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During the meetings, the study Committee was represented by M.M. Sforzini, Chairman of the Study Committee, Mr. C. Gary, Convener of the working Group on Corona effects and magnetic fields and by Dr. B.J. Maddock (United Kingdom).

A Brief History of AC Surge Arresters

E. C. Sakshaug, Consultant

Much of the material in this history, particularly that relating to sizes and protective characteristics, is from General Electric Company sources. It is possible, therefore, that some devices manufactured by other companies are not mentioned.

Since the beginning of ac transmission, approximately 100 years ago, lightning protection of transmission equipment has been provided by gaps and by nonlinear resistors, alone or in various combinations. Gaps were used alone in the early years, gaps combined with nonlinear resistors were used for about the next 70 years, and nonlinear resistors without gaps have been used for the last 15 years. Many of the arresters manufactured 50 or more years ago are still in service, but the time periods given below are approximations of the periods during which generic arresters were manufactured.

Lightning arresters, or surge arresters as they are now designated, are applied to protect equipment against the effects of lightning or other surges conducted by the system to the equipment being protected. That is, stations are almost always protected by rods or other shielding so that the lightning or surge currents almost always reach the stations by being conducted along transmission lines. To protect insulation at any instant, arresters are permanently connected from line to ground near the equipment being protected. An arrester must act as an insulator, conducting at most a few milliamperes of current at normal system voltage; change to a relatively good conductor capable of carrying thousands of amperes—with a current times resistance, IR or discharge voltage, lower than the voltage withstand of the protected equipment; and extinguish or clear the current flowing from the system through the arrester ("power follow current") after the lightning or switching surge has been dissipated.

1892 to 1908: Air Gaps With Modifications

Protection during the early part of the period was provided by simple air gaps from line to ground. Gaps can be designed to spark over at voltages low enough to provide excellent lightning protection with practically no discharge voltage. However, simple air gaps will not clear power follow current unless a resistance is connected in series to limit the current magnitude and improve the power factor of the interrupting circuit. A linear resistance large enough to produce the required current limitation will exhibit discharge voltages, even at moderate lightning currents, higher than the voltage withstands of reasonable insulation systems; therefore, air gaps are nonclearing devices requiring a circuit breaker or fuse operation to clear power follow current.

Some of the improvements made during this time period were the development of so-called "nonarcing" electrodes made of copper or brass, and development of graded multiple gaps. Even so, the degree of lightning protection was limited by erratic sparkovers caused by air pressure and humidity and by electrode erosion resulting from high follow currents.

1908 to 1930: Nonlinear Resistors Based on Puncturing and Reforming of Films

The first arrester employing a nonlinear valve element was the aluminum cell arrester introduced in 1908. An aluminum cell arrester comprised a sphere or horn gap in series with a tank containing the aluminum cells. The cells, each rated 300 volts, were inverted cones about 0.3 inches apart. Electrolyte was poured in the cones to partially fill them, and the group of cones, still in an inverted position, was placed in a tank of oil. A film formed on the plates could be punctured by a lightning discharge, but it would re-form or "heal" rapidly after the discharge. Current limitation was very good, but the discharge voltages were high and somewhat erratic. In addition, the arresters were physically large and required a considerable amount of maintenance, including the need to close the series gap for an "instant" once each day. The reason for the daily closure is that the film on the plates would gradually dissolve when current did not flow, and the momentary closure allowed current to flow and re-form the film.

1920 to 1930: Oxide Film Arresters

Oxide Film arresters were produced for transmission applications from about 1920 to 1930, and a modified version for distribution applications was produced until approximately 1955. These arresters consisted of gaps in series with a number of cells containing lead peroxide. The end plates of the cells were coated by an insulating film. When the insulating film was punctured by a surge, the resistance became low and current flowed. The lead peroxide near the point of current flow was changed to "red lead and litharge which have high resistance" by the heat produced by the flow of power follow current, and the resistance became high enough for the gaps to clear. The arrester could be operated many times before the cells required reconditioning.

1930 to 1954: Silicon Carbide Non-Linear Resistors With Nonactive Gaps

Nonlinear valve blocks made of silicon carbide and a high temperature bonding system were introduced in 1930. Valve blocks of this general type were used in station arresters for approximately 50 years; the voltage across these blocks was roughly $V=Ki$ with in the range of three to six depending on the silicon carbide grain and the bonding and firing. Most of the changes made were to improve the lightning discharge capability of the material because protective levels on switching surge waves were too high for many of these operations to occur. Furthermore, most lines were relatively short and, with a few exceptions, operated at voltages below 230 kv. The silicon carbide arresters were a considerable improvement over earlier arresters. Discharge voltages were reduced about 40 percent compared to oxide film arresters. In addition, arrester height was reduced by 30 percent and physical volume reduced by nearly 80 percent.

Most of the insulation coordination concepts still in use were developed during this time period. Adoption of basic impulse insulation levels in 1941 established an impulse insulation strength (BIL) for each voltage class of protected apparatus. Improvements in impulse testing and standardization of impulse voltage and current wave shapes permitted definitions of margins of protection provided by arresters. By the late 1940's, reductions in gap sparkover levels by gap preionization, and improvements in gap reliability, primarily as a result of using rubber gasket materials to resist moisture ingress, made it possible to protect insulation one BIL step from the full established level.

1954 to 1976: Silicon Carbide Nonlinear Valve Elements With Active Gaps

Active arrester gaps are arranged so that a magnetic field produced by a coil or by some other means moves the power follow current arc from its point of initiation to a place in the gap structure where extinction occurs. The time period for active gap arresters might be divided into two periods. During the first five to ten years, the active gap arresters did not limit current, and for about the last 15 years, almost all station arresters had current-limiting gaps.

Movement of the follow current arc by magnetic action increases the current-interrupting ability of gaps because elongation and cooling of the arc results in more reliable current zero extinction of even fairly high current arcs and the tendency of the gap to reignite is reduced because the location where the arc would reignite is comparatively cool. An additional advantage of arc movement is that the arc terminals may be moved from the point of minimum gap spacing. This movement reduces the tendency to restrike, and reduces heating and erosion at the point of minimum spacing so that changes in sparkover are minimized.

Improvement in gap interrupting ability allowed a reduction in valve element resistance and reduction in arrester discharge voltage. The discharge voltage reduction, together with lower sparkover by improved preionization and by less electrode erosion, made possible further reductions in the BIL of protected equipment. Arresters made during the first five to ten years of the period made possible insulation level reductions of two full steps, 650 kv to 450 kv for 138 kv system equipment for example. At a system voltage of 345 kv, a level of voltage just coming into use, the full BIL was never used, and 1050 kv, a two step reduction, became the normal insulation level for 345 kv.

Valve elements in some of these arresters were designed to discharge high switching surge currents because applications at 230 kv were increasing and some 345 kv applications were being made. The arresters were not expected to provide much, if any, switching surge protection for other apparatus, but it was necessary for the arresters to survive if sparked over on a switching surge.

Current Limitation

In the early 1960's, the principle of arc movement and elongation was extended by increasing the magnetic field strength, increasing the number of gaps per unit of rating, and using the increased field strength to increase arc length to the range of seven inches per kv of rating. Arc cooling caused by the long arcs in contact with relatively cool gap plate material caused a voltage across the gaps, that, together with the valve element voltage, was greater than the rated power frequency voltage by an amount sufficient to force the current to zero within 20 or 30 electrical degrees under most conditions.

The increase in ability to clear power follow current made possible a considerable reduction in valve element resistance and discharge voltage. Furthermore, the reduction of energy required to be absorbed by the valve element because of the energy absorbed by the gap and the short duration of current flow made possible a reduction in valve element size.

Improvements made in the early 1960's included the use of porous gap plate material to increase arc cooling, and the use of gap electrodes configured to reduce the tendency of high current arcs to "stick," or fail to move from the point of arc initiation. The significance of the improvements was that the improved arresters limited current in circuits capable of delivering high fault current; they also limited current in switching surge operations. The gap improvements made possible operations under severe conditions without change in gap sparkover. Development of preionizing arrangements capable of adequate ionization on long wave fronts as well as on short wave fronts, and development of gap triggering techniques, made possible controlled and low sparkovers on slow front switching surges. As a result, a generation of arresters provided switching surge protection for apparatus for the first time. Three step reductions in insulation strength at system voltages of 230 kv and higher became reasonably common.

In the 1950's, arrester failures caused by external contaminants, such as salt or industrial pollutants, began to appear with frequency sufficient to cause the phenomenon to be investigated. A number of measures including increasing arrester grading current, modifying sparkover circuitry, and increasing the creep lengths of housings were implemented. It was found that the use of a single housing instead of multiple housings reduced the effect of external contaminants to some degree by eliminating paths for transfer of external leakage current to the interior of the arrester through the metal and fittings of the multiple housings. In addition, a significant reduction in arrester height, to be discussed later, made single housings more economical than multiple housings of sufficient creep to withstand the effects of contaminants. For these reasons, most if not all current limiting gap arresters for use at system voltages up to and including 345 kv were made using single piece housings.

Most of the arresters manufactured prior to 1960 were used at relatively low transmission voltages such as 115 kv. These arresters were usually in multiple housings, and the height per kv of rating was typically one inch or more. Arresters for system voltages of 230 kv or 345 kv required some sort of external support arrangement. Because the demand for arresters for higher voltage systems was becoming greater, some reduced height and larger diameter arresters were built prior to 1960 to be self supporting at the higher voltages. However, the reduction in size of internal elements made possible by the use of current limiting gaps in addition to the use of one piece housings, made all arresters designed for service at 345 kv and lower self supporting. Current limiting gap arresters made in the middle 1960's were about 40 percent of the height of arresters made in the middle 1950's.

Violent failures of arresters, although infrequent, could cause severe damage to nearby equipment in stations. Most arresters were designed with some arrangement to vent the internal pressure resulting from failure of the internal elements, but these arrangements were generally not effective at fault currents experienced on systems after about 1950. Tests were standardized in the 1960's to show the level of fault current that an arrester could withstand without violent housing failure and minimum values were specified in the standard. As would be expected, it was found to be extremely difficult to obtain high pressure relief ratings for arresters for 345 kv systems in single housings which were often more than 12 feet long. Fortunately, surveys of systems indicated that fault currents at 345 kv were lower than the currents at lower voltages and were lower than the expected currents at higher voltages. This allowed the minimum pressure relief current for 345 kv system arresters to be set at 25,000 amperes rms symmetrical, and at 40,000 amperes or higher for other ratings.

Five Hundred and Eight Hundred KV Systems

In the mid 1960's, it became apparent that 550 kv would become a reasonably common transmission voltage, and 765 kv was also being introduced. Because the performance of current limiting gap arresters at the lower voltages was excellent, the same technology was employed at the higher voltages with some important modifications:

1. The arrester heights were too great to permit the use of single housings; therefore, multiple housings with increased external creep were generally used. Shorter housings allowed a substantial increase in pressure relief capability over the single housing capability at 345 kv.

2. Protective levels were reduced from the previous levels at lower voltages. To control sparkovers, even with the increased external creep, it became necessary to treat each arrester section as part of the whole arrester rather than a separate entity. For this reason, the units or sections could not be used as lower voltage arresters.

3. Switching surge energy increases approximately as the square of the system voltage while arrester rating increases as the first power of the system voltage; therefore, 550 kv and 765 kv arresters required higher energy discharge capability than arresters designed for lower voltage systems. Furthermore, it was shown that it was necessary to limit the gap voltage to switching surges because: Voltage at the arrester = Surge voltage – (Current x surge impedance).

When the current was limited too much on switching surges, the protective level (voltage at the arrester) became too high. This problem was more severe at 550 kv and 765 kv because surge impedances were lower than at lower voltages.

The combination of higher energy at high voltage and the need for the valve elements to absorb most of the energy led to the use of extra valve elements that could be shunted by gaps at high currents. After some experience at 550 kv and 765 kv, the levels of switching surges specified by users were reduced, and the lower surge levels in combination with valve element improvement made it possible to eliminate the shunted sections.

It was shown that the triggered gaps used to provide low and controlled sparkovers were so stable that they would not restrike even when subjected to overvoltages in the range of l.25 times arrester rating after a high energy arrester discharge. This capability, subsequently extended to lower voltage arresters, permitted a considerable simplification of arrester applications on many systems.

1976 to present: Zinc Oxide Arresters

Production of zinc oxide valve elements capable of withstanding system voltage without series gaps began in 1976. The valve elements, made of zinc oxide with a number of additives to produce desired characteristics, are in the form of disks with the cross sectional area approximately proportional to the energy the disk must dissipate in a high energy operation, and the length approximately proportional t5o the voltage rating assigned to the disk.

For valve elements 3 inches in diameter, a current change of five orders of magnitude, 0.1 amperes to 10,000 amperes, results in a voltage increase of approximately 50 percent. Energy dissipating ability on a volume basis of a zinc oxide valve element is more than twice the discharge capability of a silicon carbide valve element and series gap. That is, a 3 inch diameter set of zinc oxide valve elements about 2.1 inches tall can dissipate about as much energy as a 3 inch diameter silicon carbide valve element and a current limiting gap *each* 2.2 inches tall.

Protective margins of silicon carbide arresters with current-limiting gaps were cvonsidered adequate on 8/20 current waves; therefore, the zinc oxide arrester discharge voltages were set at approximately the same level. Because of the moderate changes in discharge voltages of zinc oxide disks with current magnitude and wave shape, protective margins on fast fronts and on switching surges are improved over the same characteristics of silicon carbide arresters.

With the need for series gaps eliminated and with the voltage grading provided by the zinc oxide valve elements, it became possible to use multiple housings having reasonable creep lengths at all voltage levels. Because the housings are relatively short, zinc oxide arresters are usually designed for pressure relief ratings of around 65,000 amperes rms symmetrical.

Heights have been reduced by only about 10 percent compared to silicon carbide arresters because of external flashover limitations. However, the reduced housing diameters made possible by the small size of the internal elements have resulted in a weight reduction of about 50 percent.

It is not possible to compare the arresters of 100 years ago or even 50 years ago in detail because of differences in testing techniques and differences in the way in which the information is recorded. However, an approximate table of sparkovers, discharge voltages, and arrester height is shown in Table 1.

(Please turn to page 40)

General Chairman, 1992 IEEE Fifth Conference on Human Factors and Power Industry, c/o Westinghouse R&D Center, 1310 Beulah Road, Pittsburgh, PA 15235. Phone (412) 256-2682

July-August 1992, First World Congress for Electricity and Magnetism in Biology and Medicine. Contact: William G. Wisecup, 120 West Church Street, Suite 4, Frederick, MD 21701. Phone (301) 663-1915.

August 30-September 1, 1993, Athens Power Tech, Joint International Power Conference NTUA and IEEE/PES, on planning, operation, and control in today's electric power systems will be held in Athens, Greece. Contact: B.C. Papadias, Conference Chairman, Department of Electrical Engineering, National Technical University, 42 Patission Str., Athens 106 82, Greece. Phone +(301) 3600.551 or 3605.604. FAX +(301) 3626.792. Telex 221682 NTUA GR.

Technical Committee Meetings

The following Technical Committees meet at the Winter and Summer Power Meetings. Consult the inside front cover for meeting dates.

Electric Machinery, D.K. Sharma, EPRI, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303. (415) 855-2302

Energy Development and Power Generation, P.A. Lewis, Public Service Electric and Gas, 80 Park Plaza, T16A, P.O. Box 570, Newark, NJ 07101. (201) 430-6634. This Committee also meets at the JPGC Conference.

Power Engineering Education, R.P. Webb, School of Electrical Engineering, Georgia Institute of Technology, Atlanta, GA 30332. (404) 894-4808.

Power System Communication, G.L. Nissen, Los Angeles Department of Water and Power, 1216 West First Street, Los Angeles, CA 90026. (213) 481-6788.
1991, September 23-27, T&D Conference, Dallas, Texas
1992, October 14-16, Orlando, Florida

Power Systems Engineering, L.L. Grigsby. Department of Electrical Engineering, Auburn University, Auburn, AL 36849. (205) 887-1823.
Power System Instrumentation and Measurements, T.R. McComb, Division of Electrical Engineering, National Research Council, M-50, Montreal Road, Ottawa, Ontario, Canada K1A OR8.

Standards Coordinating, T.R. Whittemore, U.S. Bureau of Reclamation, P.O. Box 25007, DFC D-3772, Denver, CO 80355.

Transmission and Distribution, J.H. Mallory, Southern California Edison Co., P.O. Box 800, Rosemead, CA 91770.

The following committees meet as indicated:

Power Engineering Society ExecBd
1991: Spring, Mexico City; Summer, San Diego, California; Fall, Dallas, Texas
1992: Winter, New York; Spring, Florida; Summer, Seattle, Washington; Fall, Houston, Texas
1993: Winter, Columbus, Ohio; Spring, Indianapolis, Indiana; Summer, Vancouver, British Columbia; Fall, Phoenix, Arizona.
The ExecBd always meets at the Winter and the Summer Power Meetings, usually on Thursday of the meeting week. Consult inside front cover for WM and SM dates.
Insulated Conductors, R.H.W. Watkins, Anixter Bros., Inc., 4711 Golf Road, One Concourse Plaza, Skokie IL 60076. Phone (312) 677-2600.
1991, November 3-6, Don Cesar, St. Petersburg, Florida
1992, April 24-30, Empress, Victoria, British Columbia, Canada
1992, November 8-11, Don Cesar, St. Petersburg, Florida

Nuclear Power Engineering, N.S. Porter. Washington Public Power Supply, 3000 George Washington Way, P.O. Box 968 Ms 981c, Richland, WA 99352. Phone (509) 377-8640.
1991, September 25-26, Charleston, South Carolina
1992, March 11-12, Tucson, Arizona
1992, September 23-24, New Orleans, Louisiana

Power System Relaying, J.A. Zulaski, S&C Electric Co., 6601 N. Ridge Boulevard, Chicago, IL 60626.

1991, October 7-11, Terrace Garden Inn, Atlanta, Georgia
1992, January 13-16, Hilton Resort, San Diego, California
1992, May 11-14, Westin Hotel, Denver, Colorado
1992, September 14-17, Wyndham Center, Milwaukee, Wisconsin
1993, January 11-14, The Monteleone, New Orleans, Louisiana

Substations, P.R. Nannery, Electrical Engineering, Orange and Rockland Utilities, One Blue Hill Plaza, Pearl River, NY 10965.
1991, July 28-August 2, Summer Power Meeting, San Diego
1992, February 2-6, Winter Power Meeting, New York
1992, May 3-7, Charleston, South Carolina
1992, July 12-17, Summer Power Meeting, Seattle, Washington
1993, April-May, Atlanta, Georgia

Surge Protective Devices, J.C. Osterhout, Operations Manager, Joslyn Corp., 9200 West Fulleton Avenue, Franklin Park, IL. Phone (312) 625-1500.
1991, September 30-October 4, Marc Plaza Hotel, Milwaukee, Wisconsin
1992, April 27-May 1, Sheraton Old Town, Albuquerque, New Mexico
1992, September 21-25, Allis Plaza, Kansas City, Missouri
1993, April 26-30, Sheraton Hotel, Charleston, South Carolina
1993, September 20-24, The Cour d'Alene, Cour d'Alene, Idaho
1994, April 25-29, Omni International, Norfolk, Virginia
1994, September 19-23, Pittsburgh, PA, Hyatt Pittsburgh
1995, April 24-28, Costa Mesa, CA, Westin South Coast Plaza

Switchgear, D.G. Kumbera, Cooper Power Systems, South Milwaukee, WI 53172. (414) 762-1200.
1991, May 6-9, Yankee Trader, Ft. Lauderdale, Florida
1991, September 30-October 3, Vancouver, British Columbia, Canada

Transformers, R.A. Veitch, NEI Ferranti Packard, Dieppe Road, P.O. Box 548, St. Catharines, Ontario, Canada L2R 6W9.
1991, November 3-6, Baltimore, Maryland
1992, March 29-April 1, Birmingham, Alabama
1992, October 18-21, Cleveland, Ohio

Sakshaug *(continued from page 13)*

Table 1.
Change in Protection 1930-1985

Year	Rating kv rms	Sparkover kv Crest		Discharge Voltages On 8/20 Waves kv Crest		Switching Surge PL kv Crest	Height Inches
		Front of Wave	1.2 x 50 or 1½ x 4	5 k	10 k		
1930	161			870	1000		224
1945	195	688	624	640	704		224
1954	195	542	449	496	544	507	224
1965	192	560	460	382	427	453	98.5
1975	192	538	427	382	427	426	98.5
1985	192	509	—	426	450	372	89

As illustrated, the development of the surge arrester technology has allowed significantly lower protective levels with each new generation of arrester. Modern arresters now protect terminal insulation and, in some applications, transmission line insulation. Arresters are applied at all voltage levels, including UHV, and offer consistent reliable protection against a spectrum of lightning and system overvoltages.