IMPROVED TRANSMISSION LINE PERFORMANCE USING POLYMER-HOUSED SURGE ARRESTERS

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1. INTRODUCTION

The energy industry is under rapid privatisation all over the world. Users are free to purchase energy from different utilities. For some industries price is the strong motivation; for others it is security and reliability of supply.

Preventive maintenance, application of arresters and redundancy increase the reliability of substation equipment. Supply interruptions, therefore, are mainly related to faults in transmission of power by aerial lines. The traditional methods for improving transmission line reliability without using surge arresters are

- Automatic re-closing after transient faults
- Earthing and/or shielding upgrade
- New or redundant supply lines
- Controlled switching (lines & capacitors banks)

To cater to the newer, tougher business climate, which may include large compensation claims for interruptions, utilities will be forced to invest additionally in one or more of the following methods employing surge arresters as a vital measure

- Extended substation protection
- Compact-insulation lines
- Switching surge overvoltage control
- Lightning protection for line insulation

This paper discusses in greater detail the role of arresters in improving the reliability of supply over HV transmission lines, the desirable electrical and mechanical characteristics for such arresters and accessories and ABB's designs to obtain such characteristics using polymeric arresters without any external gaps.

2. NON-ARRESTER APPLICATIONS

2.1. Automatic Re-closing

Automatic re-closing (both single-phase and three-phase) minimises interruptions in supply for transient faults and has been the most common method employed for increased reliability. However, some process industries may not tolerate outages even of short duration. The situation is made more complex by the pervasive use of computers for most processes and for many other applications in banking, airlines and similar industries. Further, circuit-breaker maintenance increases and that needs additional resources including planned outages.

2.2. Earthing/Shielding Upgrade

A considerable number of transmission lines have not been provided with overhead shield wires for their entire length. Many have no shield wires at all and most have limited lengths - 1 to 2 km from sub-stations - to reduce the probability of a direct lightning stroke on the phase conductors near the sub-stations. For system voltages up to 145 kV, shield wires may not serve the intended purpose, except marginally, due to the relatively low insulation of such lines. For higher voltages, there could be a considerable reduction in line interruptions by the installation of a new shield wire along the complete length of the line. However, this is often quite expensive, as the towers may need to be modified or strengthened - unless such a contingency has been visualised at the design stage.

A high tower footing impedance increases the occurrence of backflashes and hence interruptions. Reduction of the impedance helps in reducing outages due to backflashes. Once again, however, it may be difficult and/or prohibitively expensive to obtain better earthing at some tower sites.

2.3. New/Redundant Supply

In many countries this approach to a more reliable supply is fraught with long delays and litigation, as the general public is no longer willing to see the countryside scarred further by new rights-of-way. It is also a very costly alternative. For extremely demanding clients, who are willing to share the burden, this may be a viable alternative.

In this connection, compact-insulation lines may be mentioned. Please see paragraph 3.2 hereunder.

2.4. Controlled Switching

Controlled switching is the method of switching each pole of a breaker individually at the optimal point-of-wave to reduce the switching overvoltages. This is achieved by special control circuits that initiate closing commands based on information from the system and the characteristics of the circuit breakers. One such example is the SWITCHSYNC equipment manufactured by ABB [1]. Additional information is available in [2] and [3].

For long transmission lines, the traditional method employed to minimise overvoltage during switching-in has been to use pre-insertion resistors. While they serve the intended purpose very well, they demand frequent adjustment and maintenance and hence there is a trend to replace them by arresters.

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3. TRANSMISSION LINE ARRESTER (TLA) APPLICATIONS

When arresters are employed for the protection of transmission lines and their hardware, they are termed TLA to differentiate them from the standard substation (s/s) arresters. Polymer-housed arresters dominate this field by virtue of their non-fragile and lightweight construction.

3.1. Extended S/S Protection

Lines should be shielded for at least a km or two from a substation to reduce/eliminate direct lightning strokes to the phase conductors very close to the station. However, backflashes may still occur. The installation of arresters on the last towers(s) prior to the line entering a station helps in greatly reducing, if not eliminating, this risk of an excessively fast or steep impulse from entering the station. This method of protection is effective for GIS switchgear, which is very sensitive to such impulses. It reduces also the need for expensive GIS arresters, which are often 6 to 8 times as expensive. Polymer-housed arresters can be hung on the line directly and need no structures, making them ideal for an already overcrowded s/s and for retrofits. Figure 1 shows such an arrester for a 420 kV station in the Middle East. Note the extreme creepage leading to a very long arrester which would have been very expensive if it was pedestal-mounted and/or porcelain-housed.

Figure 1

3.2. Compact-insulation lines

Increased power flow on existing transmission line may be achieved by increased transmission voltage. Arresters are employed to work within the available clearances and to permit the use of the existing BIL of the insulators. To reduce the right-of-way in case of new line, compacting the insulation as above may be necessary. As one of many examples, reference is made to [4] which describes an innovative method of using TLA for compaction of a 400 kV line.

3.3. Switching overvoltage control

The switching overvoltage profile along a long high voltage transmission line can be manipulated by the provision of surge arresters at the ends of the line and additional arresters at different points along the line. Polymeric arresters are ideally suited for this purpose as they may be installed directly on the conductors or under the insulators at the relevant towers without the need for building a mini substation.

The subject is dealt with in detail in[5] and [6] and is mentioned here only for completeness.

3.4. Lightning protection

This application is described in greater detail in this paper since the most frequent cause for line trips is due to lightning strikes on the line or nearby it. In this connection, it is useful to have the best available data regarding the isokeraunic activity along the line so that TLA protection could be optimised. Such data is now available on national basis in many countries.

The following remarks may be taken as a general guide to the application of TLA.

General

Collect available records of lightning activity along the line and interruptions due to it. Note the topography along the line to locate particularly exposed towers and line sections.

Note the footing impedance at each tower, especially along the more-affected sections.

Note the present and the desired outage rates. The desired outage should not be unrealistically low (approaching zero) as this may lead to provision of a very large number of very heavy energy arresters leading to an uneconomic solution

Shielded lines

For shielded lines, backflashes are the major cause of interruption and these occur mostly at tower locations with high footing impedance. Note that for such locations, the risk of flashover is not reduced significantly unless TLA are placed in all phases. See Figure 2. Hence, target such sections for protection in the first instance.

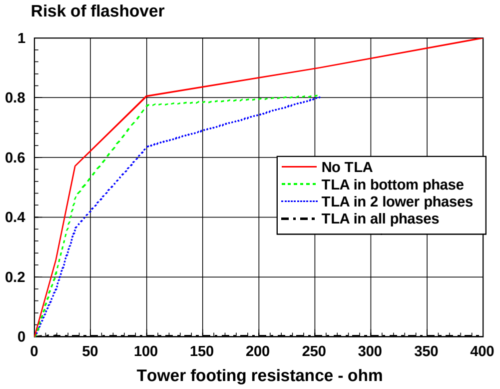

Figure 2. Protection of different number of phases for a triangular line configuration, LIWL 750 kVp

The arrester energy must be considered w.r.t. both the strokes to towers and shielding penetration. For high tower footing impedance (approx. 100 ohm and above), the stroke to the tower is the dimensioning criterion while shielding penetration will be the major factor to be considered for low footing impedance (under 100 ohm). Figure 3 shows the energy requirements for TLA on a 275 kV line, which is effectively shielded with two overhead ground wires. The calculations are made for a protected line section with arresters in 23 towers, rated voltage 228 kV, LIPL 536 kVp with the following assumptions:

- **Stroke to tower** with a probability of the charge and current to be exceeded of 0.004 per flash approximately corresponding to once in 25 years for a ground flash density of 8.
- **Distant shielding failure** with a probability of the charge to be exceeded of 0.4 per flash corresponding to once in 25 years for a shielding penetration rate of 0.1 per year for the complete line. Stroke current is limited to 10 kAp due to line insulation.
- **Close shielding failure** with a probability of the charge to be exceeded of 0.8 per flash corresponding to once in 25 years for a shielding penetration rate of 0.05 per year for the protected line section. Stroke current is set to 20 kAp, which is assumed as maximum current for shielding failure.

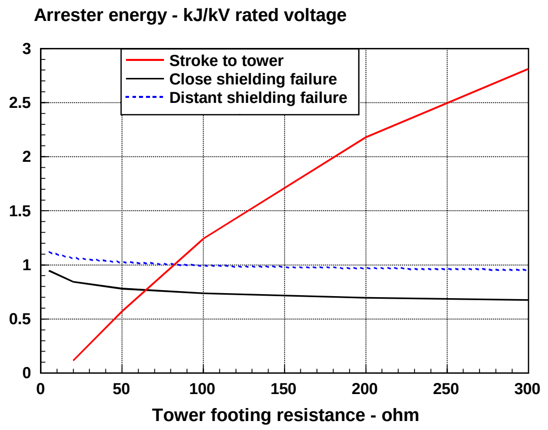

Figure 3

The probability distribution for lightning parameters (amplitude and charge) are taken from [7], [8] & [9]. The study shows that, for a well-shielded line, higher energy class arresters are required only for towers with high footing impedance.

Strokes to the towers (for both shielded and unshielded lines) result in high energy if the footing impedance is high and vice-versa. However, there is a good sharing of charge/ energy in the arresters in different phases.

Unshielded lines

Due to the absence of the shield wire in unshielded lines, direct strikes to phase conductors must be considered seriously. For such strokes, a high tower footing impedance results in lower energy and vice versa. Also, sharing between arresters is poor since a max. of two arresters are present in the same phase in the adjacent towers.

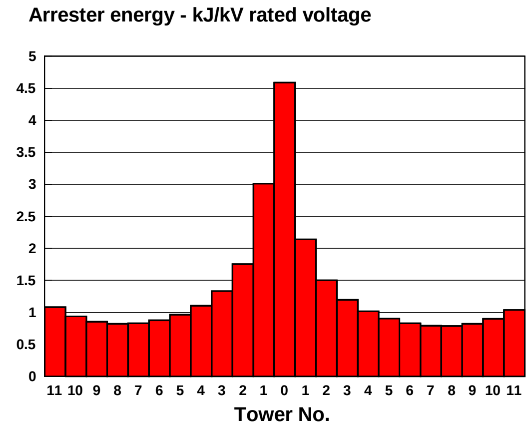

Figure 4.

Figure 4 shows the distribution of arrester energies for a case with lightning stroke to phase conductor ¼ span length from a tower. The line is unshielded, with continuous counterpoise and tower footing resistance of 150 ohm. The arrester LIPL is 423 kVp at 10 kAp. Lightning stroke is 54 kAp and charge 17 As corresponding to a probability of 0,2 of its being exceeded. The calculated energy lies in the range of capability of an IEC class 3 arrester.

The above and other similar studies show that arresters with IEC line discharge energy classes 1 to 2 (sometimes class 3) are suitable for shielded lines. On the other hand, unshielded lines, especially in high lightning areas, need arresters with a greater energy capability (class 3 and 4) if a low failure risk is needed.

An interesting observation for such lines is that arresters with a lower energy class could protect the non-exposed phases (e.g. the centre-phase of a flat line configuration). However, since the mechanical strength of a polymer-housed arrester is generally related to its electrical capability, the lower class arresters may not be suitable mechanically.

Double-circuit lines

For increased power supply in limited right-of-way, two (or more) circuits are strung on the same tower or on adjacent lines close to each other. In such a case, to maintain supply continuity and avoid risk of system instability, double-line faults should be avoided.

This is not easy to achieve without arresters especially when the grounding conditions are difficult (e.g. mountainous areas). However, with TLA employed in at least one of the circuits, not only are the double-circuit faults eliminated (with arresters in all phases of one circuit) but also the lightning performance of the other circuit is improved. This is illustrated in Figure 5 which shows the risk of double-circuit and single-circuit faults for line section with towers with two 400 kV circuits. Calculations were made for lightning conditions with a ground flash density equal to 1.0. Towers were modelled with high footing impedance.

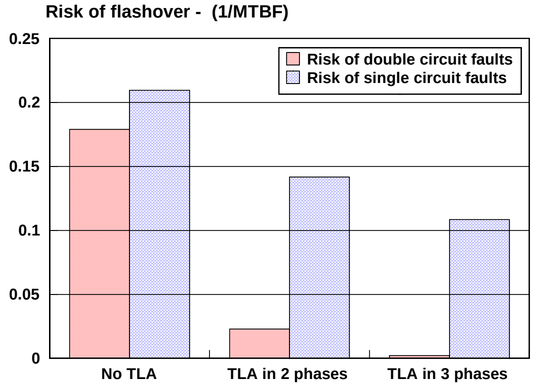

Figure 5

4. TLA CHARACTERISTICS

One basic requirement for arresters, in general, is good protection of other equipment (with sufficient margin). This is somewhat in contradiction with the other basic requirement of high reliability during a long service life, i.e. the ability to withstand

- Continuous operating voltage (Uc)
- Temporary overvoltages (TOV)
- Energy & current stress due to overvoltages
- Varying ambient conditions (solar radiation, temperature, wind, rain/snow, and pollution)
- Mechanical forces (terminal, wind & snow, seismic)

4.1. Electrical Characteristics

For arresters located in sub-stations, the protection performance is more vital and the current and energy stresses from lightning are comparatively low. For TLA, the situation is reversed.

It is not permitted to disconnect the s/s arresters automatically in the event of their being overloaded since the insulation of the substation equipment is generally non self-restoring and should not be re-switched in without protection. On the other hand, automatic disconnection of TLA is necessary to permit recharging of the line without delay as soon as the transient fault disappears. (The line insulation is generally self-restoring).

4.1.1. Protection levels

In general, the lightning impulse withstand level (LIWL or BIL) of the insulator strings is higher than the LIWL of station equipment and this permits choosing an arrester with a higher rated voltage (Ur) with its attendant advantages of higher energy capability and better TOV capability. This may be sufficient, sometimes, to avoid using more expensive arresters of a higher energy class. At the same time, since we are dealing with steeper-fronted impulses with larger amplitudes, it is necessary that the arresters are mounted close to the insulator or the benefit of a higher U_r should be given up to maintain a good protection margin.

4.1.2. Energy capability

The energy capability tests in the present standards are related to station arresters and consist of high current, 100 kAp (65 kAp as per ANSI) fast-front impulses, 4/10 µs, and low current, long duration impulses represented by the line discharge parameters.

Various studies, [10] [11], claim that the energy impulse wave-shape in lightning is better approximated by a medium current, medium duration impulse typically represented by 10 to 30 kAp, 200 µs, ½ sine wave. An energy test with these parameters has been proposed [12] and is under consideration in the relevant IEC working group.

The quantities of TLA involved for such applications are normally quite large. Hence the required energy capability must be computed more accurately to avoid having to purchase higher-than-necessary-class of arresters.

4.1.3. Short-circuit capability

Unlike station arresters, TLA are subject to higher and more frequent lightning impulses. They are also placed in exposed areas with a higher possibility of damage or injury to other material or persons should they not be short-circuit safe. The ABB design caters specifically to this need as will be evidenced by the arresters' description in chapter 5.1.

4.1.4. Climatic considerations

Along a long transmission line, the climatic conditions may vary widely and violently. The TLA cannot be inspected easily or often. Hence, they must be highly pollution- and flashover-resistant and care must be exercised in choosing suitable creepage and material. Silicon rubber has shown itself to be the ideal for such application by virtue of its excellent hydrophobic and UV-resistant [13].

4.2. Mechanical Characteristics

Since TLA are employed on towers and along the transmission lines, they must be light and non-brittle. Except for special installations where the arresters are located in guarded areas, the possibility of using porcelain-housed arresters is ruled out. Hence, only polymer-housed arresters are considered here.

Most TLA are hung under the line insulators or on the conductors or on cross-arms of towers. By employing a moment-free coupling, the mechanical forces can be reduced greatly and this also favours the use of polymer-housed arresters.

Any replacement of overloaded or failed arresters should not result in a line outage for any significant period. Hence, many utilities prefer hot-line maintenance for such arresters. For these applications, special hardware needs to be provided.

5. THE PEXLINK CONCEPT

The ABB family of silicone polymer-housed surge arresters, PEXLIM, is the basic component of the ABB TLA. The concept, termed PEXLINK and illustrated in Figure 6, uses the PEXLIM arresters with suitable disconnectors and hardware (including insulators in some cases). In this way, standard components are used for widely different applications.

ABB has chosen to use only silicone polymer composite material for all the HV equipment as experience and research has shown the same to be the most suitable material for long and stable lifetime in all conditions. This view is shared to a large extent now by many other manufacturers and utilities all over the world.

Figure 6

5.1. Arrester Design

ZnO blocks are manufactured in a highly automated factory under precise control and testing at each stage. The blocks have very low power losses and a low residual voltage related to the rating.

The blocks are housed in a “module”, which is a cage formed of fibreglass loops placed on yokes at each end. The assembly is kept under heavy compression to maintain good contact between the blocks up to the recommended maximum useable bending moment. Additional loading is permitted under dynamic conditions and is taken care of by a special pivot in each module.

Special aramide fibres are wound on the module. Their purpose is to prevent any large pieces from bursting out of the cage through the housing at severe short-circuit conditions. See Figure 7**.**

The silicone polymer is specially prepared and consists of silicone with some "fillers" to impart the desired qualities. The polymer housing is directly moulded (vulcanised) on the module under high temperature and vacuum so that no air is trapped inside and hence there is no p.d. under service conditions. The module is also effectively sealed without the need for any gaskets. The process is known as high-temperature vulcanising (HTV).

The arrester is built-up of modules of different ratings (lengths) and completed with the required grading rings (where needed) and hardware to suit the application. The arresters have been tested as per relevant IEC stipulations and meet also the ANSI standard.

Figure 7

5.2. Disconnector Design

TLA are more exposed to heavy lightning strikes and energy than station arresters. Further, TLA are geographically widespread and often located in terrain not accessible easily or quickly. In the event of an arrester failure, therefore, it must be automatically and quickly disconnected so that the line can be charged again automatically. This is achieved by inserting an automatic disconnecting device in series with the arrester.

The TLA disconnector is different from the one used with distribution arresters in that it must withstand higher impulse currents (that are within the arrester capability) compared to the disconnectors for distribution arresters. Spurious operations will reduce overall reliability and confuse the maintenance staff as to the health of the disconnected arrester. The TLA disconnector, therefore, needs to be tested differently as suggested hereunder:

- High current, 4/10µs: 2 impulses, 130 kAp
- Rectangular, 4 ms: 20 impulses, 3 kAp
- Half-sinusoidal, 200 µs: 6 impulses, 25 kAp

The power frequency current characteristics for such a disconnector are shown in Figure 8. The type A disconnector is normally used with TLA while the type B disconnector is normally used with distribution arresters. If the fault current is less than approx. 2 kAp (which may be the case with high-ohmic systems), the type A characteristic may not be satisfactory. Presently the type B disconnector is used in such cases and some spurious operations are tolerated. For such low fault currents, a suitable TLA disconnector, incorporating the two conflicting requirements, needs to be developed.

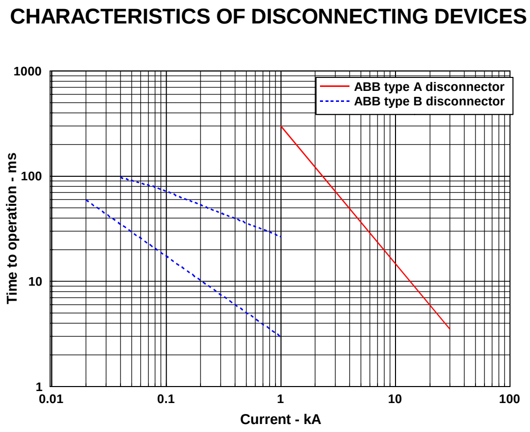

Figure 8

5.3. Hardware

The hardware is selected from standard, easily available equipment and depends on the configuration. Hardware for hot-line insertion and removal of TLA, however, is of special design.

Special attention should be paid to the earth-lead. It should be of sufficient cross-section to accept the system fault current yet small enough to present a low wind resistance and not load the arrester. It should also be flexible enough so that it is does not break by mechanical fatigue due to swinging in the wind

6. INSTALLATION OF TLA

The installation alternatives are many and varied and depend on the line and tower profiles [14]. They have their advantages and disadvantages. Some common alternatives are

1. Vertical mounting, hanging under the line.
   The advantages are simplicity of mounting with standard hardware and a very reliable disconnection function. If the connection is moment-free, there are the added advantages of low load on the line and low bending stress on the arrester. A fixed connection is cheaper but loads the line and stresses the arrester to larger values and this may outweigh the lower costs of the clamps and other hardware.

   Under extreme wind conditions and a disconnected arrester, there is a probability of a flashover between the arrester and the tower. This risk is lower for moment-free installation and can be reduced further by adding weights under the arrester.

2. Vertical mounting, hanging on the cross arm of the towers.
   If the cross arms are sufficiently long, this is a good alternative with all the advantages as above. Further, the line or insulators are not loaded. To avoid the possibility of a flashover to the tower from a disconnected arrester at high winds, the mounting on the outside of the insulator suspension point is preferred.

3. Angular mounting on the tower or a lower cross-arm.
   Once again, this is a simple mounting. A steel bracket is fixed to the tower and the arrester is attached to this bracket. However, the arresters must withstand high bending loads during strong wind and ice load conditions. The dead weight of the arrester adds to the bending load on the arrester.

4. Parallel mounting with insulator.
   Due to the fact that the arrester must be mounted at an angle relative to the insulator to ensure safe disconnection, the hardware will be relatively complicated and may be expensive. This concept applies a lot of stress on the hardware. In some cases of strong wind, the disconnection of the arrester will be more or less impossible because the wind will press the arrester towards the insulator and it will not disconnect. If these limitations are dealt with, the concept is a relatively simple one.

Some general remarks apply as follows:

- Sufficient clearances must be achieved under normal conditions and for "design" wind speeds and ice loading in order not to increase the risk for phase-to-ground or phase-to phase flashover.

- For an arrester which has failed and has been disconnected, the clearance must be at least the same as the flashover distance for the line insulators considering normal conditions as well as "design" wind speeds and ice-loading.

- Even though transmission line arresters often are mounted moment-free vertically hanging under the line, they occasionally face substantial loads from ice, snow and wind (e.g. during helicopter inspections). Therefore, an arrester and its hardware should be able to withstand them. For voltages of 145 kV and above, the recommended minimum strength is 700 Nm statically and 1500 Nm dynamically. A heavier tensile strength is also recommended; typically of the order of 5000 N.

- The disconnector device is often mechanically weak. Hence, the conductor connecting the arrester to ground or phase must be sufficiently long to ensure that the arrester and/or the insulator can swing around without interference from the wire. If the conductor is too short, there is a risk that the disconnector device may break off and appear to have electrically disconnected at a subsequent field inspection.

7. CONCLUSIONS

a) Transmission line surge arresters (TLA) offer a robust, efficient and cost-effective alternative for minimising/eliminating outages due to lightning surges and for limitation of switching surges along transmission lines.

b) The energy requirements for TLA applications vary based on applications. Compared to s/s arresters, it is higher for TLA used for lightning protection. The station arrester placed at the open line end will see a higher energy than TLA used for switching control.

c) Energy capability for lightning TLA cannot be judged correctly based on present standard tests and a new test has been proposed to cater to this application.

d) Energy requirement for TLA for shielded lines is generally met by arresters of IEC line discharge class 1 or 2 (or 3 in some cases).

e) Unshielded lines demand higher energy capability; often line discharge class 3 or 4.

f) Double-circuit line outages could be eliminated by proper use of TLA on one of the circuits.

g) Mechanical strength is often a function of block size and hence energy capability. Since the mechanical demands may be decisive in many cases, a higher-energy arrester is automatically obtained and gives a safety margin.

h) Polymer-housed high-energy transmission line surge arresters suitable for lightning and switching TLA applications are available for all HV & EHV systems up to and including 800 kV.

i) Application of TLA opens up the possibilities for compacting lines and upgrading of existing lines.

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9. AUTHORS

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Lennart Stenström was born in Sweden in 1951. He received a M.S. degree in Electrical Engineering from Chalmers University of Technology, Göteborg, Sweden, in 1975. From 1975, he has been with ABB, working on metal-oxide surge arrester design, development and application. He is a member of IEC working groups dealing with surge arresters and their applications. He is also, since many years, secretary of CIGRÉ WG33.11 "Application procedures for station and overhead line insulation co-ordination. He has authored and co-authored several technical papers. He is a member in IEEE since 1986.