



Zinc oxide surge arrester

Application guidelines for transmission line switching overvoltage control

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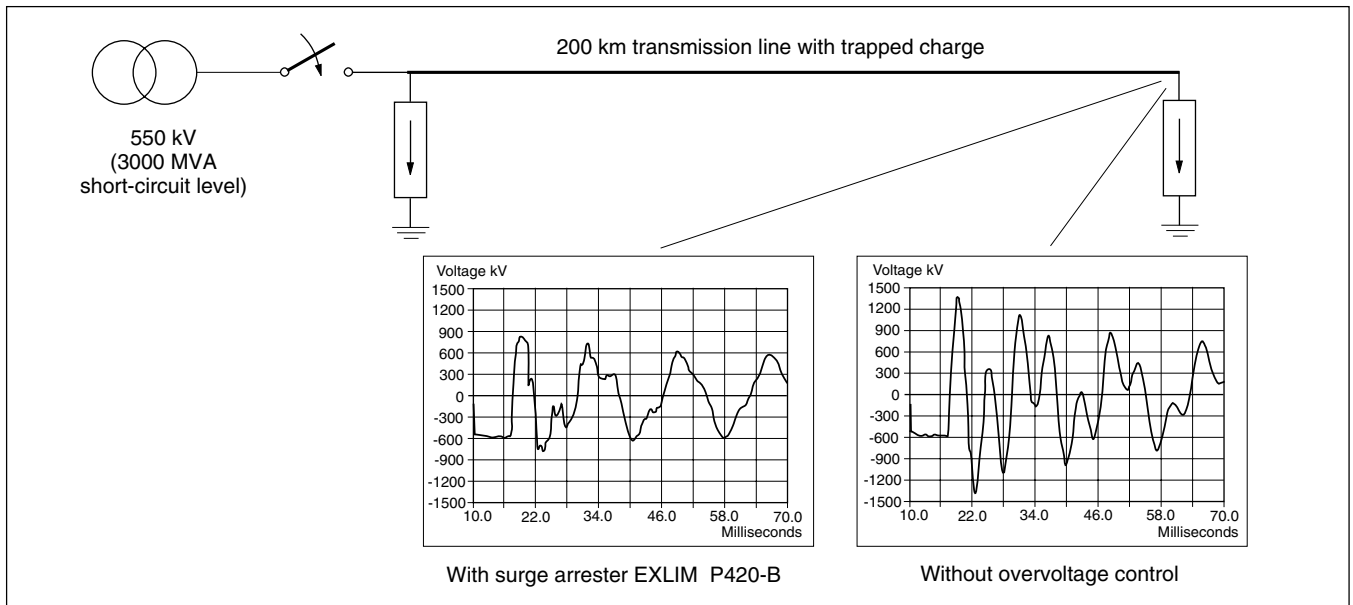


Figure 1. Transmission line switching overvoltages – reclosing of line with trapped charge

Introduction

In any complex electromagnetic system, a sudden change in state gives rise to transient oscillations which, in turn, can cause high overvoltages unless suitably damped. See Figure 1. For EHV systems it has been common practice for many years now to equip circuit-breakers with closing resistors, as a means of controlling such system transient interactions during closing or re-closing operations. The closing resistors are inserted in series with the load circuit being switched for a short period of time, before closing the main contacts of the breaker – thereby damping the transient overvoltages. Optimum overvoltage control requires correct choice of the resistor value in relation to the source impedance level, the line length and the line parameters. Although a well-proven technology, breakers equipped with closing resistors inevitably involve relatively complex mechanical constructions.

In recent years several large utilities have experienced problems with the long term mechanical reliability of closing

resistor mechanisms (especially in older circuit-breakers) – with adverse impact on overall system reliability – and have begun to examine alternative approaches to switching surge overvoltage control.

Foremost amongst these is the installation of suitably chosen zinc oxide surge arresters at both ends of the transmission line being switched (Ref. [1,2]). Given the availability now of ZnO arresters having low protective levels and high discharge energy capabilities, this proves to be a particularly economical and very simple way of controlling transmission line switching surges – without any dependence upon complex mechanisms or sensitive timing systems.

The purpose of this paper, therefore, is to provide general dimensioning guidance for practical transmission line switching surge control in EHV systems – using ZnO surge arresters alone.

Simple approximation

As a very rough guide, the current through an arrester and its corresponding residual voltage when switching-in a transmission line of surge impedance Z (with trapped charge), is given by the intersection of the surge arrester protective characteristic and the system prospective overvoltage load line — as shown in the Selection Guide for ABB Surge Arresters (Ref. [3]). This assumes that the surge travel time of the line is short compared to one power frequency cycle — yielding a rectangular current impulse with duration twice the travel time.

An example is shown in Figure 2 for 550 kV system, using the arrester EXLIM P420-B, and assuming a system prospective overvoltage of 3.2 p.u. (This value corresponds approximately to the upper limit of possible switching over-voltages in such a system — implying three-phase reclosing without closing resistors and an uncompensated system (Ref. [4]).

Here;

$$1 \text{ p.u.} = 550 \times \sqrt{2} / \sqrt{3} = 449 \text{ kV}_{\text{crest}}$$

Figure 2 thus implies an arrester residual voltage of about 1.87 p.u. and a peak discharge current of about 1.8 kA.

Assuming a simple rectangular pulse of current the corresponding discharge energy in the arrester would be about 2000 kJ for a 200 km line length. This is equivalent to a specific energy duty of about 4.8 kJ per kV rated voltage for the EXLIM P420-B (which has a rated voltage $U_r = 420$ kVrms). This duty is well within the rated capability of 7 kJ/kVrms U_r , for this type of arrester (IEC line discharge class 4).

In practice, however, due to travelling wave effects and to the complex interactions amongst phases and between the power system source and line parameters, the actual current through the arrester will not be rectangular. In addition, the residual overvoltage will not be constant along the line length. In particular, with an arrester at each end of the line, a voltage profile will develop along the line, reaching its highest values around the mid-point (i.e. at the greatest distance from the arrester).

Practical application of arresters for transmission line switching surge control thus requires a more detailed analysis of such interactions and of the effects of system and line parameters.

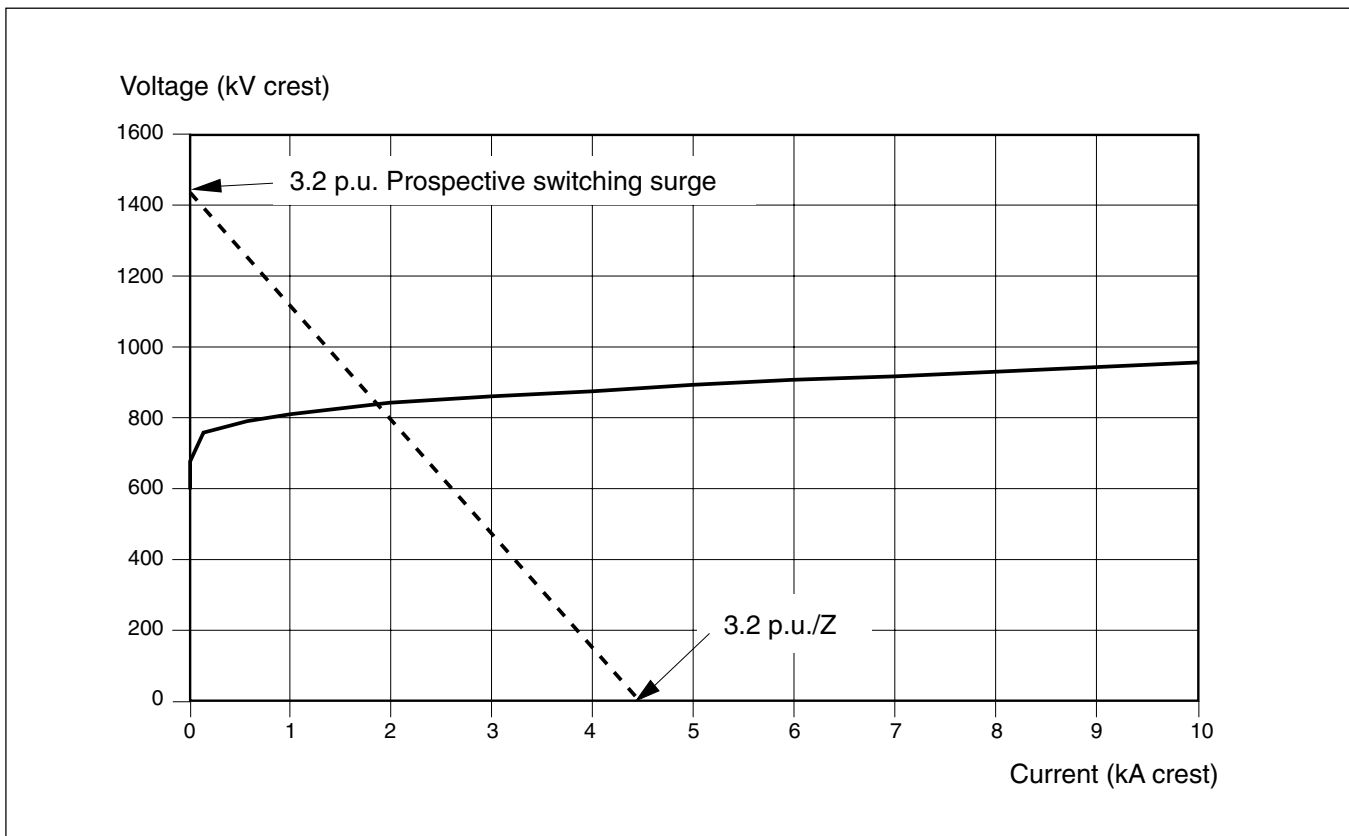


Figure 2. ABB ZnO surge arrester EXLIM P420-B. Switching surge load-line estimation.

Parametric analysis

In order to illustrate such effects, sample results from detailed system parametric analyses are illustrated in Figure 3 for 550 kV systems — as studied using the digital computer program EMTP (DCG/EPRI version).

For this purpose, the ANSI 550 kV standard reference transmission line parameters were used (ANSI C37.06-1987), in a full three-phase simulation, with representation of the power source, transmission line and circuit-breaker behaviour all in general accordance with its recommendations. Two main sets of parameter variations were carried out. 550 kV source short-circuit power was varied from 1000 MVA up to 20000 MVA, and line length was varied from 10 km up to 600 km. Minimal power frequency source damping was assumed; $X/R = 10$.

A 'worst-case' approach was followed throughout. For example, full trapped charge was taken into account — assuming a prior opening operation, including the voltage rise effects of weak sources, and of excluding compensation on longer lines (i.e. trapped charges always ≥ 1.0 p.u.). Closing angles were chosen such that the actual voltages across the breaker pole at the instant of closing were thus always ≥ 2.0 p.u. However, to avoid unrealistically high voltage rise effects of weak sources and consequent extreme surge arrester duties the use of the lower short-circuit powers has been limited as follows:

- 1000 MVA source was used for line length ≤ 200 km
- 2000 MVA source was used for line length ≤ 300 km
- 3000 MVA source was used for line length ≤ 300 km
- 5000 MVA source was used for line length ≤ 400 km

In all cases in this example, ZnO arresters of type EXLIM P420-B were considered installed at the sending and receiving ends of the lines. This arrester, which has a rated voltage of 420 kVrms, is one "common choice" arrester for 550 kV systems — as explained in the "Selection Guide for ABB Surge Arresters" (Ref. [3]). The full non-linear protective characteristics of these arresters were also correctly represented.

Four sets of overvoltage results are summarised in Figure 3, all expressed on the above per unit base;

- the phase-ground voltages at the receiving end
- the phase-ground voltages at the line mid-point
- the phase-phase voltages at the receiving end
- the phase-phase voltages at the line mid-point

Several important observations may be summarised;

- the phase-phase and phase-ground overvoltages at the receiving end are largely insensitive to line length, or to source power, remaining ≤ 4.0 p.u. and ≤ 2.0 p.u. respectively throughout — for this choice of arrester.

This is of course due to the excellent nonlinearity of the

arrester voltage-current characteristics. Even if the discharge current varies strongly the residual voltages remain practically the same.

- the main sensitivity lies in the overvoltages developed around the mid-point of the line. For short lines up to around 100 km higher short-circuit power gives higher overvoltages. For longer lines there is no clear dependency with short-circuit power and the overvoltage variation with line length is not so pronounced either. Generally, irrespective of line length and source power, the phase to phase and phase to ground overvoltages remain below 4.8 p.u. and 2.5 p.u. respectively.

Note that these overvoltage levels are specific to the choice of arrester — in this case EXLIM P420-B. An arrester with lower protective levels would lead to lower overvoltages on the line. This can be achieved by;

- choosing another arrester type with lower protective levels for comparable temporary overvoltage capability (e.g. EXLIM T420-A or EXLIM P420-C with rated voltages 420 kVrms).
- or, where temporary overvoltage amplitudes are limited and accurately known by using arresters with lower temporary overvoltage capability (i.e. lower rated voltage) such as EXLIM P396-B (rated voltage = 396 kVrms); in which case, in this example the overvoltages at the line mid-point would be reduced by the order of 3-5% i.e. the reduction will not be directly proportional to the lower arrester protective level at the mid-point as will be the case at the receiving end.
- or, a combination of the above, such as the use of arrester type EXLIM T396-A with a rated voltage of 396 kVrms.

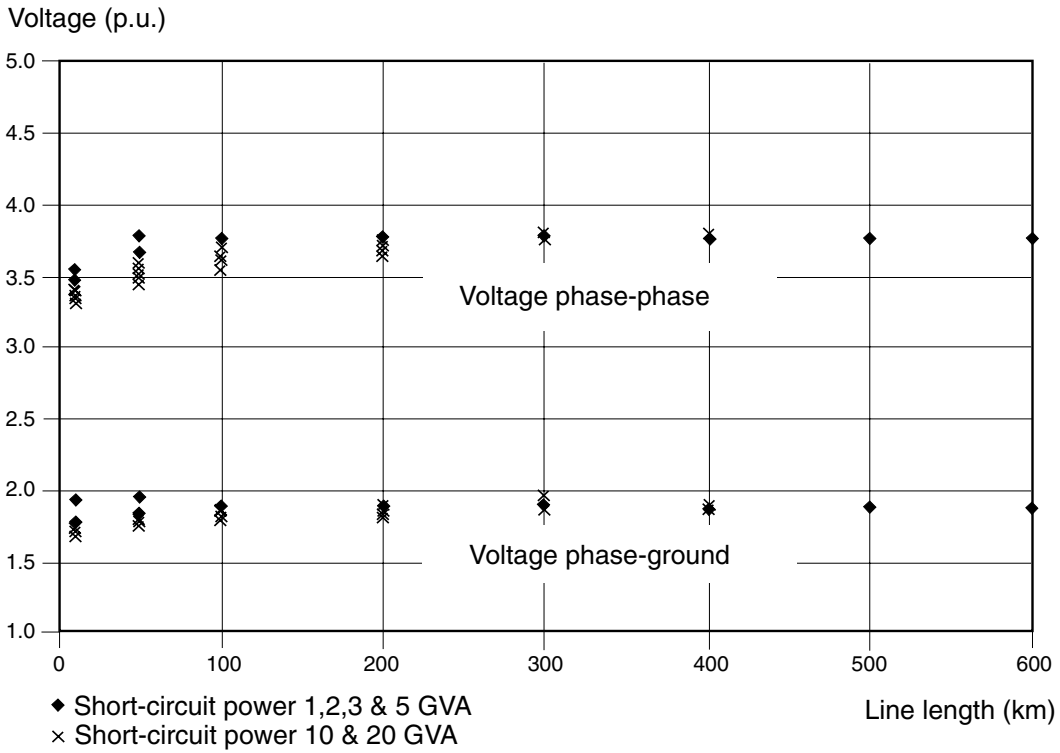
The implications, of course, depend upon the switching impulse withstand characteristics (SIWL) of the transmission line insulation, but, by way of comparison, note that the preferred rated SIWL for 550 kV equipment corresponds to 2.6 p.u., on the above per unit base (IEC 71-1976).

Alternatively, ANSI C37.06-1987 requires that the rated line closing switching surge factor (i.e. the 2% overvoltage) be 2.2 p.u. for breakers designed to control closing over-voltages.

Similarly for phase to phase overvoltages, rated SIWL for 550 kV equipment corresponds to 4.0 p.u. as per IEC 71-3/1982.

In practice, application considerations are best determined on a simplified statistical basis relating the statistical switching overvoltage (i.e. 2%), to the line insulation switching impulse statistical withstand voltage (i.e. having 90% withstand probability), through the use of a 'statistical' safety factor, as for example, in IEC 71-1976.

Voltage phase-ground and phase-phase receiving end



Voltage phase-ground and phase-phase mid-point

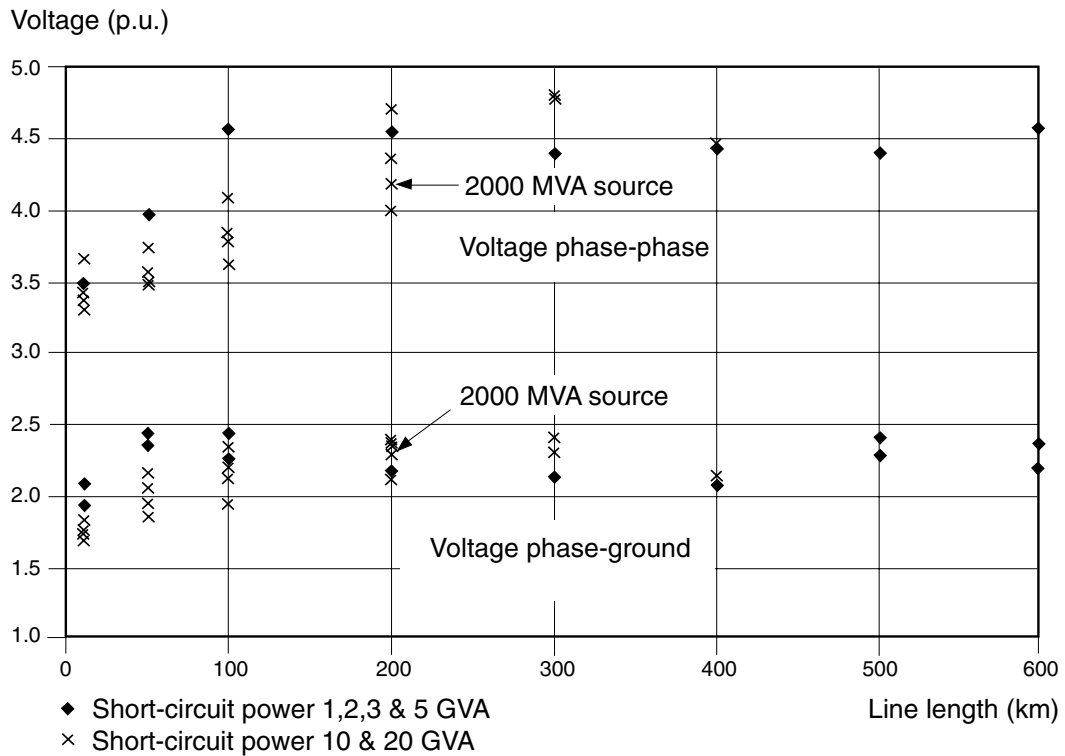


Figure 3. Reclosing overvoltages — with ZnO surge arrester EXLIM P 420-B. Parametric analysis (550 kV system; ANSI transmission line parameters)

Statistical consideration

Figure 4 illustrates the results of a full statistical switching surge overvoltage analysis; in this case, for a 550 kV system, having 200 km line length and a source power of 2000 MVA — again computed with "common-choice" arresters at each end of the line (EXLIM P420-B). In contrast to the 'worst-case' analyses of Figure 3, where the closing angles were always taken at the peak of the voltage across the open poles, in Figure 4 the closing angles have been allowed to vary stochastically and the statistical spread of closing times amongst the three poles has also been included — as would occur in reality. 300 different switching sequences have been performed to obtain the result in Figure 4.

Although comparatively wide ranging overvoltage values are possible, the effect of the arrester is to give strongly skewed overvoltage frequency distributions — with a steep fall. Comparison of the results in Figures 3 and 4 (for the 200 km/2000 MVA case) shows that the values given in Figure 3 correspond quite closely to the upper limits of the frequency distributions — indicating that the values in Figure 3 do approximate the 2% levels at the line ends. The maximum voltages at the mid-point are determined by statistical evaluation only.

The simplified "worst-case" approach is thus not sufficient to determine the overvoltages along the line. The same parametric analysis as for Figure 3 therefore has been repeated but with a full statistical analysis with each case representing 300 separate 3-phase reclosures. The obtained overvoltages (2% values) are shown in Figure 5.

A comparison with Figure 3 confirms that for longer lines the overvoltages at mid-point are strongly underestimated by the simplified approach as is also indicated by Figure 4.

Practical 550 kV transmission lines generally involve minimum air clearances in the range of 3.2 to 4.5 m (Ref. [5]); corresponding to SIWL (90%) about 1155 - 1380 kV or about 2.6 to 3.1 p.u., on the above per unit base.

Applying the simplified procedure of IEC 71-1976 and (Ref. [5]), assuming 300 meters between the towers and that the voltage is above the 2% value for half the line length for the most severe switching sequence, it is found that a switching surge risk-of-flashover below about 10^{-2} , can be obtained

through a statistical safety factor of 1.1 to 1.15 for line lengths 50-600 km. The required line SIWL based on these assumptions is also plotted in Figure 5.

This implies that for practical lines having a statistical SIWL in the upper range of used insulation levels and with "common-choice" ZnO surge arresters at the ends of the line alone, switching overvoltages could readily be controlled up to line lengths of 250 to 300 km irrespective of short-circuit power.

In those situations where the line insulation SIWL may be lower and the temporary overvoltages limited, installation of arresters having lower rated voltage and/or reduced protective levels further extends the scope of practical application (Ref. [1]) — as would be the inclusion of phase-phase arresters in ultra-compact systems.

Alternatively, location of an additional arrester at the midpoint provides a simple means of further reducing system switching overvoltage levels (Ref. [2]).

Figure 6 shows the result from a full statistical analyses based on the same assumption as used for the calculation presented in Figure 5 but now with additional arresters at line mid-point. A "required" line SIWL is also plotted in the figure based on a target risk of 10^{-2} per switching operation, 300 m between line towers and that the overvoltage exceed the 2% overvoltage value along 1/4 of the line length for the most severe switching sequence.

Compared to the costs and complexity of installing a number of closing resistors in a large switching station, the location of arresters at each end of the line, together with an extra set at the mid-point, still proves to be the more economical and more robust solution.

In general, installation of an additional set of arresters at the line mid-point increases the application range of "common-choice" arrester to all lines with $SIWL \geq 3.0$ p.u. and lengths up to at least 400 km for 550 kV transmission line switching surge control.

This is calculated with the conservative ANSI parameters. Using real parameters (i.e. for source and line) usually gives considerably lower overvoltages.

Surge discharge energy considerations

Figure 4 also depicts the statistical variations in surge arrester discharge duty during the detailed analysis of the 550 kV 200 km example. As could already be inferred from the approximations of the load-line analysis of Figure 2, control of line reclosing overvoltages is not a particularly severe duty for this type of arrester.

In Figure 7, maximum arrester discharge energy is plotted as a function of line length with the short-circuit power as parameter.

The energies are taken from the full statistical analysis with 300 switching operations for each case and the maximum energy (not the 2% value) obtained is plotted in Figure 7.

Arising out of the analysis of Figure 7, the following observation may be noted;

- EXLIM P-B arresters may safely be used to control switching surges in 550 kV lines up to at least 260 km irrespective of source short-circuit power.
- EXLIM T arresters may safely be used to control switching surges in 550 kV lines up to at least 340 km irrespective of source short-circuit power.

– EXLIM P-C arresters may be used to control switching surges in longer 550 kV lines up to at least 420 km.

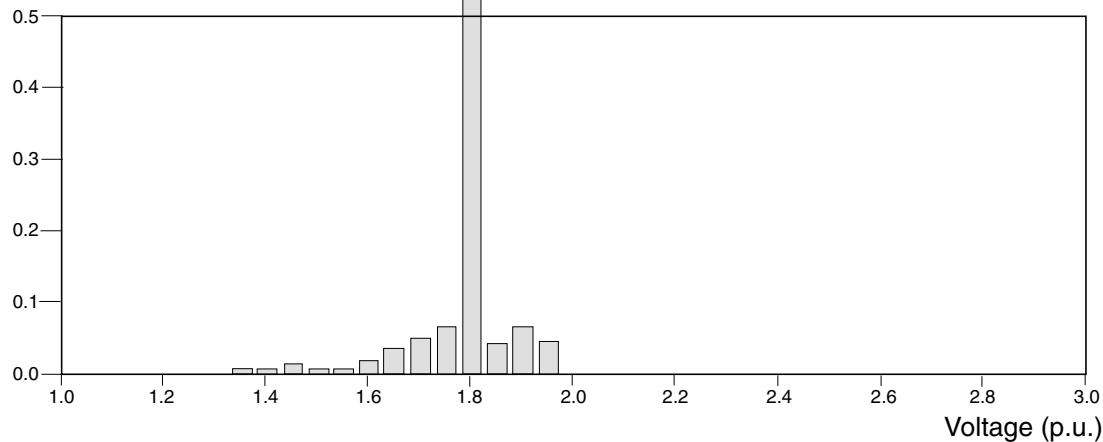
As noted earlier, the preceding analyses have been made on a conservative basis — with minimal damping. Experience with field tests, involving comparative measurements and computed switching surge discharge duty in practical installations have shown consistently that the practical surge arrester discharge duty is significantly less than that computed.

Bearing in mind that the ANSI reference transmission line parameters themselves are conservative (the basis of Figure 3 to 7) it is clear that the above surge arrester switching surge control application limits will also be generally conservative.

The use of mid-point arresters will reduce the maximum arrester energies by 10 to 20% — thus further increasing the use of different arrester types on even longer lines.

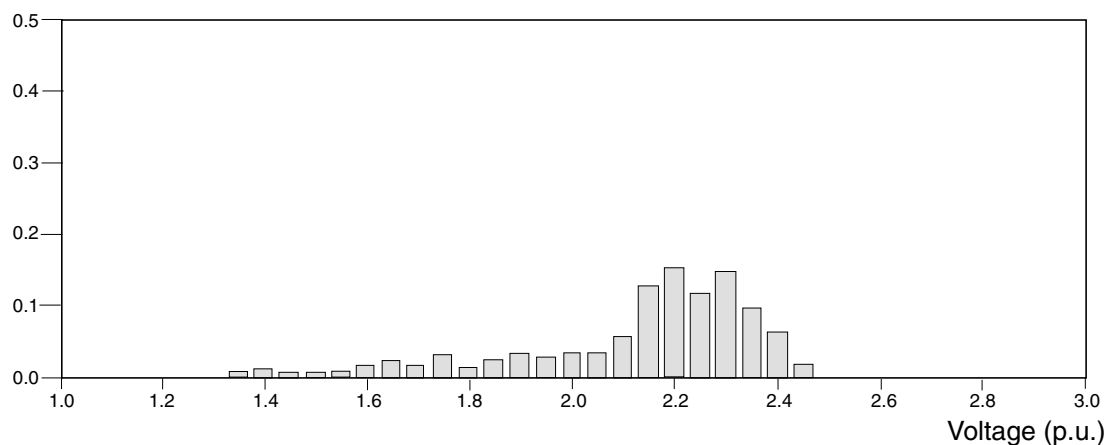
Voltage to ground receiving end

Relative frequency



Voltage to ground mid-point

Relative frequency



Surge arrester discharge energy in p.u. of rated energy of 2.94 MJ

Relative frequency

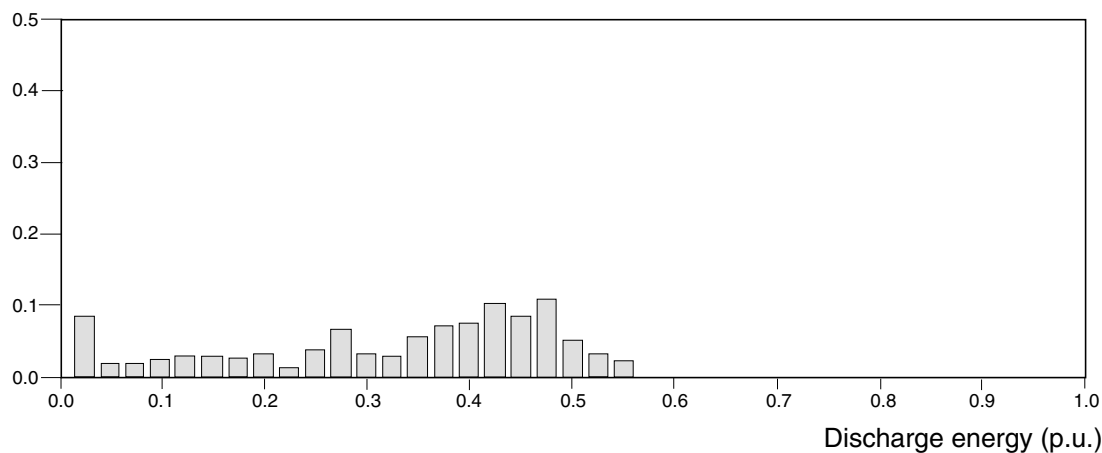
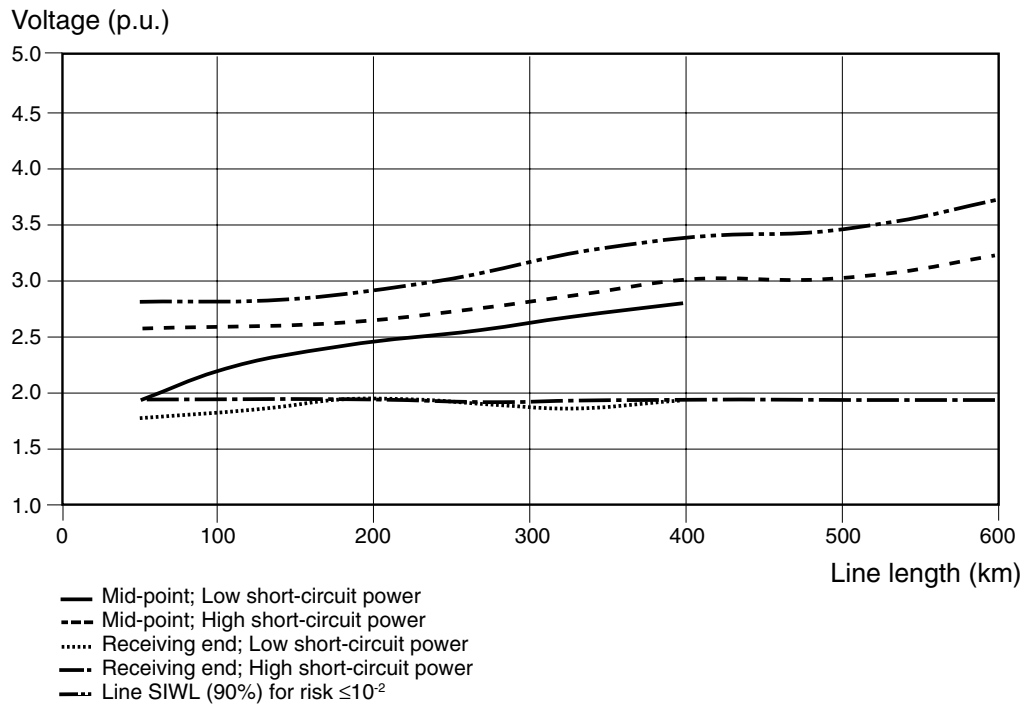


Figure 4. Reclosing overvoltages — statistical analysis with ZnO surge arrester EXLIM P420-B; 550 kV system; 200 km line length; 2000 MVA source

Voltage phase-ground with arresters at line ends alone



Voltage phase-phase with arresters at line ends alone

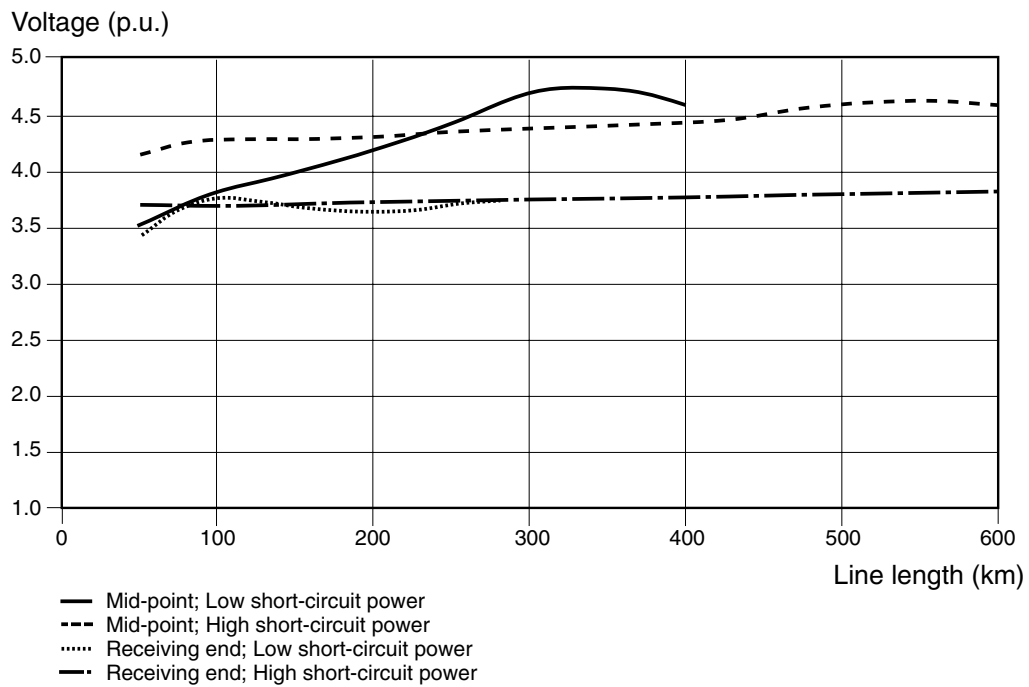
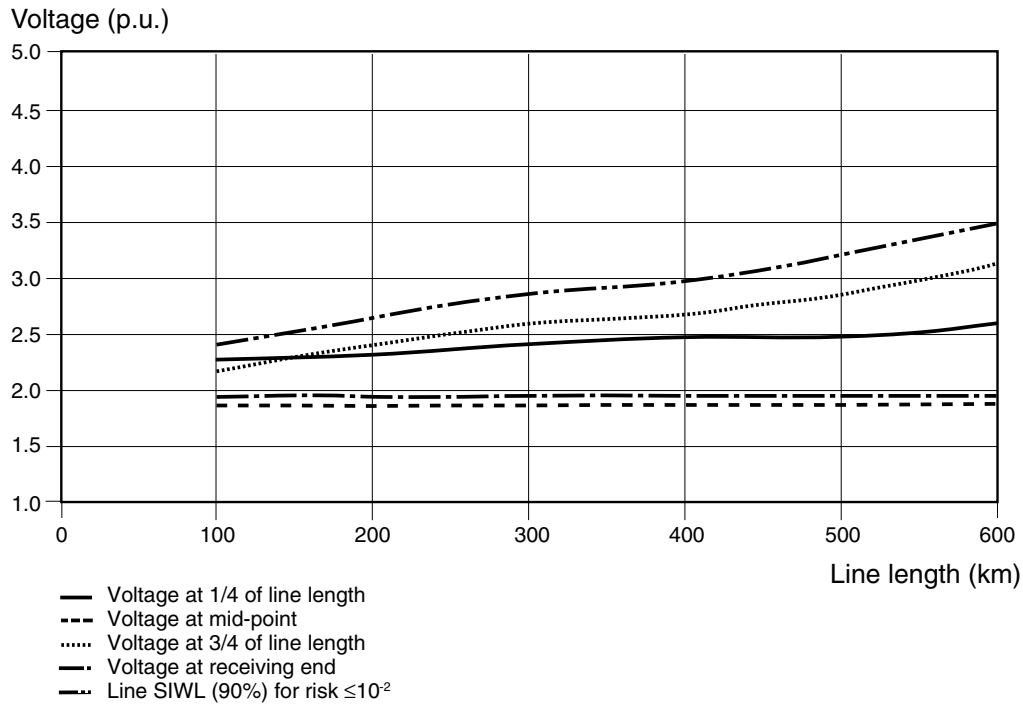


Figure 5. Reclosing overvoltages — full statistical analysis with ZnO surge arrester EXLIM P420-B; 550 kV system; 50 - 600 km line length, 1000 - 20000 MVA source. (2% overvoltage values)

Voltage phase-ground with arresters at line ends and mid-point



Voltage phase-phase with arresters at line ends and mid-point

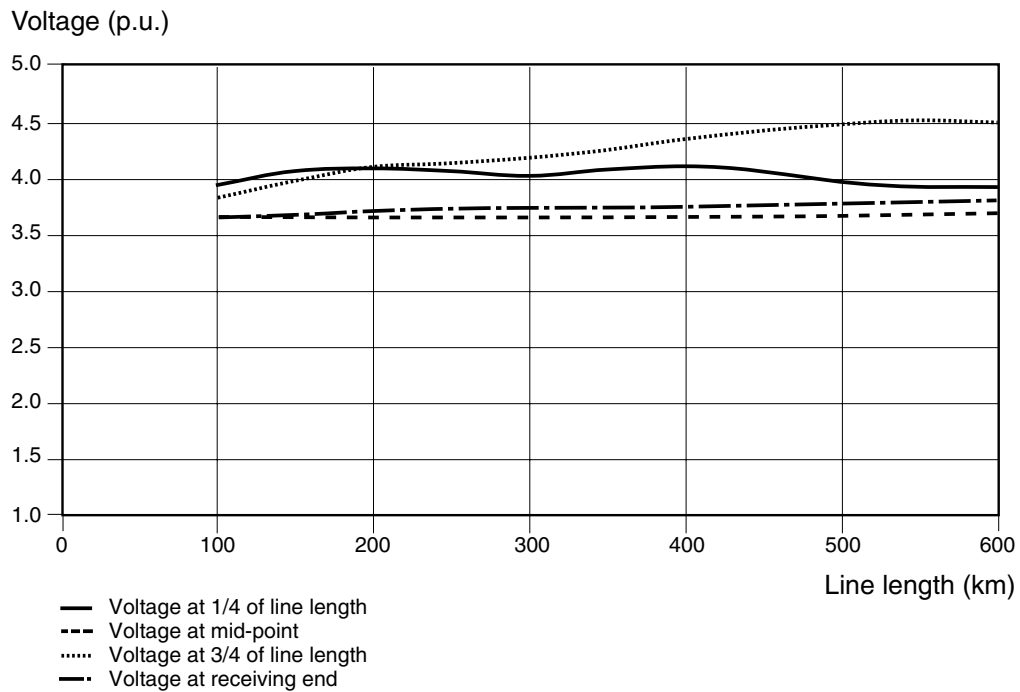


Figure 6. Reclosing overvoltages — full statistical analysis with ZnO surge arrester EXLIM P420-B; 550 kV system; 100 - 600 km line length; 1000 - 20000 MVA source. (2% overvoltage values). Effect of additional arresters at line mid-point.

Effect of reactors and inductive potential transformers

In practice, on opening an unloaded line with reactor directly connected, the line/reactor system will tend to oscillate with a natural frequency which is nearly that of the power source. This causes the development of a different voltage across the open poles of the breaker which oscillates itself at the beat frequency between the two systems (i.e. the source, on the one side, and the line/reactors on the other side, of the breaker). In principle, therefore, from the point of view of the voltage across the poles at the moment of closure, this hardly differs from the normal situation of a line with a DC trapped charge — except in respect of the frequency of the differential voltage across the open poles.

The 'worst-case' analyses of Figure 3, which always involved differential voltage ≥ 2.0 p.u. and closure at or close to the peak, thus adequately represent the case of compensated lines as well.

Experience in practical installation has also shown that the connection of inductive potential transformers on the line-side of the circuit-breaker can greatly facilitate the use of

arresters alone as an effective means of controlling line switching surges. This is because such PTs will rapidly drain off any remnant trapped charges on the line — thereby significantly reducing the prospective overvoltage.

Measurement with practical PTs has shown that typical levels of trapped charge still left on the line — during rapid reclosure — amount to only about 0.2 to 0.3 p.u.; in contrast to the ≥ 1.0 p.u. assumed throughout in Figures 3 to 7.

Due to the very flat protective characteristics of ZnO surge arresters the resultant switching overvoltages on a line protected by ZnO arresters will only be slightly reduced, compared to the case with ≥ 1.0 p.u. trapped charge — but the surge discharge duty on the arrester is very significantly reduced.

The general conclusions of the preceding sections thus remain fully valid — both for lines with reactors or PTs except that in the case of PTs, "common-choice" arresters may be applied even more extensively for switching surge control on even longer lines than indicated in Figure 7.

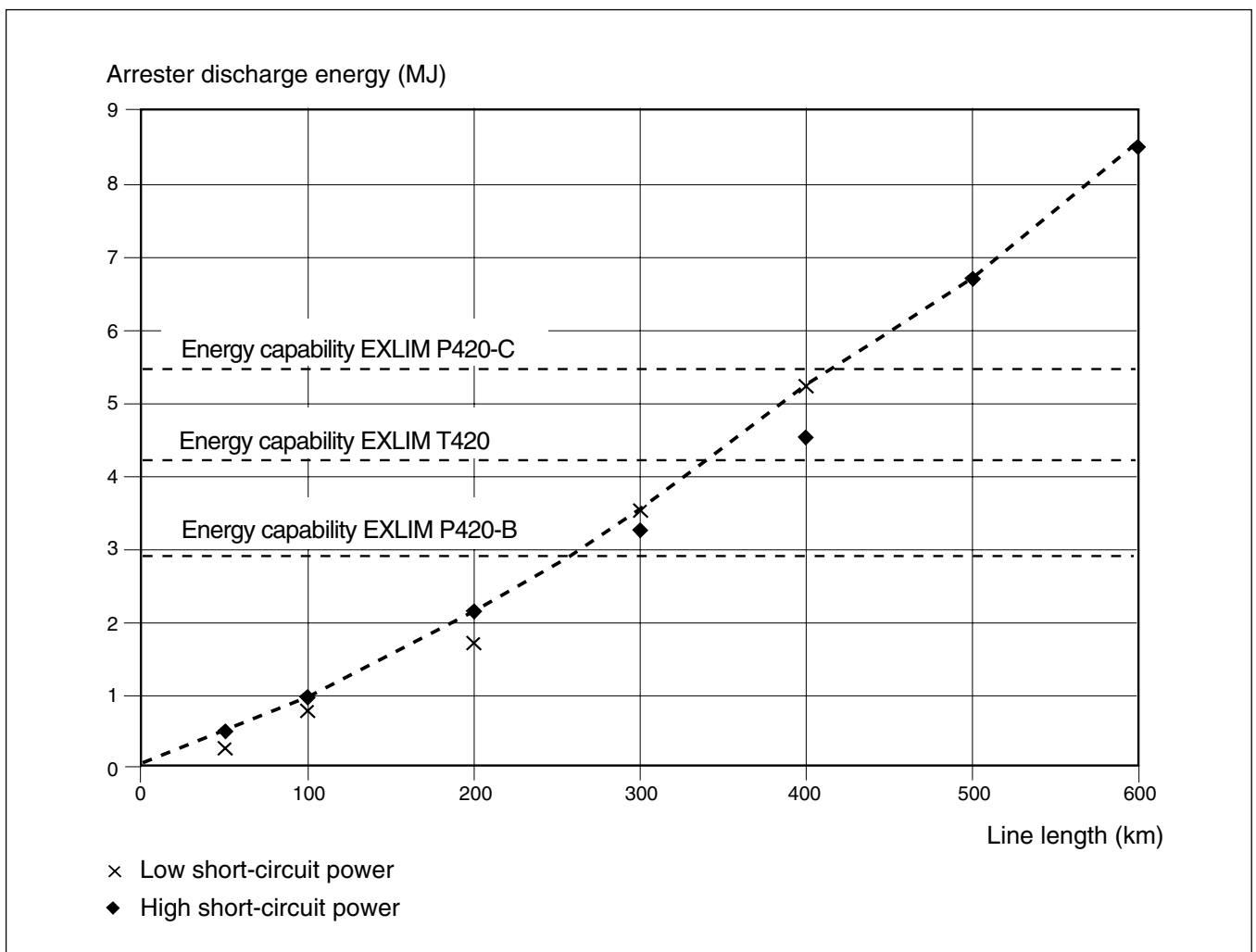


Figure 7. Energy duty by reclosing with surge arrester EXLIM P420-B. Full statistical analysis; 550 kV system; ANSI transmission line parameters. "Low" short-circuit power = 1 - 5 GVA "High" short-circuit power = 10 - 20 GVA.

Application to other overvoltage levels

The preceding analyses and observations have all related to the 550 kV system voltage level — which is considered to provide the widest scope for applying surge arresters for transmission line switching surge control, as an alternative to closing resistors.

However, these results all apply with equal validity to lower voltage systems, over the general range 300 - 550 kV for two principal reasons;

- the calculation basis of Figure 3 to 7 (i.e. the ANSI line parameters), remain unchanged over this voltage range
- the specific protection characteristics of ABB ZnO surge arresters (i.e. the relationship between their residual voltage characteristics and their rated voltages) also remain unchanged over this voltage range.

Similar calculations have also been made for 800 kV system voltages — leading to the conclusion that the surge arrester method of switching surge control still offers meaningful application prospects even at this voltage level. Transmission line insulation design is more critical at this voltage however, due to the very non-linear trend in the SI withstand strength characteristics of longer air gaps — which generally requires lower switching overvoltages.

Step-by-step simplified procedure

Effective for assessing the viability of the ZnO surge arrester approach for transmission line switching surge control — for system voltages ≤ 550 kV, with/without compensation reactors — based on the use of 'common-choice' arresters:

With inductive potential transformers connected to the lines;

- Estimate reclosing overvoltage for your line length from Figure 5.
- Confirm that reclosing overvoltage (mid-point) is significantly below your design SIWL (90%) for your line insulation (recommended statistical safety as per Figure 5). If not, check if installation of additional set of arresters at the line mid-point will ensure sufficient overvoltage protection, see Figure 6. Review also system temporary overvoltages and the possibility to use arresters having lower protection levels and scale the values for the receiving end of line proportionally. For the mid-point use only half of the reduction obtained by proportionally scaling!
- Proceed with arrester selection, but generally as per "Selection Guide for ABB Surge Arresters" (Ref. [3]) (EXLIM P-B typically for line lengths ≤ 400 km, EXLIM T for line lengths ≤ 500 km and EXLIM P-C for even longer lines).

No inductive potential transformers connected to the lines;

- Estimate reclosing overvoltage for your line length from Figure 5.
- Confirm that reclosing overvoltage (mid-points) is significantly below your design SIWL (90%) for your line insulation (recommended statistical safety as per Figure 5). If not, check if installation of additional set of arresters at the line mid-point will ensure sufficient overvoltage protection, see Figure 6. Review also system temporary overvoltages and the possibility to use arresters having lower protection levels, and scale the values for the receiving end of the line proportionally. For the mid-point use only half of the reduction obtained by proportionally scaling.
- Proceed with arrester selection (EXLIM P-B typically for line lengths ≤ 260 km, EXLIM T for line length ≤ 340 km and EXLIM P-C for line lengths ≤ 420 km.) For even longer lines discuss discharge duty and required energy capability with ABB.

Conclusions

In general, the preceding parametric analysis indicate that there is a relatively wide scope for dispensing with closing resistors and for installing surge arresters alone at the ends of transmission lines — as a highly effective means of controlling switching overvoltages and of ensuring high system reliability.

In those cases where questions may remain concerning the viability of this approach for specific applications (e.g. situations perhaps outside the framework of the preceding sections), then it is strongly recommended that the application still be discussed with ABB.

A very conservative line was taken in the background calculations to Figures 5, 6 and 7 for example, and it would be relatively simple to analyse the viability of specific application projects using the actual system parameters involved. In most cases, practical networks would lead to less severe arrester discharge duty and line overvoltages than estimated in the preceding analyses - thereby allowing an even wider scope for such arrester applications and for fully realizing the operational benefits of the mechanical simplicity, robustness and long term reliability.

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Data and dimensions are subjected to changes without notice.

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