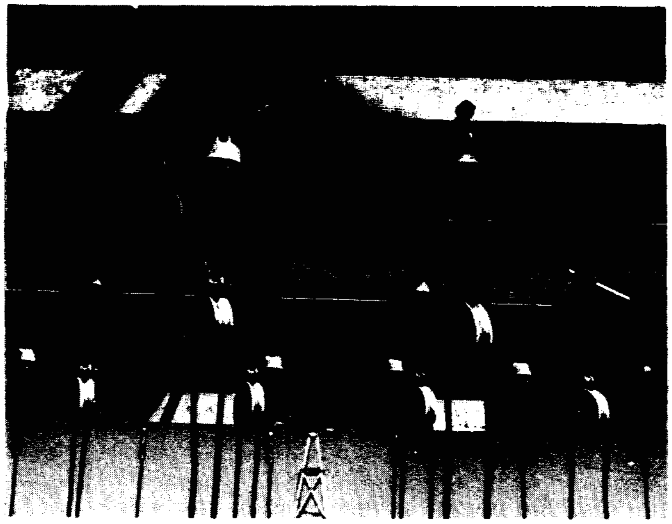

Fig. 12. Upper assembly.

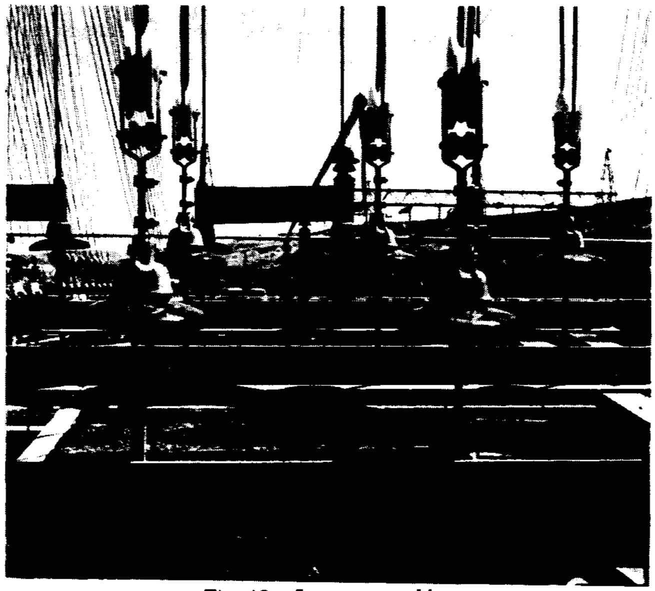

Fig. 13. Lower assembly.

F temperature rise during a 3-second 4000-A brake operation causes the lower rack to drop about 9 inches. As shown in Figure 11, six of these racks are supported progressively around the tower with the grid wires connected in series between racks.

Prototype Tests

The BPA high-current test facilities limited the maximum length of wire used to approximately 120 ft. Two test setups were used. The first was an 8-wire element with 11 ft between upper and lower supports at 1-ft spacing and the second was a 2-wire element with up to 60 ft between upper and lower supports at various spacings. These tests, with a maximum current of 4,000 A for 3 seconds, were used to determine:

(1) The type of hardware and fittings required to withstand repeated heat cycling.

(2) The frequency and magnitude of wire movement vs. tension from magnetic forces of attraction and repulsion.

(3) The energy dissipation characteristics of the resistor.

(4) Installation problems, etc.

Observations from these tests, which included up to 500 heat cycles, are as follows:

(1) Bolted metallic suspension and strain clamps used on the wire as end supports would cause the steel strands to burn apart from arcing in as few as six energizations. The arcing was caused by the current seeking a parallel path through the clamp having comparatively low resistance. The solution was to use compression jumper terminals for end termination and special 5-inch high-alumina ceramic sheaves as intermediate suspension supports. Porcelain sheaves failed within 11 energizations, whereas the alumina ceramic sheaves withstood 500 heat cycles without damage.

(2) To prevent interwire contacts, the midspan spacing between grid wires was increased from the original 1-ft design spacing to 2 ft and the wire tension at the lower end of the grid was increased from 60 pounds to 95 pounds (The maximum tension permitted by the 115-kV towers).

(3) Tests with 7-strand wire showed that, for ease of installation, the wire should be 19-strand, 1/2-inch stainless steel, annealed to a tensile strength of 80,000 to 100,000 psi. Type 321 was selected for its excellent resistance to corrosion at temperatures up to 1500 degrees F. To prevent distorting the wire during installation, it was found necessary to form the 60-ft 5-wire elements on the ground by means of the plywood jig shown in Figure 14. After installation of compression jumper terminals, the elements were then lifted into place over the ceramic sheaves.

Fig. 14. Element forming jig.

Field Tests

The completed resistor was energized at the site using five test sequences to verify the adequacy of the resistor design and to record data for comparing system behavior with simulation studies. The following switching sequences were chosen as representing typical single and multiple brake operations:

(1) Two tests two hours apart, each energized for 0.5 seconds.

(2) Two tests two hours apart:

(A) 0.5 seconds energized, 5.5 seconds de-energized, 0.5 seconds re-energized.

(B) 0.5 seconds energized, 2 seconds de-energized, 0.5 seconds re-energized.

(3) One test energized for 1.0 second to determine effects of delayed circuit breaker operation.

The cyclic movement of grid wires was photographed to determine amplitude, frequency, and decay rate during and after energization. Temperature measurements were recorded on and adjacent to the wires. Key lines were monitored on the system to obtain recordings of voltage and power swings. The four 0.5-second tests with and without re-energization caused no electrical or mechanical problems. For the tests without re-energization, the maximum outward deflection of the corner grid wire was the predicted value of 10.25 inches, 0.42 seconds after energization, and the maximum inward deflection was 9.8 inches, 0.5 seconds later. Grid wire temperature reached 200 degrees F.

During the final 1.0-second tests, diagonally adjacent wires contacted at 0.82 seconds with numerous contacts continuing until de-energization at 1.0 second. Grid wire temperature reached 400 degrees F. Seventy percent of the wire contacts occurred on the upper half of the grid where the supporting ceramic sheaves (Figure 12) were twisted by grid wire tension toward the diagonally opposite wires in adjacent rows. Also most of the contacts occurred one-third of the loop length from the top where the diagonal space was further reduced by the converging of the wires toward the 5-inch diameter sheaves (Figure 11). The outward thrust of the outer grid wires within the grid complex permitted some slackening of the internal grid wires as was the case in the 8-wire element prototype test. This resulted in random motion after approximately 0.58 second. This random motion of the inner grid wires, along with the reduced spacing between the diagonally positioned wires, permitted the attracting forces of the diagonal wires to override the opposing forces between the adjacent wires within a grid row. Two sets of diagonal wires actually welded together. Numerous pit marks were observed on diagonally attracting wires but the damage was negligible.

System behavior during the tests was as predicted by system studies, with the bus voltage at Chief Joseph Substation dropping only 2%. The following modifications are being made to prevent wire contacts during longer-than-normal operations:

(1) Increase tension of lower end of grid wires from 95 pounds to 145 pounds. This requires stiffening and reinforcing the upper and lower wire racks and adding redundant bracing in the cage of the towers. The increased tension should reduce the movement of outer grid wires by about 25%.

(2) Maintain alignment of ceramic sheaves by installing clevis bar stabilizers between sheave pairs on both upper and

lower positions of each five-wire grid element. This should prevent at least 70% of the contacts that occurred during the 1-second test.

(3) Install midspan spacers on one 5 x 8 wire rack for operational experience in the event that wind action and future energization periods up to 3 seconds may require additional stabilization of the wire grid. The spacer is simply a 3/4-inch diameter solid epoxy fiberglass rod, 104 inches long attached across each five-wire grid element by means of heat-shielding double U-bolt clamps. Tests show that the installed rods had less than a 90 degrees F temperature rise when the conductors reached 1250 degrees F during a 3-second test. The rods are capable of operating at up to 400 degrees F. A camera will monitor wind action on the braking resistor during the first year of operation.

(4) For design information, one 5 x 9 wire rack will be weighted temporarily for a final test with 195 pounds tension on the lower end of the grid wires. This should be adequate to prevent excessive reduction of tension on the inner grid wires with the present lower rack design.

Future Braking Resistor Design

Following are suggestions for future design:

(1) Eliminate the expensive supporting ceramic sheaves by dead-ending individual wires with compression fittings. This will permit installing the wires parallel to maintain the 2-ft spacing throughout their length. This will also aid in adjusting wire tension.

(2) Weight inside wires by a separate inner rack connected by means of jointed spacers to the outer weighted rack to prevent excessive reduction of tension on inner wires during energization.

(3) Use heavier towers to permit an average wire tension of 200 pounds. This should assure a minimum of 150 pounds tension in the wires with allowance for tension variations between individual wires.

FUTURE DEVELOPMENTS

Dynamic braking is an effective means of controlling radially connected generating plants as well as large closely coupled areas. Recently braking resistors have been added to the radially connected El Chocon generating plant in Argentina and it can be expected that additional installations of this type will be made. BPA has plans to use a brake at the Hot Springs Substation in Montana when a 500-kV line is installed between BPA and the Montana Power Company Colstrip steam plant in 1978.

The generating capacity of the BPA system itself is also continuing to grow. Presently there is approximately 5 GW of generation in the Chief Joseph – Grand Coulee area and approximately 20 GW total in the PNW. System planning studies show that these figures will increase to 10 GW and 32 GW, respectively, by 1980. It is very likely that a second brake may be needed at that time.

As operating experience is gained with the Chief Joseph braking resistor, improvements will undoubtedly be made in the brake control system. Such improvements may include multiple brake applications per disturbance and more complete coordination with each interconnected area and the corresponding transient control facilities which are added.

CONCLUSIONS

Several aspects of the BPA Chief Joseph 1400-MW dynamic braking resistor have been described. This brake which was designed and tested by BPA will be used to prevent instability between the Pacific Northwest and interconnected areas for severe PNW faults. Use of the brake increases the secure loading of the PNW-SW intertie by approximately 900 MW.

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APPENDIX

The phase planes for the one-machine infinite-bus example are based on the well known dynamic swing equation

$$M\frac{d^2\delta}{dt^2} = P_i - P_m \sin\delta$$

where

M = inertia constant of machine,
δ = displacement angle of rotor with respect to the infinite bus,
P_m = the maximum synchronising power over the connecting transmission line

and

P_i = the net injected power.

The term P_i can be further expanded to illustrate the effect of the braking resistor by

$$P_i = G - L - P_B(t)$$

where

G = the net mechanical input power,
L = the normal bus load on the ideal machine

and

$P_B(t)$ = the brake dissipation power which is either on or off.

When the brake is applied P_i is reduced causing a de-accelerating effect on rotor angle to counteract the overspeed resulting from a fault.

Discussion

W. H. Croft (Consulting Engineer, Phoenix, Arizona): I congratulate the authors for adding another fine paper to the slowly growing technical literature on the application of braking resistors to modern transmission systems and interconnected systems. As evidenced by 1, 2, 3 I have been a long time advocate of this method of correction for transient instability problems where it can be justified economically. Despite the massiveness of the resistors required, either the cast iron grid requiring acres of land or the tower type presented by the authors the economics appear good. Because of certain irreduciable data such as that environmental problems and land availability the advantage of a good economical solution may be voided, when such massive resistor are used. Research and development is required to develop a resistor of small size for its capacity to make this method more generally used and I believe if more system planners and designers would study the braking resistor method as a solution to their transient instability problems and a demand for better and more acceptable resistors is created that the industry will respond to the need. Several years ago one prominent manufacturer was pursuing resistor development for this purpose in his laboratory and I understand that a resistor was designed using already available materials which met the requirement of small size for its volume, however I have never seen any thing in the literature or in the marketplace about this development.

The design of the resistors shown by the authors presented an interesting and challenging problem in its self aside from the application to the system problems and is a start in the effort of research and development so necessary to develop a resistor for the problem of braking. Were other types of design considered in lieu of the tower type which would appear to present some environmental objections due to its massiveness? I am also curious if the designers considered the environmental impact such high and bulky might present even in such a presently remote location? The paper also mentions other probable uses of braking resistors, do you anticipate the use of the tower design at other locations, such as Hot Springs mentioned in the paper?

Also, would the authors comment on the type of faults considered in their study, and what effect, if any, do the different type of fault play in the sizing of the resistors?

Manuscript received August 5, 1974.

REFERENCES

[1] D. L. Bryner, W. H. Croft, D. E. Martin, R. A. Tynes, and R. F. Walker "Integrated Planning For Five State Rocky Mountain Area" AIEE CP 60-1159, National Power Conference, Philadelphia Pa. Sept. 1960 p. 8
[2] W. H. Croft and R. H. Hartley "Improving Transient Stability By Use Of Dynamic Braking" TP 61-798 PA&S No. 59, April 1962. pp. 17-26.
[3] W. H. Croft and R. H. Hartley "Improving Transient Stability By Use Of Dynamic Braking II" AIEE CP 61-1059 Fall Meeting Detroit, Mich., October 1961.

M. L. Shelton, W. A. Mittelstadt, P. F. Winkelman, and W. J. Bellerby: We sincerely appreciate the interest shown by W. H. Croft in his discussion. The Bonneville Power Administration (BPA) considered other types of braking resistor designs but they were rejected because of higher costs. Cast iron resistors in oil tanks were priced higher than the final design by a factor of approximately three. One design which strung the conductor horizontally on wood poles was discarded due to mechanical and electrical considerations. The initially proposed location for the brake was at Grand Coulee Dam. However, the brake was installed at Chief Joseph, which is electrically close to Grand Coulee, since a 230-kv breaker position was available making the installation costs lower.

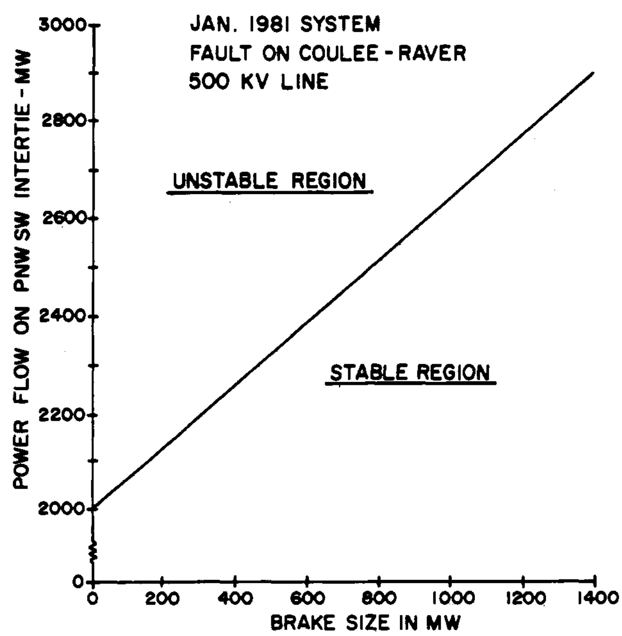

Fig. 1. Influence of brake size on PNW-SW intertie capacity.

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It should be pointed out that the visual impact of the BPA braking resistor is not greatly different than other types of high-voltage switchyard and transmission equipment.

BPA is considering other brake installations, using a tower design with a lower profile.

R. H. Park (2) has designed a compact resistor which might be used when small size is a requirement.

BPA used three-phase faults to determine the size of the resistor since this is the disturbance used in our planning criterion and is consistent with the reliability criteria of the Western Systems Coordinating Council (WSCC). Obviously, lesser faults would not require as large a resistor.

Our comments on Figure 3 in the text indicate that the capacity of the PNW-PSW Intertie could be raised by approximately 600 MW by using two-cycle clearing. The transient stability limit as a function of brake size for a fault near Coulee on the Coulee-Raver line is shown in Figure 1 below. This figure shows the increase of 600 MW over that shown by Figure 3 in the text.

well as the control system for its operation.

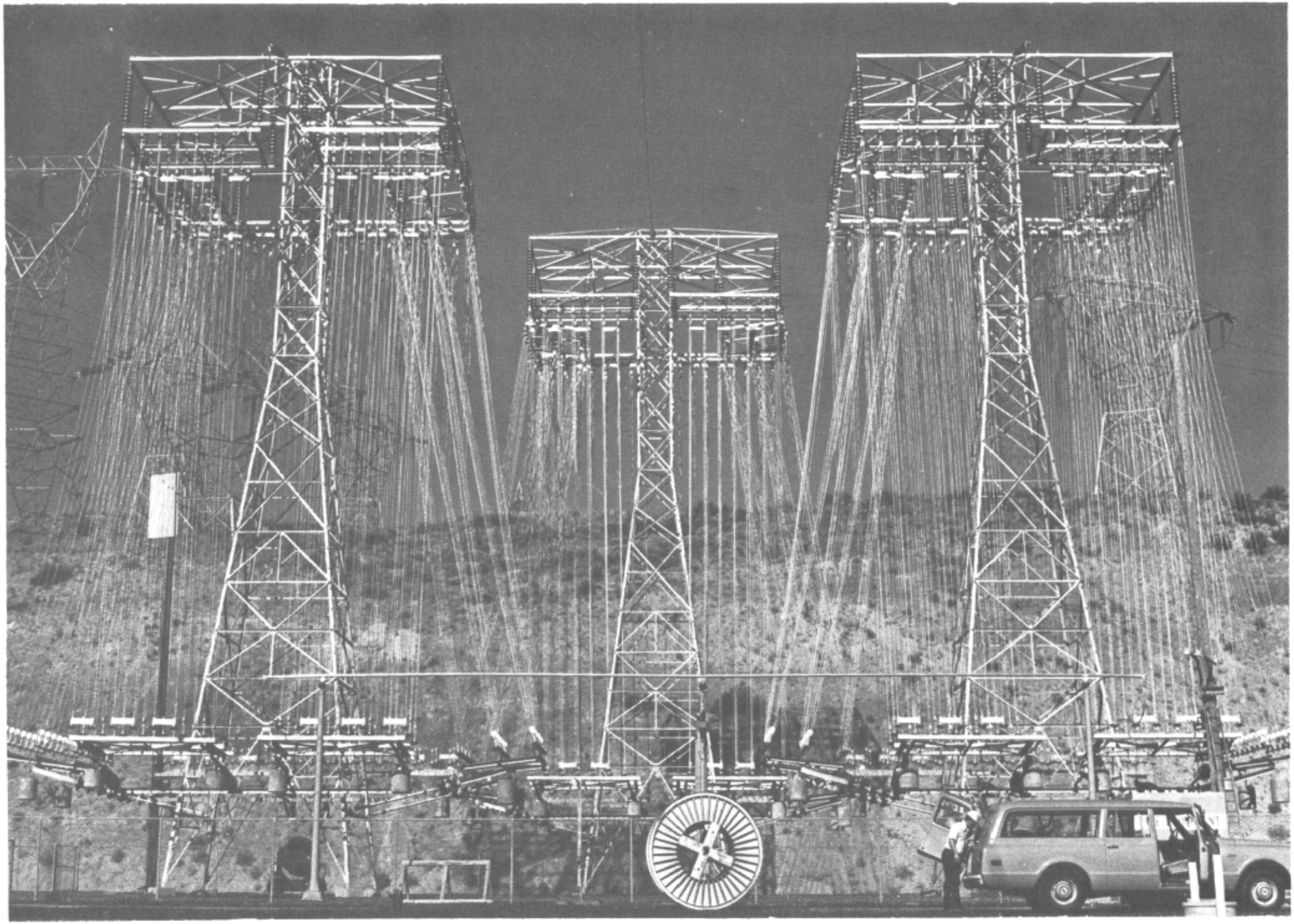

Fig. 1. Photograph of Chief Joseph dynamic braking resistor.

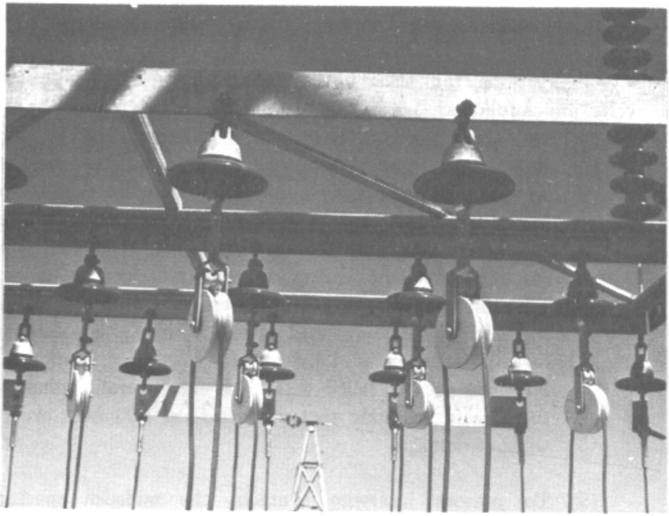

Fig. 12. Upper assembly.

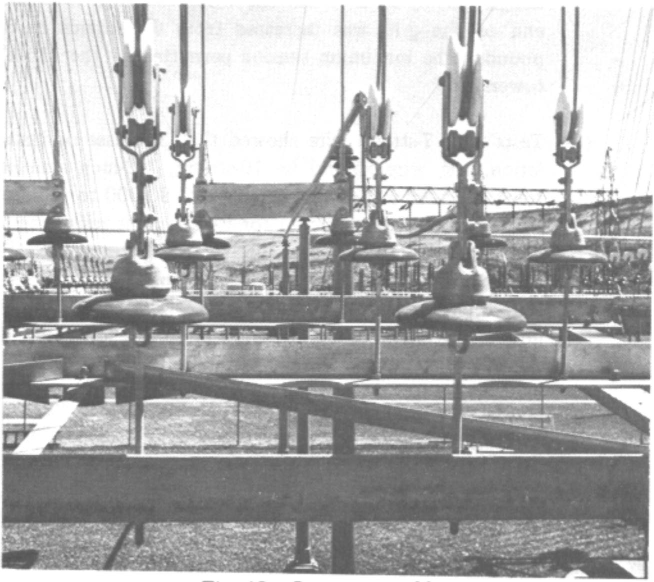

Fig. 13. Lower assembly.

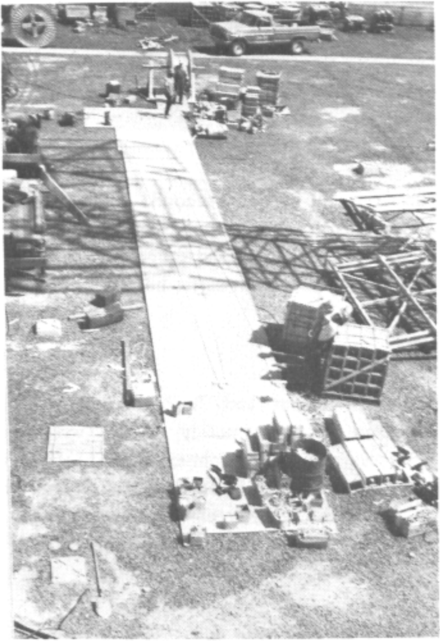

Fig. 14. Element forming jig.