Introduction

A growing demand for power has resulted in the need for an increase of transmission capacity and power quality. Many developed countries cannot afford to build new overhead transmission lines (OHLs) due to systematic public opposition and environmental considerations. It becomes necessary for them to “uprate” the existing power systems. In many cases, even though the public authorization is granted, line designers and utilities are requested to create new concepts of transmission structures in order to reduce footprint and visual impact. Line Compaction and Line Uprating involve the need to review conventional ratings and standard designs which apply for decades.

The latest developments of composite insulators and surge arresters allow compact line designs as realistic alternatives to the standard line designs for the utilities to build discrete and aesthetic line structures. Taking the surge arrester’s operating principle into consideration, structures’ clearances and insulator arcing distances can be significantly reduced and at the same time power availability can be improved. Conventional ratings, such as lightning and switching impulse withstand values of insulator assemblies can be coordinated with transmission line surge arresters to achieve advanced insulation coordination ratings. The integration of arresters will bring the Compact Line concept to the next level.

This paper describes, after a short introduction to the principles of transmission line surge arresters, the idea and the opportunities which can be accomplished for transmission line capacity and power quality optimization. The paper addresses also the main technical challenges which must be considered before the implementation of compact power system solutions.
1 Overvoltages and their mitigation by using surge arresters

The voltages which can occur in a high-voltage electrical power system are shown in Error! Reference source not found. where the different types of (over-)voltages (red-colored curve) versus duration of their appearance are summarized and compared to both, equipment’s (blue-colored curve) and arrester’s (green-colored curve) withstand voltages, respectively.

Figure 1: Schematic representation of the magnitude of voltages and overvoltages in a high-voltage electrical power system versus duration of their appearance (1 p.u. = \( \sqrt{2} U_s / \sqrt{3} \))

The red curve shows that the insulation withstand voltage of the equipment (blue-colored curve) is excessively exceeded in case of lightning and switching overvoltages. By using surge arrester these overvoltages are being safely reduced, as it can be seen in the green curve, which is below the blue-colored withstand voltage of the equipment to be protected [1].

Conventional application of station class arrester aims to protect valuable equipment in the substations as a local insulation for power transformers, entrance of substations, instruments transformers and gas-insulated switchgears. The application of Line Surge Arresters (LSA’s) serves a different purpose.

LSA’s prevent flashovers on insulator strings along the transmission line caused by lightning strikes. Installed on multi-circuit transmission lines, they are an excellent solution to eliminate any possible double-circuit failure. They can also be used on EHV ¹ lines to control switching surge factors.

The main commercial application for LSA’s is to improve the lightning performance on existing lines as retrofit activities. Such applications require to analyze the line parameters and investigate the environmental conditions in order to optimize the LSA’s configuration and their effectiveness.

¹ EHV: Extra high-voltage
Figure 2 shows schematically an example of a shielded transmission line equipped with LSA’s installed in parallel and next to the insulator strings to prevent a shielding failure since the lightning stroke hit directly the phase conductor.

There are the two basic scenarios to understand the principle of flashovers due to lightning activities. Back-flashover and Direct-flashover (also known as shielding failure).

**Back-flashover is when the lightning stroke hits the shielding wire or the tower top**

Insulator back flashover rates can be efficiently reduced in case of shielded overhead lines located either in high lightning activity areas or having poor footing resistance. These types of outages could be reduced by placing arresters in all phases or only on the phase(s) with lowest coupling factor to the shield wires which normally is the bottom phase in high footing resistance areas. In these areas, it is important to apply the arresters not only on structures in the areas of high footing resistances, but also on one or two structures with good (low) footing resistances right next to the high footing resistance areas. This will prevent flashovers at the low resistance structures caused by the arrester operations at the high footing resistance structures. The higher the footing resistance, the higher is absorbed energy by each individual LSA’s.

**Direct flashover is when the lightning stroke directly hits the phase conductor**

Insulator flashovers result from so-called shielding failures mostly observed on unshielded transmission lines and very infrequently in shielded lines that may experience lightning strokes directly to the high voltage conductor. For unshielded transmission/distribution lines, those direct lightning strokes to the phase conductors will be much more frequent than for properly shielded lines, since these lines are simply not protected (shielded) against lightning at all. In such cases, line arresters can also be used to address shielding failure flashovers by applying the arresters on the uppermost exposed phases.

Further system flashover cases induced by lightning strokes are observed on multi-circuit towers, i.e. on underbuilt distribution lines or on double-circuit transmission lines which generally leads to severe impacts on the whole transmission system.

**Double circuit outage reduction**

Line arresters can be used on double-circuit transmission lines to be installed on all three-phases on one of the double-circuit systems to prevent double-system failures. This approach can be effectively used for all system voltage rates, including EHV systems [4].
Underbuilt distribution lines

If a distribution line shares a tower or a pole with a shielded transmission circuit, the underbuilt distribution conductors are not likely to be struck directly, since they are actually shielded by the transmission circuit above. However, the distribution line is prone to back flashovers, because the coupling between distribution conductors and shield wires is weak.

The insulation strength on the distribution line is also lower than on the transmission line. Once a distribution conductor flashes over, the coupling to the transmission conductors will increase and minimize the risk of a back-flashover on the transmission circuit. The transmission circuit’s lightning performance may improve at the expense of the underbuilt distribution circuit’s lightning performance. This issue can be reliably avoided with application of line arresters on the underbuilt distribution circuit. Usually arresters are needed at every tower or pole, on at least one of the three phases.

2 different designs of LSAs are available with advantages and inconveniences:

- Non-Gapped Line Arresters (NGLA) also called gapless
- Externally Gapped Line Arresters (EGLA)

1.1 Non-Gapped Line Arrester (NGLA)

Non-Gapped Line Arresters, comparable to the station surge arrester, have a direct connection to the high-voltage conductor and on the other side they are grounded to the tower (see Figure 3 and Figure 4). A transmission line can be operated without LSA’s while a substation cannot be operated without station class arresters due to high risks and obvious reasons. Therefore, the NGLA are equipped with disconnecting device that immediately operates and galvanically disconnects the LSA’s from the system voltage in case of thermal overload and arrester fault. This allows the affected overhead line to be reenergized and further operated until the replacement can be scheduled in the next convenient time [3].

![Figure 3: NGLA hanging from the transmission line and grounded to the tower 500 kV](image1)

![Figure 4: NGLA mounted on the tower and connected with the lead to the transmission line 123 kV](image2)
1.2 Externally-Gapped Line Arrester (EGLA)

Externally-Gapped Line Arresters are defined by IEC 60099-8 as a lightning protective device consisting of two individual components – an active part called *series varistor unit* (SVU) representing the surge arrester part and an external gap in series, see Figure 5 [5].

![EGLA Diagram](image)

*Figure 5: Standard configuration of an EGLA [5]*

The main difference between the NGLA and EGLA is the external series gap, which isolates the SVU galvanically from the system as per Figure 6. The purpose of this “gapped” LSA’s is specifically to handle lightning overvoltages and extinguish the arc between the electrodes of the series gap within a half-cycle of the power-frequency voltage on the system. The surge current, which is flowing as a result of a controlled flashover in the gap, is called the *follow current*. It is the sum of the current flowing through the metal oxide varistors of the SVU and the pollution current on the SVU-housing. Since the follow current is limited by the metal oxide varistors to a very low level of several amperes the ignited arc is being extinguished and the follow current interruption acts within some milliseconds. There is no earthing fault caused in the system and hence, no necessity of a line breaker operation to eliminate any failure.

![EGLA Diagram](image)

*Figure 6: EGLA mounted inside of a suspension V-string in a 220 kV System*

The energy ratings of the MO-varistors are tested with the lightning discharge test to verify the repetitive charge transfer rating, Qrs, according to IEC 60099-8.
Furthermore, in the very unlikely event of an EGLA failure the series gap must withstand switching overvoltages of the system in order to be able to reenergize the transmission line. For this purpose, the switching withstand tests on the EGLA gap are being performed with a shorted SVU and under wet condition to verify the case that the transmission line can be operated further even with a failed EGLA.

Figure 7 shows schematically where the EGLA operational area is located between the lightning and switching levels of the system.

![Figure 7: Operating area of EGLA between Lightning and Switching voltages](image)

The dimensioning of the EGLA gap is essentially related to lightning and switching voltages. The maximum gap distance is limited by the minimum lightning impulse flashover voltage of the insulators and the minimum gap distance is limited by the maximum switching impulse withstand voltage of the transmission line.

![Figure 8: EGLA limits lightning impulse voltages in a suspension V-string configuration in 500 kV system voltage](image)

The reduction of the insulator string length and consequently the tower height is achieved by using preferably the EGLA design, due to its compact design in comparison to the NGLA. Since the EGLA is not continuously energized, the SVU requires less volume of MO-varistors, which is an advantage regarding weight, installation efforts and maintenance. The NGLA has a much larger size due to its
disconnector and associated ground lead, which may short-circuit the subjacent phases on the tower when falling down during an arrester overload (triggering of the disconnector). Furthermore, the substantial reduction in material for the EGLA design allows a more compact size and a better integration in the tower. It offers also a wide range of installation options.

The correct configuration of an EGLA includes the SVU ratings (energy rating, residual voltage, arcing distance), the dimensioning of the gap distance with respect to lightning- and switching voltages, as well as the mechanical design which differs often from the installation arrangement. Engineering efforts are required to integrate properly the EGLA into the structure. It can be installed on the cross-arms, on the structure or directly on the insulator string. The main requirement is to have stable gap distance under vibration and galloping of the line. New transmission lines offer generally more option than existing lines.

The main factors for the optimal dimensioning of a reduced insulator’s arcing distance are the min. creepage distance and the lightning impulse withstand voltage. The higher the system voltage, the more important becomes the switching surges, especially above 300 kV system voltages.

2 Reducing clearances by using EGLA

The insulator string’s length is conventionally defined by the minimum arcing distance of the insulators which is calculated from the required maximum lightning and switching impulse withstand voltages. The combination of an insulator string with an EGLA changes the common dimensioning approach, so that the arcing distance of the insulator or the lightning impulse withstand voltage of the string is not the decisive criteria anymore, but rather the lightning impulse spark-overvoltage of the EGLA air gap. The smaller the gap of the EGLA, the lower the operating lightning sparkover-(protective-)voltage of the EGLA, the shorter the necessary arcing distance of the insulator string, and finally, the shorter the needed insulator length. The lower limitation of the gap distance changes with the required switching impulse voltage. The correlation of EGLA gap (‘D’) and insulator arcing distance (‘L’) is shown on Figure 9 which is a result of testing experience over many years. The amplitude and shape of the curves depend on the insulator assembly configuration and the electrode shapes of the EGLA.

![Figure 9: Relation of EGLA gap distance to flashover distance of insulator](image)

Two exemplary illustrations of insulator assemblies with EGLA can be seen on Figure 10.
In order to obtain the most compact solution, the required switching impulse withstand voltage must be available. The lower the switching surge factor, the more compact the system can become. A typical 420 kV transmission line in Germany has a switching impulse withstand voltage level of 850 kV. The insulators have an arcing distance of 3 m. In combination with the EGLA, the arcing distance of the string can be reduced to 2.7 m which corresponds to a reduction of 10% on the insulator itself. This reduction factor applies to all circuits and all phases of a specific line as per Figure 11:
2.1 Simulation of switching performance of overhead lines

The reduction of switching surge factor on the transmission line is essential to achieve an efficient compaction or uprate of the transmission line, since it is the dimensioning factor for the lower limit of the EGLA gap distance. To determine the occurring switching overvoltages, the performance of an overhead line was simulated with a simulation tool (Sigma SET) and the following parameters [6]:

- Transmission line length: 100 km
- Line span length: 365 m
- Basic insulation level of line insulator: 1425 kV
- Closing time of a 420 kV circuit breaker: 65 ms

![Hypothetical model for analyzing the switching performance of a 420 kV transmission line](image)

The simulation results in a switching overvoltage of 3,12 p.u. \((1 \text{ p.u.} = \frac{\sqrt[3]{2} \times 420 \text{ kV}}{\sqrt{3}} = 343 \text{ kV})\) for the given exemplary transmission line without surge arresters at the substations. With the usage of station arresters in the beginning and the end of the line, the switching overvoltage can be limited to 1,84 p.u.

![Spatial distribution of magnitudes of overvoltage due to line re-energization along the whole length of a 420 kV transmission line of 100 km length with surge arresters rated voltage \(U_r\) of 336 kV at both ends](image)

| Table 1: Simulation results with exemplary transmission line in Sigma SET |
|---|---|---|
| Overvoltage / p.u. | SI voltage /kV (incl. safety margin 7,8 %) |
| without surge arrester in substation | 3,12 | 1153 |
| with surge arrester in substation | 1,84 | 664 |

The safety margin results in 7,8 % based on the factors Sigma and X according to IEC 60099-8:

With Sigma = 6 % and X= 1,3
With the switching impulse withstand voltage of 664 kV the EGLA has approximately a gap distance of 1.36 m. The correlating arcing distance of the insulator string is 2.1 m, which is compared to the initial arcing distance of 3 m a length reduction of 30% to the standard 420 kV transmission line. In theory it means that typical 245 kV strings can be used for 420 kV system.

Depending on the system parameters as line length, short-circuit ratings and voltage levels, the switching surge factor is generally mitigated and reduced with the help of closing resistors and/or shunt reactors. The station class arrester in the substation can also be improved by reducing their residual voltage and increasing their energy handling requirements. Anyhow, the most cost-efficient method remains the use of NGLA at few locations along the transmission lines. Simulations must be carried out to define the energy rating and their exact location.

In this specific simulation case, it is assumed that the line length is only 100 km which is limiting the factor for switching surges. Typical transmission lines for 245 kV and above are generally much longer and we might expect higher switching surges. Therefore, NGLA application for switching surge control becomes even more justified for longer transmission lines.

2.2 Further challenges
There is a clear opportunity to review conventional ratings and standard designs to achieve line compaction and line uprating. The potential of using EGLA to decrease the arcing distance of insulators and to increase energy availability is obvious but several important aspects should be considered and investigated before final solutions can be implemented.

The reduction of insulators’ arcing distances involves the increase of the creepage factor, e.g. by using new shed profiles and larger shed diameters.

Existing designs of compact and uprated lines demonstrate the importance of insulated cross-arms and specific string designs as line post insulators to suppress horizontal line movement. [7]

Reducing clearances and increasing the system voltage result in higher corona activities that must be controlled and suppressed. Innovative insulator string designs and specific hardware components should be considered. Furthermore, new technologies of high temperature conductors bring new designs of clamping systems in order to carry more current loads. All latest development should be integrated in the design stage to optimize compact line solutions for the users.

In some countries, the minimum clearances are regulated by official authorities. The same ratings have applied for decades without a consideration to get lower values by using line arresters. The protection level of metal oxide varistors is a safe method to reduce clearances but unfortunately often misunderstood. Technical committees and working groups of standardization should work more closely with line designs and surge arrester manufactures to offer more flexibility for the regulations of electrical clearances.

2.3 Conclusion
Reducing clearances of insulator strings and transmission lines with the help of Line Surge Arresters has a great potential for line compaction. The various simulations show that it is technically feasible to reduce the clearances and dimensions of a conventional 420 kV transmission line up to 30% by using EGLAs and appropriate station class arresters. EGLAs installed on each tower and each phase will not only optimize the design and reduce the clearances, but also offer a reliable protection against lighting outages. The concept of downsizing the line’s geometry applies for line compaction
as well as for line uprating since the principle is the same. The approach developed in this paper and its outcomes can be used also to uprate an existing 245 kV line to a new 420 kV system as a retrofit application. Such a modification along with necessary insulators strings adaptation can result in a significant increase of the power capacity without modifying the main structures, the max. clearances and especially the existing Right-of-Way (ROW). This ensures a reliable reduction of the environmental footprint and visual impact in our landscaping.

It has been demonstrated in different publications that the EGLA application is the most appropriate solution for the reduction of lightning outages. The arcing distance of the insulator strings can be reduced to their minimum if the insulation coordination is verified between EGLA protection level and the insulators withstand levels. The smaller is the EGLA air gap, the more compact will be the clearances. Depending on voltage levels, generally 245 kV and above, and line parameters, as the length, the switching surge factors are becoming critical. NGLA application is a simple and efficient solution to reduce switching surges and minimize compactions. Switching studies are often required since reclosing operations are not sensitive for conventional designs of 245 kV systems and above. NGLAs installed in few locations along the transmission line represent a moderate investment associated with outstanding results.

Several utilities, surge arresters’ manufacturers, line designers and engineering consultants are currently working on feasibility studies. Pilot projects will be implemented first in developed countries where existing networks must be updated, and innovative solutions must be developed especially in Europe where the space is limited. Similar applications are already in service, for example, on catenary systems under bridges and in small tunnels. Further challenges related to creepage distances, RIV/Corona, insulators design and mechanical aspects have to be further investigated, analyzed and solved. An improved cooperation between arrester manufacturers and line designers is necessary to enter in the new era of transmission lines.

3 References


[7] Innovative Tower Solutions & Line Uprising, Konstantin O. Papailiou, INMR website