METAL-OXIDE SURGE ARRESTER APPLICATION FOR PROTECTION OF 6-500 kV CABLES

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During the operation of the equipment, its insulation is exposed not only to the operating voltage of the network, but also to various types of overvoltages, such as lightning, switching, quasi-stationary (among them are regime, resonant, ferro-resonant, arc-type). Let's consider the issues of protecting cable lines from overvoltages with the help of a metal-oxide surge arresters.

Keywords: cable line, cross-linked polyethylene (XLPE), switching overvoltages, lightning overvoltages, insulation protection, surge arrester.

1. INTRODUCTION

The main danger of overvoltage is for the internal insulation of equipment, since it is not self-healing, i.e. its breakdown leads to the need for long-term expensive repairs. Overlaps of external insulation (for example, insulation of an overhead line), although they lead to a short-circuit, and cause disconnection of equipment and consumers, but they are not dangerous for the insulation itself, and its repair is not required.

To protect the insulation of equipment from lightning and switching overvoltages in networks of all classes of rated voltage up to 750 kV, metal-oxide surge arresters (MOA) are used (previously, valve arresters were used for these purposes).

MOA are not designed to limit quasi-stationary overvoltages due to their insufficient energy intensity of nonlinear elements. Therefore, to combat this type of overvoltage:

– in networks of all classes of rated voltage up to 750 kV, circuits are designed in such a way as to exclude adverse processes;
– equipment with anti-resonance properties is used;
– in medium voltage 6-35 kV networks, resistive neutral grounding is used.

One of the important areas of application of MOA is the protection of cable lines from lightning and switching overvoltages, to which this article is devoted. As for the need to install a MOA at power transformers and on busbars, the listed issues will not be considered here.

2. PROTECTION AGAINST SWITCHING OVERVOLTAGES

Traditionally, it was believed that in 6-220 kV networks, the main danger for the insulation of equipment is only lightning overvoltages, and switching due to large insulation strength reserves are not decisive.

For example, according to standard GOST [1], the insulation strength of equipment under the influence of switching impulses was normalized only for 330-750 kV networks, and the insulation of 6-220 kV equipment was tested only by lightning impulses and one-minute AC voltage of industrial frequency of 50 Hz.

The same conclusion can be drawn from standard GOST [2], according to which, for classes 6-220 kV, the industry produced valve arresters of the RVO, RVS, RVMG series, which triggered only from overvoltages of large magnitude that is characteristic of lightning processes. Protection of equipment insulation from switching overvoltages could be performed only with the combined valve arresters of the RVMK series, which were not in the norms for classes 6-220 kV, and were produced and installed only for 330 kV and higher.

Therefore, the first question that designers have is: "is it necessary to protect 6-220kV cable lines with the help of a MOA if cables are laid in urban cable networks and industrial networks where there are no lightning overvoltages"? I.e. there are no lightning overvoltages in urban cable networks, and switching overvoltages, according to GOST [1,2], are not dangerous. Does this mean that when designing such networks (Fig.1), there is no need for cable lines to be protected from overvoltages with the help of MOA installed at their ends?

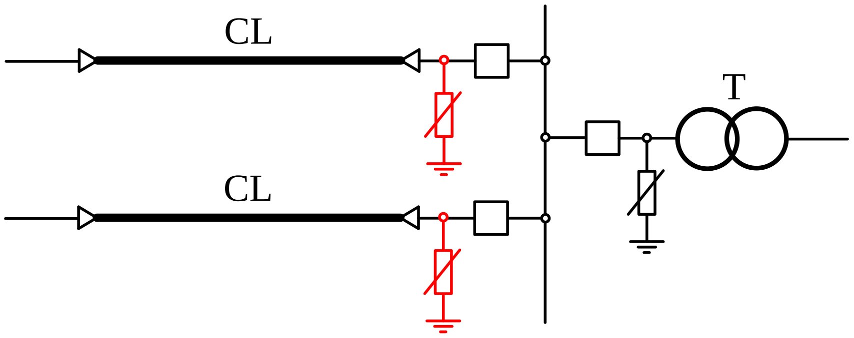

Fig.1. Protection of the cable network from overvoltages.
The red color shows the MOA, the need for which is questionable.

The cost of a MOA is negligible compared to that for any cable line. For example, a three-phase 110 kV MOA kit costs about 3 thousand euro, while a 110 kV cable line, taking into account its installation, costs up to 1 million euro for each kilometer of the line route. Because of this, designers prefer not to take responsibility and provide for protective MOA in the schemes. However, let's try to answer the question: "Is there really a need for a MOA in urban networks of 6-220 kV?" – not from an economic point of view, but from a technical.

The danger of the switching overvoltage to the equipment insulation (recall that there are no lightning overvoltages in urban networks) is determined by two factors:

– the insulation strength of the equipment;
– the level of overvoltages, i.e., the properties of switches.

Since the release of standards GOST [1,2], the requirements for the insulation strength of networks have not changed, but the park of switches has changed – instead of oil and air switches, vacuum and SF6 ones are now used in networks. Consequently, the question of the need to protect the insulation of urban cable networks of 6-220 kV can be replaced by another question: did the replacement of switches with new types lead to an increase in the magnitude of switching overvoltages or to a critical change in the shape of their pulses? If new vacuum and SF6 circuit breakers create more dangerous overvoltages than the old types (oil and air), then protection against overvoltages may be required, if less dangerous, then protection is obviously not required, because even before it was not needed (see [1,2]).

In my opinion, in 6-220 kV networks, after the renewal of the switch park, switching overvoltages have become less dangerous, that is, in urban networks, the installation of a MOA on cable lines to protect them from switching overvoltages was not required before, and now is not needed even more. The same opinion is held by well-known experts in the books [3,4].

Switches have three characteristics that directly affect the overvoltages they create:

– cut-off current i_{CC};
– the speed du/dt of restoring electrical strength between contacts after arc quenching;
– the critical speed di/dt of approach of the current to zero, at which it is still possible to extinguish the arc.

Cut-off current

The cut-off current is the amount of current that the switch can spontaneously cut off by extinguishing the arc, without waiting for the AC current to pass through the zero value. When switching off inductive elements, such as reactors and transformers, an instantaneous current interruption (current cut-off) leads to overvoltages, because inductance does not allow a sudden change in current. Since modern vacuum and SF6 circuit breakers have a cut-off current of no more than 2-3 A, which is less than the cut-off current of oil and air switches, there is no danger to the equipment. Strictly speaking, the cut-off current is a phenomenon that does not manifest itself in any way when switching cable lines, which are more capacitance than inductance, and therefore could not be considered here.

The speed of recovery of electrical strength

The rate of restoration of electrical strength determines the number of breakdowns of the gap between the contacts, which can be during switching. If, when disconnecting the connection, the arc in the switch goes out, then a voltage will arise between the contacts, and the gap must withstand it. If the speed of restoring the insulation strength of the gap was insufficient, then the voltage between the contacts after extinguishing the arc will lead to a breakdown of the gap and a new ignition of the arc. Since each new breakdown is, in fact, a new activation of the connection and a recharge of its capacity from one voltage to another, switching overvoltages occur at the connection, and of a higher magnitude than when it is normally (with no breakdowns) switched on under network voltage.

Modern vacuum and SF6 circuit breakers have a higher strength recovery rate than oil and air-type switches. Therefore, the switching of cable lines by modern switches is not accompanied by repeated breakdowns of the contact gap and switching overvoltages of increased value.

The critical speed of the current approach to zero

The critical speed of the current approach to zero is also the parameter that determines the number of breakdowns of the contact gap, and hence the level of switching overvoltages. The critical speed of the current approach to zero characterizes the ability of the switch to extinguish AC currents of a particular frequency. For example, a vacuum switch is able to extinguish currents even of very high frequency, because near the moment of the transition of alternating current through zero, an arc in vacuum is capable of rapid decay (these are the properties of vacuum). The SF6 switch, on the contrary, is not able to extinguish high-frequency currents, because in the short time when the alternating current of the arc is near the zero value of the sine wave, the arc decay processes do not have time to complete. In other words, the SF6 switch reliably extinguishes only low-frequency currents that are close to the zero value of the sine wave for a time that is sufficient for quenching and decay of the arc. Let us explain why the ability of a vacuum circuit breaker to extinguish AC currents of almost any frequency in some cases is fraught with the appearance of dangerous switching overvoltages.

Suppose that the switch has received a command to turn off the three-phase connection, the phase AC currents of which have a shift of 120°. Let the industrial frequency current in phase "A" be close to the zero value of the sine wave, and therefore, almost immediately after receiving the shutdown command in phase "A", the arc will go out, which will lead to incomplete power supply of the connection in phases "B" and "C". In these two phases, in addition to the industrial frequency current, a current of a higher frequency will appear, associated with a transient process in the circuit that began after the arc was extinguished in phase "A", and the formation of the mentioned incomplete-phase mode.

The SF6-operated switch would not react in any way to the appearance of high-frequency components superimposed on the AC current of 50 Hz in its disconnected current. A vacuum circuit breaker, on the contrary, with a sufficient value of the high-frequency component of the current in comparison with the AC current of 50 Hz, can react to it and extinguish the current not to zero of the AC current of 50 Hz, but to one of the zeros of the total current having both 50 Hz and a high frequency. Moreover, it should be noted here that there can be many zeros of the total current, and they appear immediately after the current is extinguished in phase "A", i.e., already with a small course of diverging contacts. It turns out that the vacuum switch, due to the reaction to the high-frequency current, will extinguish the arc of phases "B" and "C" almost immediately after the arc has extinguished in phase "A". In other words, the command to disconnect the connection has just been received, and in all three phases the arc has already gone out (in phase "A" – due to the natural transition through zero of the 50 Hz current, in phases "B" and "C" – due to the reaction of the vacuum switch to the high frequency current that appeared after the phase arc was extinguished "A").

The rapid extinguishing of the arc, which occurred immediately after receiving the shutdown command, i.e. with a small distance between diverging contacts, is bad because there is not yet sufficient strength between the contacts due to their proximity. Consequently, after the arc is extinguished, the voltage that appears between the contacts will certainly cause a repeated gap breakdown, and, as explained earlier, it leads to overcharging of the connection capacity and switching overvoltages of a higher magnitude than with a simple switch-on with zero initial conditions.

The ability of a vacuum circuit breaker to turn off AC currents of both low and high frequency is its remarkable feature, which is useful, for example, in various special-purpose equipment. But in the power industry, where currents have a frequency of 50 Hz, the ability to turn off high-frequency currents, unfortunately, is superfluous and spoils the reputation of a vacuum circuit breaker, since it generates switching overvoltages.

In fact, the problem of the switch's reaction to high-frequency currents is only where these currents are noticeable against the background of the industrial frequency current. This situation sometimes occurs when switching motors [3,4], but when switching cable lines in urban cable networks, it is uncharacteristic. Hence, insulation protection against switching overvoltages in 6-220 kV networks was not required before, and now it is not required too. The exception is networks having motors of 6-10 kV.

The 6-10 kV motor switching by vacuum switches may be accompanied be repeated gap breakdowns due to the rapid quenching of the current arc containing high-frequency components. Thus, motors require insulation protection against switching overvoltages. Strictly speaking, motors in comparison with other network equipment have the smallest insulation strength reserves, and therefore their insulation protection against overvoltages is always recommended, regardless of the type of switching device.

Despite the above considerations, which indicate that there is no need for a MOA at the ends of cable lines in urban cable networks, such MOA are common. If in 110-220 kV networks this can be explained, for example, by the high cost and responsibility of cable lines, then for 6-35 kV lines the presence of MOA in cable sections is surprising. The fact is that although the MOA is able to limit switching overvoltages, it does not work effectively in 6-35 kV networks. This is due to the fact that any MOA begins to pass noticeable currents through itself only at voltages twice its maximum operating voltage, which in networks with isolated/compensated neutral is selected equal to the linear voltage of the 6-35 kV network. This means that the 6-35 kV MOA begins to pass currents and thereby limit overvoltages only when their value is more than $1.73 \cdot 2 = 3.5$ p.u. with respect to the phase voltage of the 6-35 kV network. At the same time, most switching overvoltages have a value of no more than 3.0 p.u. of the phase voltage of the network, i.e. less than the value of 3.5 p.u., at which the MOA effectively enters into operation.

So, in urban networks, protection of 6-35 kV cable lines from switching overvoltages is not required for two reasons:

- with any type of circuit breakers, there are no switching overvoltages that are dangerous for cable insulation;
- even if dangerous overvoltages did occur, modern MOA, selected for the line voltage of a network with an isolated/compensated neutral, would be ineffective in limiting them.

Despite the well-known arguments given, often each cell of a 6, 10, 20 kV cable line has a set of MOA, partly due to the low cost of MOA. At the same time, the possible damage in case of poor-quality manufacturing of the MOA and its damage is enormous – this is not only the burnout of the cable cell, but also in some cases a short-circuit on the busbars with their full blackout.

As for 110-220 kV cable lines, here, as well as in 6-35 kV cable networks, switching overvoltages in most cases have a magnitude of no more than 3.0p.u., which is not dangerous for insulation. However, unlike 6-35 kV in 110-220 kV networks, the use of MOA makes some sense, because they are selected not for linear, but for the phase voltage of the network, and therefore limit overvoltages not to the 3.5 p.u. level, but to 2.0. Reducing overvoltages from the 3.0 p.u. to 2.0 level can be considered useful from the point of view of saving insulation resource of expensive 110-220 kV cable lines.

3. PROTECTION AGAINST LIGHTNING OVERVOLTAGES

The need for protection against lightning overvoltages of cable lines of any voltage classes (from 6 to 500 kV) at first glance is not in doubt, and therefore, when designing cable lines at their ends, as a rule, the installation of an MOA is provided. First of all, the MOA is placed in transition points of overhead lines to cable, because the main source of lightning overvoltages are lightning strikes into overhead lines.

For example, if there is a cable insert into an overhead line of 6-500 kV, then sets of MOA of the appropriate voltage class are installed on the transition towers at both ends of the insert (Fig.2a). If the cable insert is used to organize the entry of the overhead line into the switchgear (Fig.2b), then the MOA is placed at the transition of the overhead line into the cable line, but at the end of the cable line from the side of the switchgear, the MOA is placed less often, because they are already available on busbars and power transformers (T).

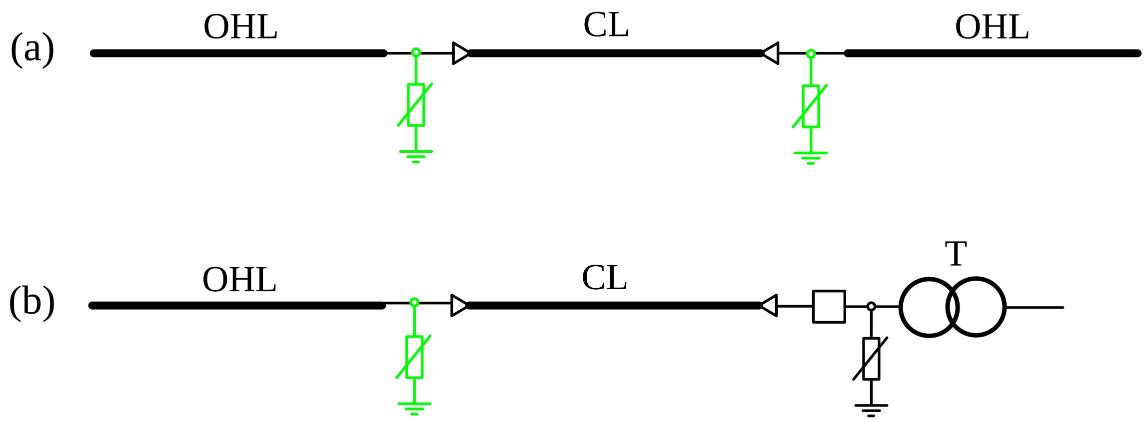

Fig.2. Protection of the mixed cable-overhead line from overvoltage.
The green color shows the MOA, the need for which is mandatory.
(a) – cable insert into the overhead line;
(b) – cable entry of the overhead line into the switchgear.

The listed rules for the placement of MOA to protect the insulation of cable lines from lightning overvoltages are simple and understandable. However, sometimes experts require project adjustments and a reduction in the number of protective MOA, while referring to one of the paragraphs of the 2nd chapter of the old national standard PUE (rules of electrical installations), which states: "Cable inserts in overhead lines with a length of less than 1.5km should be protected at both ends of the cable from lightning overvoltages by tubular or valve arresters ...". From this point of the PUE, it follows that with a length of cable inserts more than 1.5 km, the installation of an MOA at the ends is not required. It is impossible to agree.

The dependence of the protection scheme on the length of the cable insert really has a justification. The fact is that the cable line has a low wave impedance, and lightning waves, passing from the overhead line into the cable, initially reduce their magnitude, but then as a result of a series of wave reflections from the ends of the cable line, the voltage on the cable increases and may pose a danger to its insulation. The longer the cable, the more time it takes for the wave to run from the line beginning to the end and back, which means that it is unlikely that as a result of a series of wave reflections, the voltage on the cable will have time to grow to a dangerous value, because as the wave propagates along the cable, it fades.

Probably, the developers of the PUE considered that for cable lines with a length of more than 1.5 km, the process of voltage rise in the cable is so stretched in time that the voltage rise will be stopped at a level safe for insulation (due to the attenuation of waves as they propagate along the cable from the beginning to the end and back).

At the same time, there is another case of lightning overvoltages on the insulation of cable inserts, which is clearly not taken into account in the PUE – it is a lightning strike into the tower of the transition point. With such a strike, the lightning current flows from the tower body into the ground, creates a significant potential on the tower body and its traverse, which can cause a breakdown of the insulation of the termination from its grounded housing to the cable core. The only way to protect the termination from such a breakdown is to install an MOA next to it, and the need for such an MOA is present at each end of the cable at each cable termination and does not depend on the length of the cable line in any way.

So, the requirements of the PUE, allowing not to protect cable inserts with a length of more than 1.5 km, are certainly erroneous. Any transition tower, regardless of the cable length, must be equipped with MOA to protect terminations from lightning overvoltages.

4. CABLE OUTER SHEATH PROTECTION AGAINST OVERVOLTAGES

Modern lines are often made with single-core cables that have a core, insulation, metallic screen, outer sheath. In such cases, in addition to protecting the main insulation, the issues of limiting overvoltages on the outer sheath also require discussion, because the outer sheath integrity influences the possibility of moisture penetration into the cable.

The need to protect the sheath from overvoltage arises because at present, in order to combat currents and losses in screens that occur with screens two-side grounding (Fig.3a), schemes of screens one-side grounding (Fig.3b) or cross-bonding (Fig.3b) have become widespread. In the ungrounded end of the cable screen or in the node of the scross-bonding it is necessary to provide for the installation of special on-screen MOA, which are placed either in the end link-boxes (ELB-MOA), or in the cross-bonding link-boxes (CBLB-MOA).

The mechanism of occurrence of lightning and switching overvoltages between the screen and the ground is described in [5], which also provides considerations on the choice of characteristics of screen MOA.

The main characteristics of the MOA are the highest operating voltage and energy intensity. Since the sheath of a single-core power cable, regardless of its rated voltage class, has the same thickness of about 5-6 mm (approximately corresponds to the insulation strength of class 6 kV), the same class of MOA can be used to protect it from overvoltage.

In other words, the main insulation of the cable between the core and the screen is protected by MOA of the appropriate voltage class (from 6 to 500 kV) installed at the ends of the cable at its terminations (if we are talking about urban cable networks of 6-220 kV, then such MOA may be absent as it was discussed above). And here is the cable sheath:

- regardless of the presence of MOA at the cable terminations, cable must be protected by on-screen MOA placed either in the place of grounding of the screens, or in the nodes of the screens cross-bonding;
- on-screen MOA must always be of voltage class 6 kV.

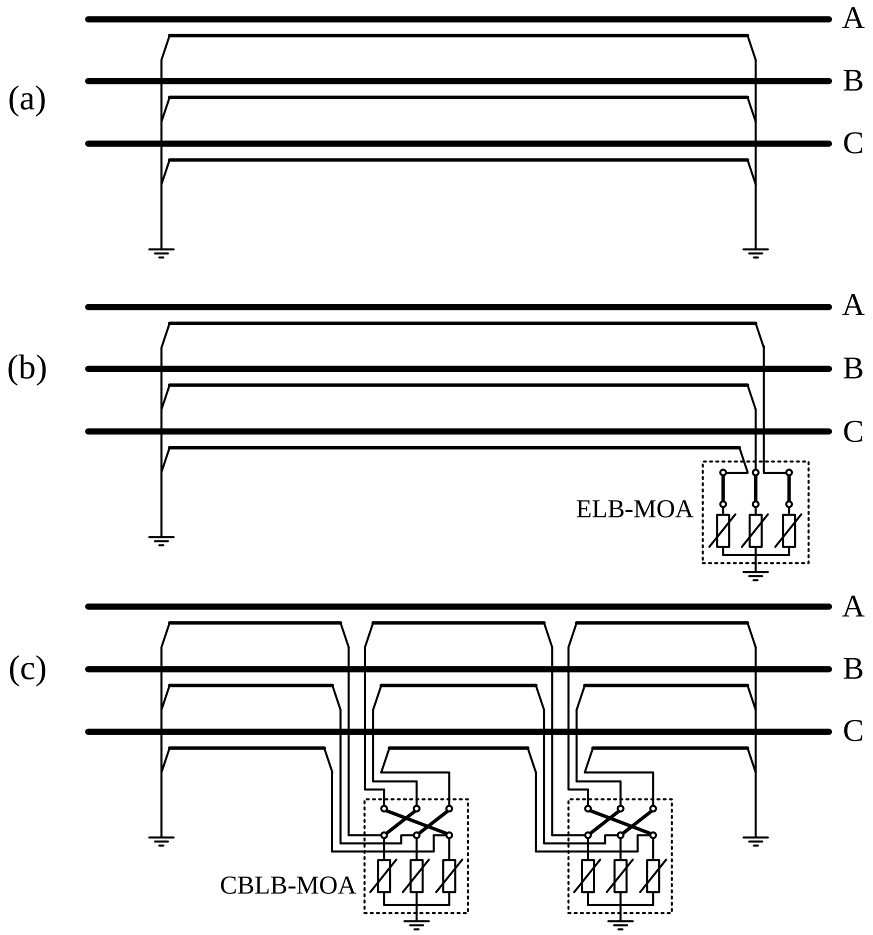

Fig.3. Schemes of screens bonding/grounding of single-core power cables 6-500 kV:
(a) – two-side grounding; (b) – one-side grounding; (c) – screens cross-bonding.

Attempts to use MOA of a voltage class less than 6 kV (say, 1.5 or 3 kV) to protect the cable sheath result in damage to such MOA, and for this reason are strongly discouraged. Unfortunately, a series of damage to the on-screen MOA on cable lines, associated with the wrong choice of the operating voltage of the MOA, for some reason gave rise to a desire "just in case" to use an MOA of increased energy intensity, although the existing energy intensity of 2-3 kJ/kV was sufficient with a margin and was not the cause of damage.

For example, in a number of projects, it is now possible to find requirements for the energy intensity of the MOA at the level of 7-10 kJ/kV (brought to the highest operating voltage of the MOA and indicated for one current 2 ms pulse). Such energy intensity values actually correspond to the limit values that the industry is currently capable of producing. As for the technical need for such a strong MOA, it is completely absent, because according to operating experience, some computer calculations, as well as according to the well-known standard of JSC "FSK EES" [6], the value of 2-3 kJ/kV is sufficient with a margin.

An attempt to put into cables a MOA with an energy intensity of more than 2-3 kJ/kV not only makes no technical sense, but is also extremely harmful, since it entails a significant increase in the dimensions of the MOA and end link-boxes and cross-bonding link-boxes in which such MOA are installed. For example, in typical well of screen cross-bonding, it turns out to be impossible to place a screens cross-bonding link-box with an MOA of 7-10 kJ/kV, if only because it does not pass into the manhole cover of this well.

There are also known several projects of cable lines where the on-screen MOA was considered a kind of "prefix", "supplement", "continuation" of the main high-voltage MOA, and on this basis the energy intensity of the on-screen MOA was assumed to be the same as that of main high-voltage MOA, i.e. more than 2-3 kJ/kV, thereby generating the mentioned problems with the dimensions of the end link-boxes and the cross-bonding link-boxes.

Once again, I would like to note that the on-screen MOA, regardless of the parameters of the main MOA, is always a class of 6 kV with an energy intensity of about 2-3 kJ/kV.

5. CONCLUSIONS

1. Protection of 6-35 kV cable lines from switching overvoltages using high-voltage MOA is not required, regardless of the type of switch. The exceptions are those 6 and 10 kV cable lines that feed the motor load. For them, the installation of an MOA is necessary, but rather for the purpose of protecting the engine than the cable insulation itself.
2. Protection of 110-220 kV cable lines from switching overvoltages using high-voltage MOA is recommended, and of 330-550 kV cable lines is mandatory.
3. Protection of 6-500 kV cable lines from lightning overvoltages is required regardless of their length. In particular, at the points of transition of overhead lines to cable and back, a high-voltage MOA of the appropriate voltage class should be installed next to the cable terminations. The requirements of the standard PUE, allowing not to protect cable inserts with a length of more than 1.5 km from lightning overvoltages, are erroneous.
4. Protection of the outer sheath of single-core 6-500 kV cable lines from lightning and switching overvoltages should be carried out in schemes with one-side screens grounding or their cross-bonding, regardless of the protection scheme of the main insulation. As a protective device for the outer sheath, an on-screen MOA of voltage class 6 kV with an energy intensity of 2-3 kJ / kV should be used. The use of an on-screen MOA of a voltage class of less than 6 kV or with an energy intensity of more than 2-3 kJ / kV is erroneous, fraught with problems during installation and accidents during operation.

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