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MODULARNA SERIJSKO-PARALELNA KONSTRUKCIJA MO ODVODNIKA PRENAPONA ZA PRIMJENE U PRIJENOSNIM MREŽAMA

SAŽETAK

Prošlo je točno 20 godina od prve komercijalne ugradnje metaloksidnih odvodnika prenapona s polimernim kućištem. U tom razdoblju, razvoj konstrukcije MO blokova i polimernog kućišta stalno su usavršavani kao i metode ispitivanja koje su pratile amandmane i dopune međunarodnih normi.

Zahvaljujući intenzivnom razvoju, u međuvremenu je patentirana jedna nova serijsko-paralelna konstrukcija odvodnika prenapona, sastavljena od dvaju ili više paralelnih kolona metaloksidnih blokova s ciljem da se zadovolje očekivani energetski zahtjevi primjereni nazivnom naponu i dužini prijenosnih linija.

U referatu se daje kratak opis serijsko-paralelne konstrukcije odvodnika prenapona, metode i postupci ispitivanja kao i prednosti kod ugradnje i održavanja u pogonu.

Ključne riječi: MO odvodnik prenapona, serijsko-paralelna kombinacija, polimer, norme, razdioba struja, raspodjela potencijala

MODULAR SERIES - PARALLEL SURGE ARRESTER DESIGN FOR TRANSMISSION NETWORKS APPLICATIONS

SUMMARY

It has been exactly 20 years since metal-oxide surge arresters with polymeric housing were first installed. During this time the development of MO blocks and polymeric housing were continuously improved as well as the test procedure that followed the updated and amended international standards.

Thanks to intensive development a new series parallel surge arrester design was patented. It comprises two or more parallel paths of metal oxide bocks in order to meet the expected energy requirements applicable to the system voltage and transmission line lengths were patented.

This paper shortly describes series-parallel SA design, test procedures as well as installation and maintenance advantages in the service.

Key words: MO surge arrester, series-parallel design, polymeric rubber, standards, current sharing, voltage gradient

1. INTRODUCTION

The modular series parallel polymeric surge arrester has had over 10 years of successful service experience at system voltages up to 500 kV, since being introduced in 1992 and is now in service in over 30 countries around the world. The patented series parallel metal oxide surge arrester is unique in construction and provides many advantages over conventional single column and multiple columns porcelain and polymeric housed designs. This paper details the history of the series parallel surge arrester from concept through to design considerations and later refinement.

The key advantages are:

- inbuilt stress grading along the full length due to the extra capacitance that the intermediate metalwork provides
- as there is no grading ring required then the footprint of the series parallel surge arrester is much smaller than an equivalent single column surge arrester with a grading ring
- no internal air gap as with porcelain house type and non-integrated polymeric house type surge arresters which eliminates the risk of explosion in service
- integrated polymeric house type surge arresters has superior pollution performance
- the lattice structure provides light weight but still extremely strong mechanically strength
- the series parallel design is capable to withstand seismic condition set in the current international standard

The unique construction of this series parallel surge arrester provides electrical and mechanical properties that cannot be obtained with single or multiple column types. In particular the geometry and unitary construction provides inherent voltage grading that does not require additional grading rings or further correction to the maximum continuous operating voltage (U_c) required for arresters of conventional construction.

2. THE DESIGN CONCEPT

There are many weaknesses for porcelain housed and non-integrated polymeric housed (figure 1) type surge arresters. To name a few, the control of uniform stress grading and the radial field strength are the most important issues in these surge arrester design types. The later in particular, high radial field would lead to discharge in the surge arrester enclosure between the porcelain inside wall and the metal oxide varistors. New patented surge arrester construction overcame this weakness by eliminating this air gap. It can be shown in figure 2 that here is no air gap in the integrated polymeric housing type surge arrester design.

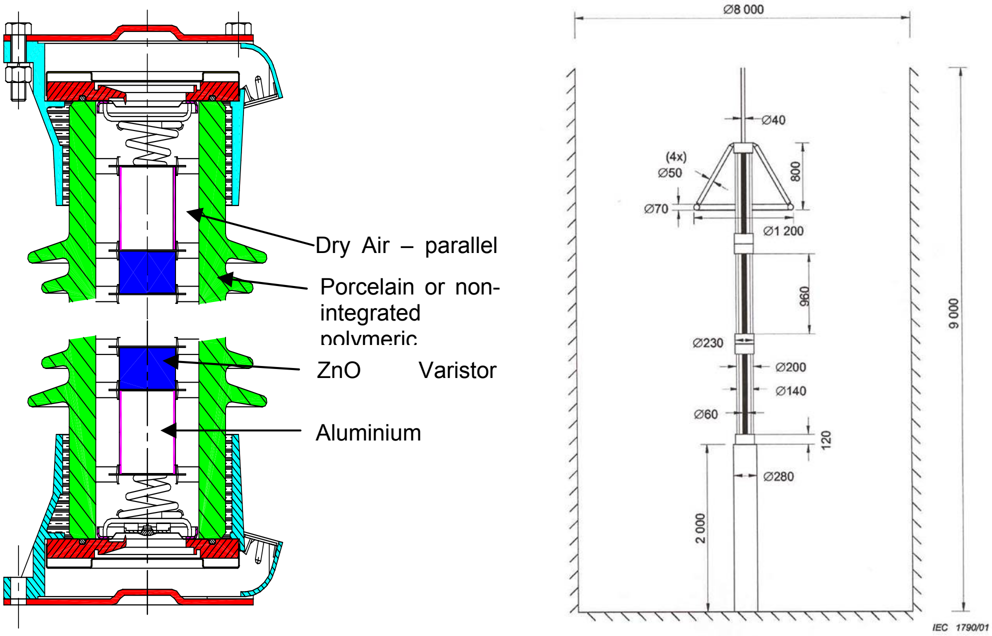


Figure 1: Non-integrated housing surge arrester and typical IEC geometry model of non-integrated housing surge arrester

The intermediate metalwork (figure 2) of the series parallel surge arresters provides additional natural grading capacitance. The equivalent cascade capacitance network gives a more uniform electric field distribution when compared it with a single column porcelain or non-porcelain house surge arrester with or without the grading ring.

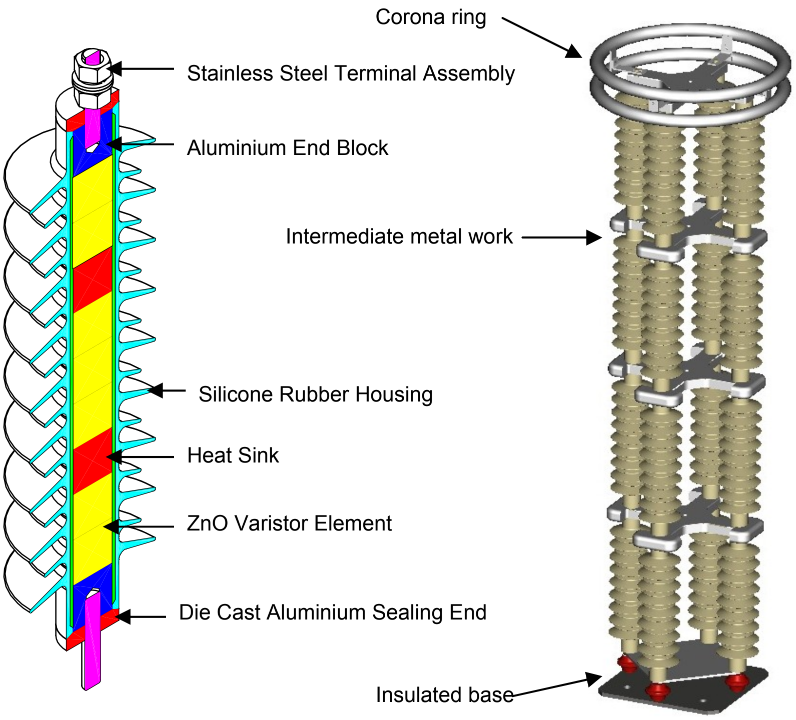


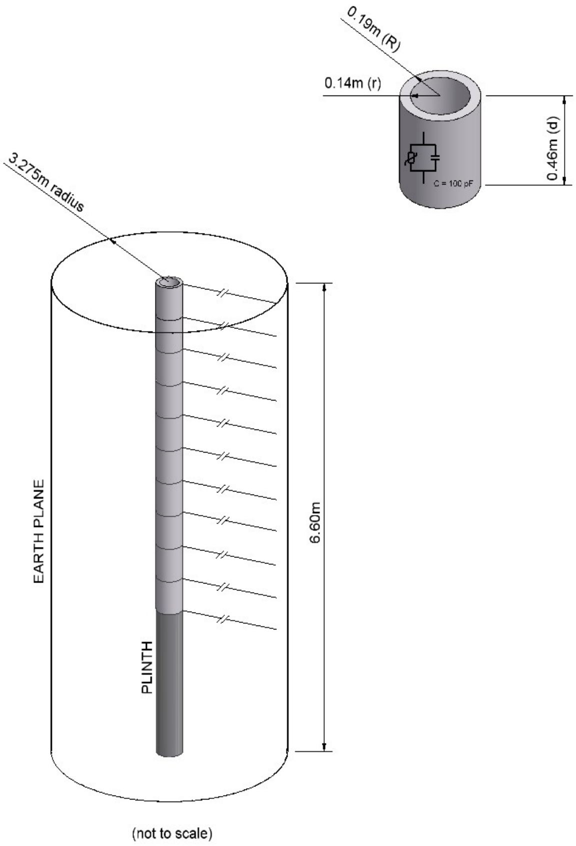
Figure 2: Surge arrester core and series parallel surge arrester

In the early stages of the series parallel design it was recognised that the geometry of the assembly would be critical. It was decided that in order to be acceptable in the UK and international HV transmission market the series parallel design must be able to satisfy at 400 kV system 20 kA nominal discharge current with a class 4 line discharge capability. These surge arrester characteristics have since been extended to include 500 kV system and class 5 discharge energy. Higher system voltage series parallel surge arresters are under development.

The overall geometry of the modular surge arrester should be such that both radial and longitudinal voltage stress was at an acceptable value at the highest system operating voltage.

In the early 90s, in order to determine an empirical value for insulation strength a basic model was constructed with the purpose of determining a value for insulation breakdown voltage at 50 Hz. For this purpose a seven stage model comprising 4 arrester units per stage was mounted on a pitch circle diameter (PCD) of 250 mm. The maximum rated voltage (Ur) of the model was 250 kV. From basic equations for dielectric stress and with the geometry of this model the breakdown of the insulation would occur at an applied voltage that was less than the Ur.

The longitudinal voltage stress distribution was calculated using a coaxial approximation electric ladder network approximation. This program examined the expected voltage field surrounding the proposed design for various positions of vertical earth plane and phase centres for a 400 kV system. Figure 3a shows the model and figure 3b shows typical results obtained and confirmed the near uniform longitudinal voltage stress distribution.



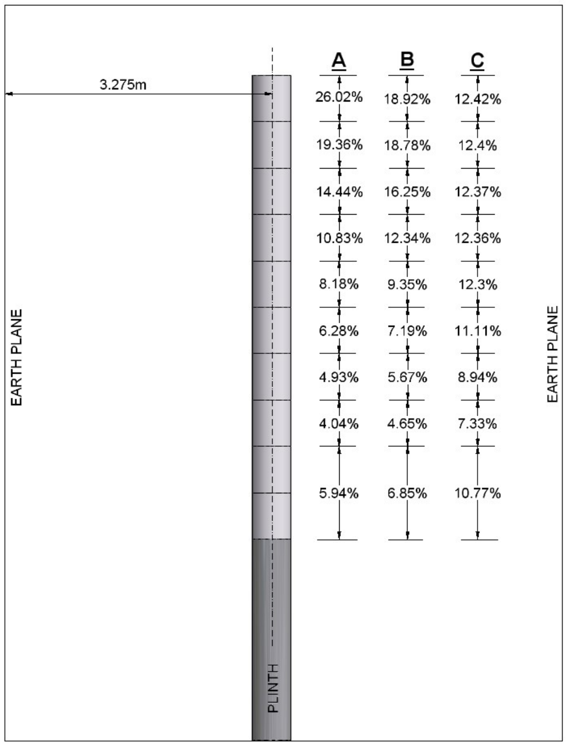


Figure 3a: Field plot of series parallel surge arrester using a coaxial circuit approximation model

Figure 3b: Field plot result of series parallel surge arrester
A – Varistor non-conduct
B – Varistor partially conduct
C – Varistor fully conduct

2.1. The Series Parallel Design (Thermal Analysis)

Having confirmed the basic dimensional requirements of the modular design, attention was turned to materials and manufacturing techniques. Salt-fog tests on prototype arresters proved that the polymer housing and shed profile was critical for good performance. The intermediate connecting plate was constructed in gravity cast aluminium with a radius at the circumference. The radius further assisted the reduction in radial stress at the highest voltage sections.

In order to confirm that the calculated results for the voltage field uniformity, tests were set up to measure the temperature of the surge arrester under various running conditions.

The series parallel surge arrester used for these tests comprised 10 series stages of 3 parallel columns designated 3P10S360 having a U_r = 360 kV and a U_c = 270 kV. Thermocouples were attached to each parallel units of the top stage. Thermocouples were also attached to the base stage and 6^{th} stage in order that the surge arrester temperature profile could be observed.

The series parallel surge arrester was energised at various voltages from Uc to Ur until thermal equilibrium was established. The laboratory walls provided an effective earth plane and thermal equilibrium normally was achieved in 30 hours.

Test results obtained are summarised herewith:

1. At Uc there were no significant temperature difference between all stages
2. At Ur the maximum temperatures recorded were
   - Top stage = 31.8°C
   - 6^{th} stage = 31.2°C
   - Base stage = 24.5°C
3. Under all test conditions the maximum difference between arrester modules in parallel stage did not exceed 2°C.

3. ELECTRICAL TESTS FOR SERIES PARALLEL SURGE ARRESTERS

It is apparent that, for the series parallel surge arrester design, the electrical matching of parallel units is important for optimum performance. The electrical considerations and manufacturing tests are described in the following section of this paper.

The following standard IEC routine testing has been done for every series parallel surge arrester units:

- reference voltage measurement
- partial discharge measurement
- leakage current measurement
- residual voltage measurement

In addition, a proprietary internal procedure was introduced to check the current sharing of parallel columns within a series parallel surge arrester. This process ensures that between parallel columns the lowest practical differences in characteristics can be employed in one complete series parallel surge arrester. Therefore, residual voltages, energy absorption and heat dissipation are shared among the parallel units.

4. FINITE ELEMENT ANALYSIS OF VOLTAGE FIELD ON SERIES PARALLEL SURGE ARRESTER

From the early work on the series parallel surge arrester design, the voltage distribution is largely governed by the surge arrester geometry and intermediate plates. The intermediate connecting plates have stray capacitances which cascade and shunt to earth. Furthermore, the resistance and capacitance of the non-linear varistors also provide voltage grading. Unlike other designs the series–parallel surge arrester does not require external means such as grading rings, to aid the voltage distribution to earth.

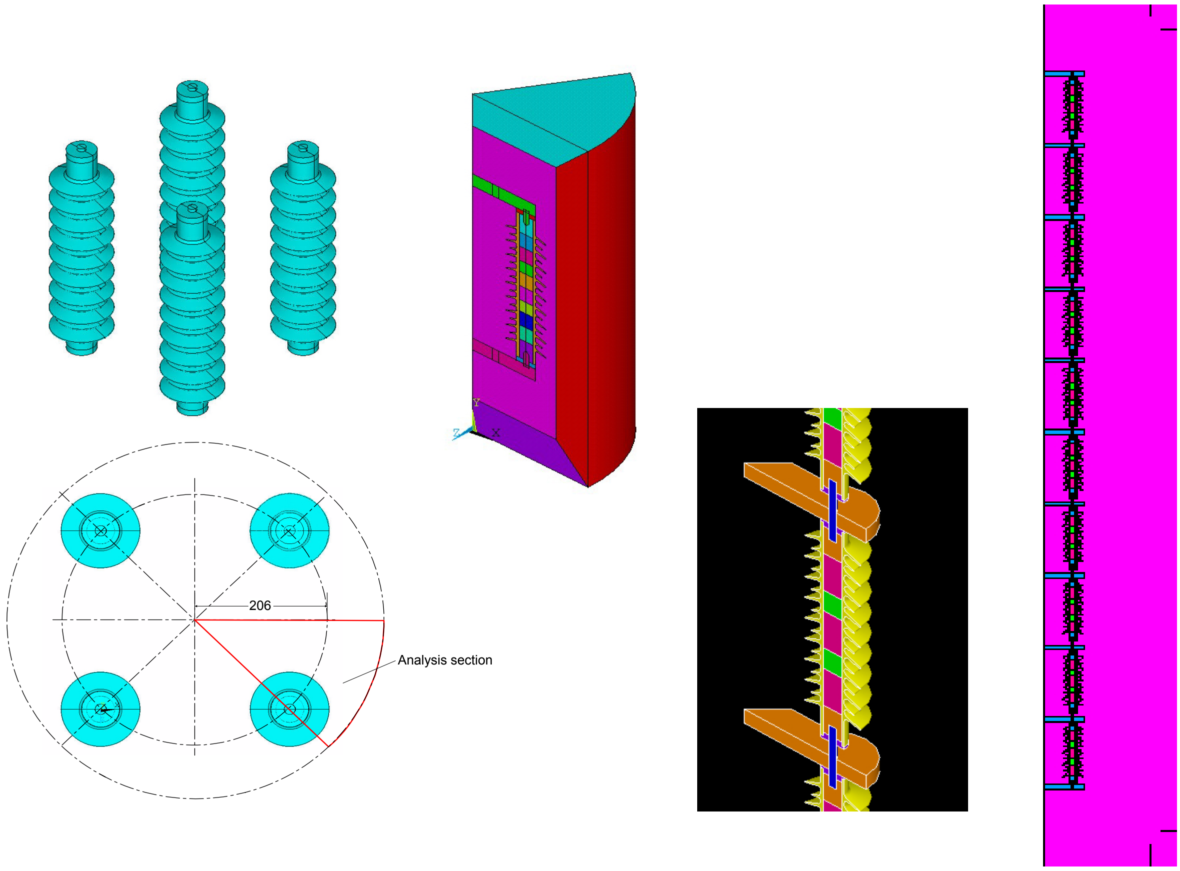
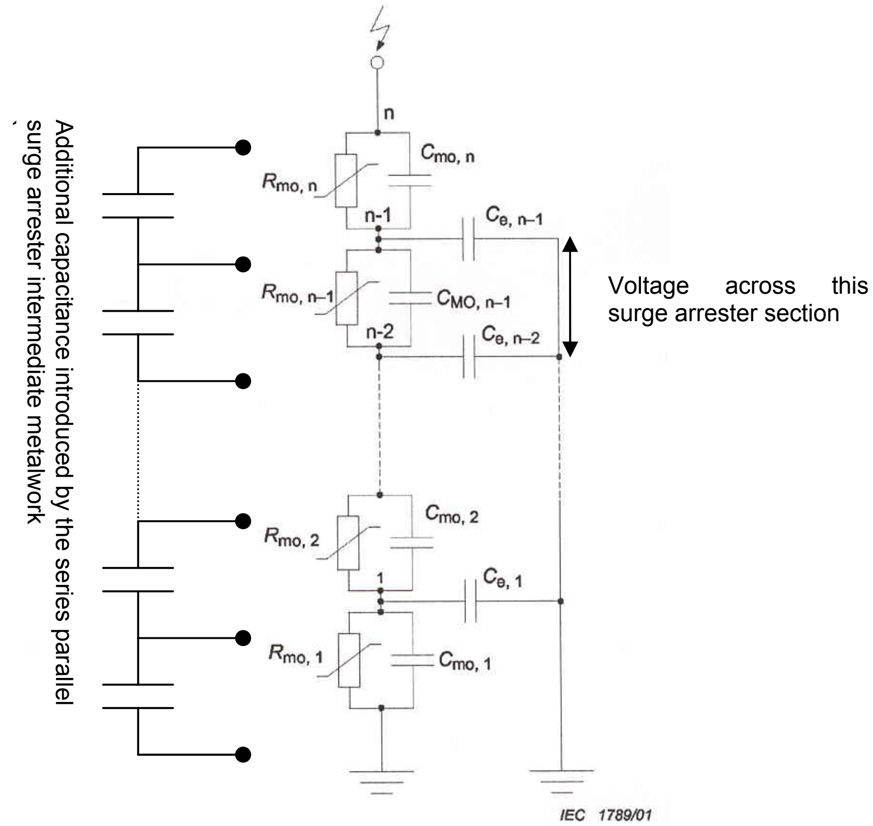


Figure 4: Series–parallel surge arrester FEA model

The Maxwell equation for electric field distribution provides a method of calculating the voltage stress along the length of a surge arrester. Theoretically without stress grading, the voltage distribution decays exponentially from the high voltage terminal to the earth. It therefore appears that the varistors at the top of the arrester would be energised to a higher voltage. However this high voltage stress is not directly from an infinite voltage source, there is high series impedance in between. This impedance acts as a self correcting means to limit the actual voltage stress applied to the surge arrester section and the metal oxide block. This phenomenon will be discussed further in this section.

Generally, the height of the surge arrester determines the degree of uneven voltage stress distribution. Voltage stress can be determined easily by Finite Element Analysis and other design aspects such as mechanical strength and thermal behaviour can also be incorporated in the FEA model. A 4P10S series parallel surge arrester FEA model is given in figure 4. Figure 5 is the standard equivalent circuit network and for the series parallel design, additional capacitance created by the introduction of the intermediate metalwork is added to each stage.



Key

R_{MO}, x	Voltage-dependent resistance of section x
C_{MO}, x	Capacitance of section x
C_e, x	Stray capacitance to earth at node x
n	Number of sections

Figure 5: IEC surge arrester equivalent electric circuit network and the additional capacitance introduced by the series parallel surge arrester intermediate metalwork

However, it is also worthwhile to point out that both the circuit and FEA approach can only handle the varistor element in its linear model either before or after the threshold “turn on” point. For the former, varistors have high resistance and it’s the capacitance that dictates the surge arrester voltage grading. Beyond the turn on point the varistors have low resistance and this dominates the voltage grading. Furthermore for the former case, although the varistor or varistors are seeing high stress, the equivalent Thévénin network as shown in figure 6, has high source impedance. Under these conditions the voltage across the varistor will collapse as soon as any significant current commences to flow. The high equivalent source impedance effectively limited the voltage and current that can be applied to the varistor elements located in the top surge arrester section high stress region. It is important to point out this difference in the IEC ageing test. For high voltage (>300 kV) and long surge arrester construction, the IEC ageing test requires the surge arrester manufacturer to use a voltage from the voltage distribution calculation or measurement but ignoring any effect due to the source impedance from the Thévénin equivalent network. It can be concluded from the thermal analysis that this phenomenon was not fully investigated or it is only applicable to surge arresters with separated housing.

Further tests were performed to energise a section of a series parallel surge arrester alone, via an “infinite” voltage source. The aim is to give the same top surge arrester section temperature rise in the test described in the previous section. In this case the required voltage was significantly lower than the value predicted from the FEA study. This experiment gives a clear indication that“high” source impedance is required in the test setup if the calculated voltage stress is adopted for the surge arrester ageing test. Alternatively a reduced voltage value from the stress calculation may be accepted for the test which has “low” or “zero” source impedance.

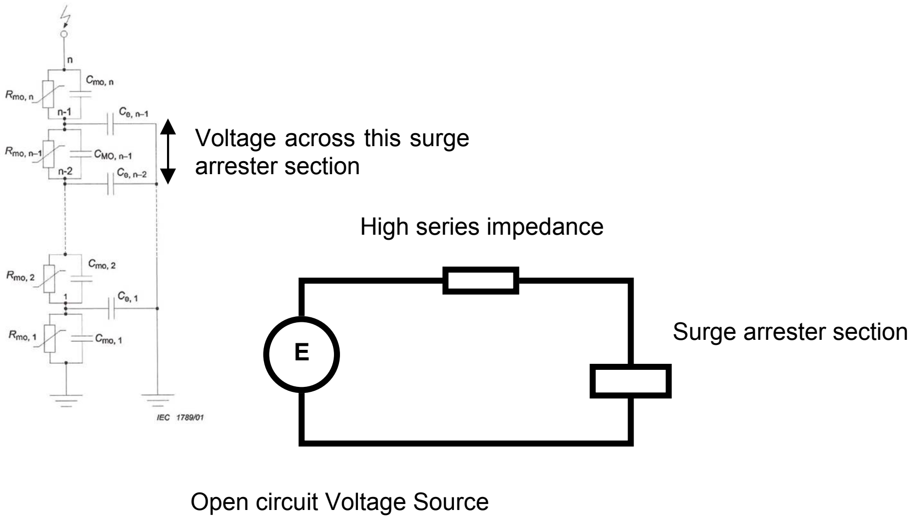


Figure 6: Voltage across a surge section and its Thévénin equivalent circuit network

5. DISCUSSION OF RESULTS

The standard IEC 60099-4 Edition 1.2 provides a modelling method under ANNEX M (informative). However, this approach is based on a single column porcelain house or non-integrated polymeric house surge arrester comprising 3 series sections referred to as “multi-stage”. The single column arrester is physically different from the series–parallel design in that there are **fewer** units in series for a given surge arrester length or voltage rating. Hence there is **less** intermediate stage (figure 1) to regulate the stress. Furthermore, at higher voltage rating and higher line discharge class the series–parallel arrester may have 2, 3, 4, or 5 parallel units per stage. For these reasons the IEC approach is different to this series parallel design.

Table I. Stress distribution on arresters

	IEC model	Series Parallel FEA result	Single column no grading FEA result
Top	50%	52%	66%
Middle	39%	32%	28%
Bottom	26%	31%	21%
Total	115%/m	115%/m	115%/m

The above table and the FEA field plot (figure 7) show a direct comparison between a single column surge arrester without grading ring and a series–parallel type of the same rating and length. Both analyses performed with the assumption that the metal oxide varistors were operating at well below their threshold "turn-on" voltage hence less resistive and more capacitive.

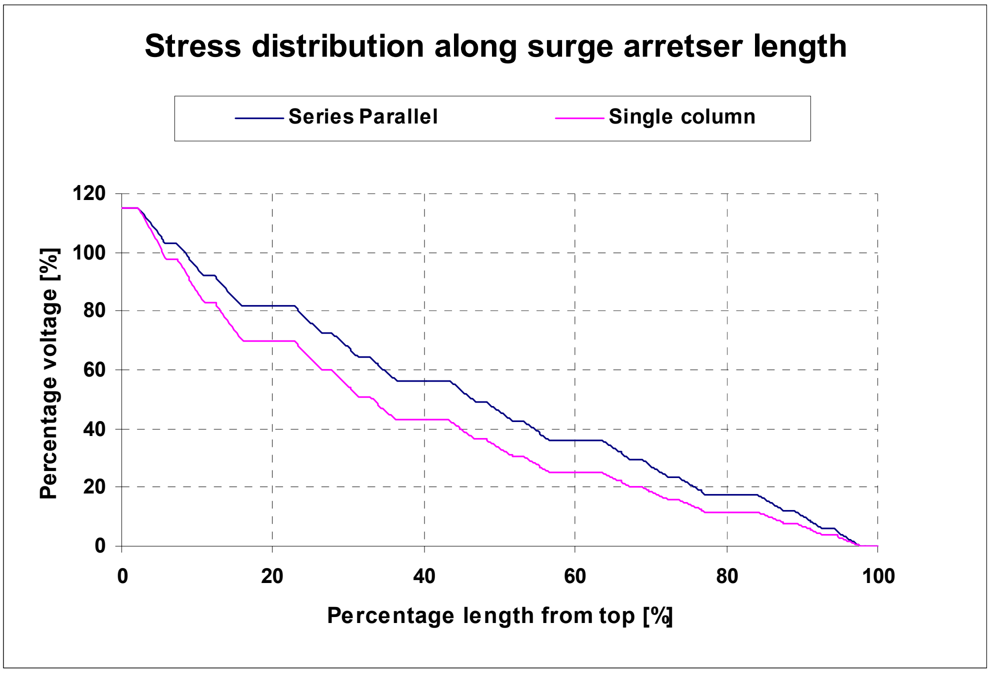


Figure 7: FEA results of stress distribution of series–parallel and single column surge arrester

There are differences and similarities between the field plot to a single column porcelain house surge arrester and the series–parallel design. They are summarised as follows:

- the series–parallel arrester has more effective grading per unit length than the single column type
- specifically a series–parallel type exhibits similar stress distribution to the IEC example calculations, but without the use of oversize diameter voltage grading rings
- radial stress is an issue for porcelain housed design due to the inbuilt air gap between the varistor and the housing inner wall but not for the gap free (integrated housing) construction

A non linear voltage grading along the length of a surge arrester is undesirable particularly if the high voltage stress results in ageing of the metal oxide varistor as well as its insulation thus reducing the life of the surge arrester design. It is in this context that further consideration must be given to actual ageing mechanism. Thermal ageing of the varistor would be caused by the lack of self limiting under the combination of high voltage stress and low source impedance. On the other hand, particularly for porcelain housed surge arresters, low energy ionisation of the parallel air gap due to the high electrical stress would lead to ageing and failure of the varistor insulation. Based on the laboratory tests and service experience, the series parallel surge arrester design has eliminated both thermal and partial discharge ageing to the metal oxide varistor.

6. SERVICE CONDITIONS AND EXPERIENCE OF SERIES PARALLEL SURGE ARRESTER DESIGNS

Where tests show that a given design of surge arrester requires additional grading components, this can be accomplished by the addition of grading rings. The correctly positioned grading ring or rings as acknowledged in IEC 60099-4 APPENDIX M will even out the voltage gradient, such that no further consideration with respect to accelerated ageing procedure need be taken. However, it could be speculated that the logic in the IEC follows the conventional porcelain designs. The grading ring in a HV surge arrester also provides a benefit of lowering the radial stress of the surge arrester. Porcelain housed and non-integrated polymeric housed surge arrester has a parallel air gap between the varistor and the housing inner wall. High radial stress would exceed the discharge inception level thus lead to ageing of the varistor. The new patented design does not have air gap, as the glass fibre and resin is bounded to the surface of the varistor which has a more superior dielectric performance than air.

The ageing of metal oxide varistor is well documented in the IEC and the testing procedure of 1.15xMCOV at 115°C for 1000 hr is adequate for all surge arrester designs. However the subject of radial stress has not been discussed and resolved fully in the IEC & CIGRE.

It has been established that partial discharge activity in close proximity to metal oxide varistors will lead to rapid ageing and premature failure. Therefore, the conventional single column arrester requires a grading ring for additional reasons other than uneven field or thermal considerations. In contrast the series–parallel surge arrester has no internal air gaps and therefore requires no grading ring to avoid internal ionisation.

Long term ageing tests on series–parallel surge arrester were performed at National Grid's Dungeness Natural Pollution Test Site in the UK. The condition of the surge arrester was checked before and after the 2 years test and no sign of any ageing was recorded.

Furthermore as part of CLP Power's switchgear renewal program, a 400 kV series–parallel surge arrester was returned from CLP Power Hong Kong, Castle Peak substation after 9 years of continuous service. Electrical routine tests and current sharing were repeated at Brighton HV laboratory. The results showed that the condition of the surge arrester was as new. Both the surge arrester reference voltage and residual were unchanged. The current sharing between the 4 branches was excellent. Partial discharge level was low and passed the latest IEC specification of 10 pC whereas this limit was 50 pC in the last edition of IEC standard. The surge arrester was stripped and the internal components were inspected. There was no sign of overstressing, discharging or ageing.

It is important to note that both Dungeness and Castle Peak are classified as extremely polluted site. Both Dungeness and Castle Peak have very high levels of marine pollution but Castle Peak also has industrial pollution.

7. CONCLUSION

- Over 10 years reliable service experience on HV/EHV systems with the series–parallel design supports the view that the stress grading is correct even though it is different from the IEC recommendation
- Close correlation between two different methods of voltage field plotting for the series–parallel arrester suggests that the IEC APPENDIX M approach is aiming for the porcelain and non-integrated polymeric housed type surge arresters with internal parallel air gap
- The thermal model of a complete series parallel surge arrester demonstrates that the inherent capacitive and resistive grading are dominant over coupling capacitance
- The thermal model of a complete series parallel surge arrester also demonstrates that the Thévénin equivalent network exhibits "high" source impedance which requires detail consideration in the ageing test.
- Both long term trial and service results from NGC and CLP Power showed no deterioration of the surge arrester metal oxide varistor due to high longitudinal and radial electric stress.
- Development work of 800kV series parallel surge arrester extension will incorporate FEA and thermal imaging technique to establish both the electrical and mechanical performance of the design.

In addition to a good stress grading without the need of oversize grading ring, the Series Parallel surge arrester also has the following advantage:

- light weight no heavy lifting equipment is required for installation
- light weight no heavy duty foundation is required for the surge arrester
- modular design quick installation and commission
- lattice structure gives exceptional strong mechanical strength
- non shatter of the surge arrester housing
- no damage to personal & nearby expensive equipments
- good pollution performance
- environmental acceptable material

– the series parallel design is capable to withstand seismic condition set in the current international standard

REFERENCE

[1] IEC 60099-4 Ed 1.2 Surge arresters – part 4: Metal oxide surge arrester without gaps for a.c. systems

[2] IEC 60099-5 Ed 1.1 Surge arresters - part 5: Selection and application recommendations