Transient Resonance in Schemes with 6-500 kV Cable Lines

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Abstract* — *The article analyzes the impact of the new generation of cable lines for transient processes in electrical networks. It is shown that modern cables with XLPE insulation have small surge impedance. This fact in circuits containing overhead lines or power transformers, is able to cause intense transients, accompanied by overvoltages dangerous to equipment.

Keywords: cable line, XLPE insulation, cable surge impedance, transient processes, lightning overvoltage, switching overvoltage, overhead line, power transformer.

I. INTRODUCTION

Over the years, more and more new cables lines (CL) with cross-linked polyethylene insulation (XLPE) have appeared in 6-500 kV power networks. In particular, they are used:

- to repair damaged sections of old cables with paper-oil insulation;
- to replace overhead lines with underground cable lines;
- to connect power transformers to the network.

The wave parameters of the new cables differ from the parameters of the old ones, and they differ even more from the parameters of overhead lines and power transformers. As a result, there are more and more objects in networks for which complex multi-frequency transients accompanied by dangerous overvoltages should be expected.

The spreading of cables with XLPE insulation requires the research of the behavior in special circumstances.[13,14].

This article is not the result of detailed computer modeling, especially with regard to assumptions about the causes of transformer damages. Only hypotheses are being expressed here, but they could be the basis for a whole scientific work, during which, perhaps, it would be possible to reliably explain a number of equipment insulation damages that have already occurred and prevent new ones.

It was noted in [1] that the electrical capacity of XLPE insulation cables can be up to several times higher than that for old cables with paper-oil insulation. Also new CLs are often built of long length and may contain several cables for each phase. As a consequence, the capacity of the modern CL becomes significant.

One example of the negative consequences of high capacity is given in the article [2], where the case was considered with CL and transformer connected to the same busbars. At the moment t_{sw} when disconnected CL was switched to the busbars, damage occurred to the inter-turn insulation of the power transformer with windings in a triangle (Fig.1). Studies showed that this CL had an electrical capacity several times greater than the total capacity of other lines and equipment connected to busbars. Because of this, CL switching caused a big charging current and in fact a three-phase short circuit at the busbars and the transformer bushings with a corresponding voltage drawdown to almost zero values and its recovery during an intensive transient process accompanied by overvoltages.

Another negative manifestation of a large capacity is that modern cables have a very small surge impedance, at the level of 10÷30 Ω, and laying several cables per phase reduces it even more. Unpleasant consequences of a small Z, as expected, can occur in circuits where voltage through such a CL is applied to network elements with a higher Z, for example:

- to an old cable line (Fig.2a),
- to an overhead line (Fig.2b),
- to a power transformer (Fig.2c).

Let's consider these cases in more detail and formulate the reasons for concerns.

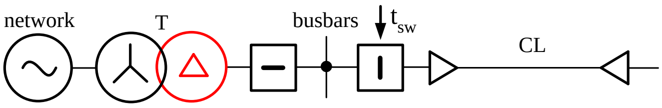

Fig.1. An example of a scheme where a transformer feeds the outgoing CL.

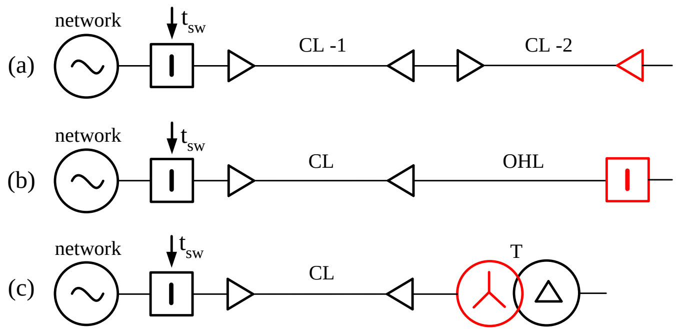

Fig.2. Examples of schemes with different CL placements.

II. SURGE IMPEDANCE OF THE CABLE

As a rule, when talking about the electrical parameters of the line, they mean its linear capacitance and inductance. However, there is a whole series of cases when the line is represented not by lumped parameters, but otherwise by using the surge impedance Z and the wave propagation velocity υ. One of these cases is the study of transients when a line of length l is energized (Fig.3).

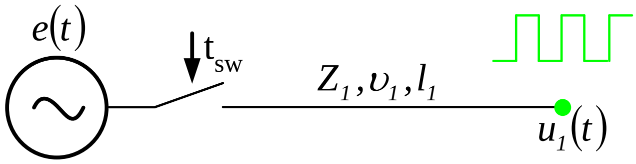

Fig.3. Energizing a line with a length of l.

Fig.4 shows an oscillogram of the voltage at the end of the line when it is switched on near the maximum of the sine wave of the network phase voltage. At the moment t_{sw} of switching on, a network voltage wave goes into the line, the magnitude of which is equal to the amplitude of the network phase-to-ground voltage, and the front has a rectangular shape. Further, this wave propagates from the beginning of the line to its end and back, undergoes a series of reflections and gradually fades due to the influence of losses. As a result, the voltage at the end of the line is obtained in the form of damped U-shaped oscillations.

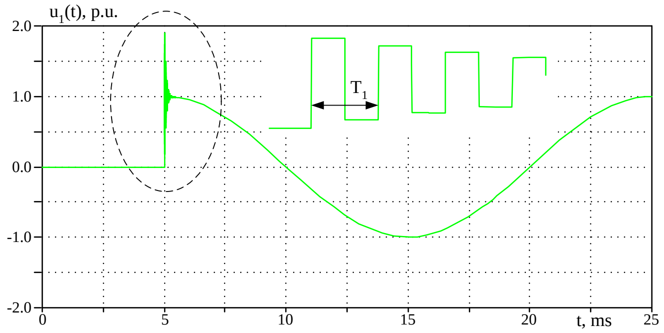

Fig.4. Voltage at the end of the line when it is switched on (for the scheme Fig.3).

The velocity of the wave as it propagates along the line can be estimated as

$$\upsilon = \upsilon_0/\sqrt{\varepsilon}$$

where υ_0 – the velocity of the electromagnetic wave in vacuum (300 m/mks or $3 \cdot 10^8$ m/s),
ε – the relative permittivity of the line insulation (for air it is 1.0, for XLPE it is 2.4 p.u.).
Thus, for an overhead line the velocity is 300 m/mks, and for the XLPE cable line it is half times less – about 200 m/mks.
The period T of voltage fluctuations at the end of the line can be calculated as 4 travel times of the wave from its beginning to the end

$$T = 4 \cdot \tau = 4 \cdot (l/\upsilon)$$

The interconnection of voltage and current waves which go into the line (at the time of applying voltage to it) is determined by the surge impedance of the Z line. Its value for CL with XLPE insulation is shown in Fig.5 (based on the ABB catalog or [1]). Also, the surge impedance is often known as

$$Z = \sqrt{L^*/C^*}$$

where L^* and C^* are the linear inductance and capacitance of the line.

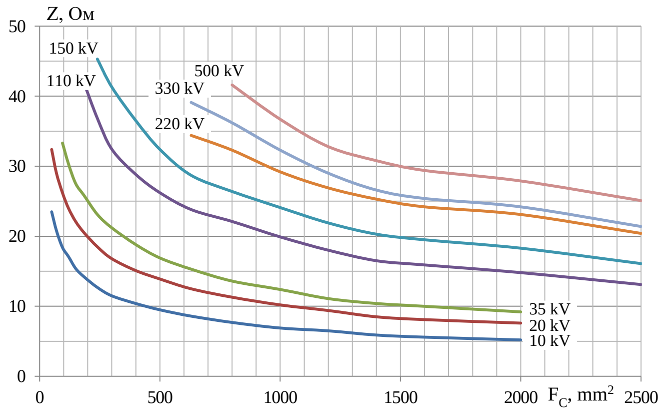

Fig.5. Surge impedance of 6-500 kV CL with screens grounded at both-sides, depending on the core cross-section F_C.

Fig.5 shows that the surge impedance of modern CLs can vary in a wide range of values from 5 to 40 Ω. If we talk about the most common core cross-sections F_C, then:
for 6-35 kV we have $Z \approx 10 \div 15$ Ω,
for 110 kV we have $Z \approx 15 \div 20$ Ω,
for 220-500 kV we have $Z \approx 20 \div 30$ Ω.
These surge impedances are typical for CLs which have simple both-sides grounding of metallic screens [1,3]. With one-side grounding of screens or their cross-bonding, the behavior of cables is different to shown in Fig.4. For example, with one-side grounding, the processes depend on whether the line is energized from the side where the screen is grounded or from the side where the screen is ungrounded. If we talk about cables with screens cross-bonding, then the processes are even more complicated here, since in addition to the ends of the line, wave reflections also occur at cross-bonding points of the route, and their nature depends on waves which propagate not only along the considered phase of the line, but also along two neighboring phases (because all phases connected by screens which pass from one phase to another). However, we will not elaborate, but focus on the main thing – the phenomenon of transient resonance.

III. CONDITIONS FOR THE RESONANCE

When an uncharged line is switched on, the voltage at its open end will not exceed two amplitudes of the network phase-to-ground voltage (Fig.4). Pulse voltages of a level of 1.5÷2.0 p.u. do not pose a danger to the insulation of serviceable equipment. However, the level of voltage may increase significantly if two serial lines are switched together (Fig.6a).

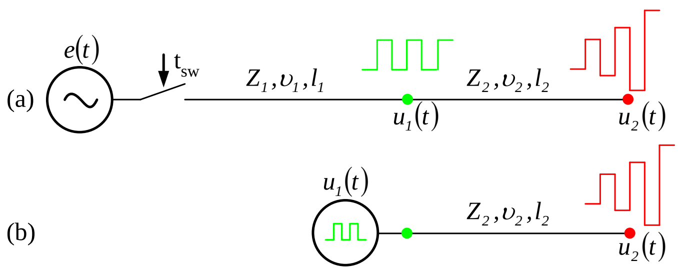

Fig.6. Energizing of two serial lines: (a) – original scheme, (b) – its equivalent.

When two lines with different surge impedances $Z_1 \neq Z_2$ connected one by one in series are energized, at the connection point the processes of waves refraction and reflection occur. The most intensive processes occur in cases of significant difference in line surge impedances ($Z_1 << Z_2$ or $Z_1 >> Z_2$). However, only the case of $Z_1 << Z_2$ is interesting, when the wave, refracted during the connection point from the 1st line to the 2nd, increases in magnitude, becoming more dangerous for the equipment insulation.

The situation when $Z_1 << Z_2$ is also notable for the fact that the transition of waves from the 1st line to the 2nd is almost not accompanied by their reflection back into the 1st line. If the wave has reached the end of the chain of lines, reflected and returned to the connection point already from the 2nd line, then it is reflected back into the 2nd line, without causing refraction into the 1st line. Thus, the condition $Z_1 << Z_2$ guarantees that the 1st line pumps dangerous voltage in the 2nd line, however, the 2nd line is not able to influence the processes in the 1st line in any way. Therefore, the 1st line can be considered as a voltage source acting on the 2nd line (scheme Fig.6b).

In the scheme Fig.6b, the source's voltage $u_1(t)$ has a periodic U-shaped waveform with an oscillation period T_1 and a frequency $f_1 = 1/T_1$. If we talk about the 2nd line, then voltage fluctuations also have the form of U-shaped pulses with a period T_2 and a frequency $f_2 = 1/T_2$.

It is known that in the case of $f_1 = f_2$, when the frequencies of the driving force of the source and the self-oscillations of the line coincide, a resonant voltage increase occurs at the end of the line in the schemes like Fig.6b. Here as a famous example can be considered a fairly well-studied capacitive effect of 330-750 kV long transmission line connected to the network only by one side, when, with an increase in the line length, the voltage increases at the open end, reaching the most dangerous values at a length of 1500 km, since the self-oscillations frequency of the overhead line becomes close to the network's 50 Hz.

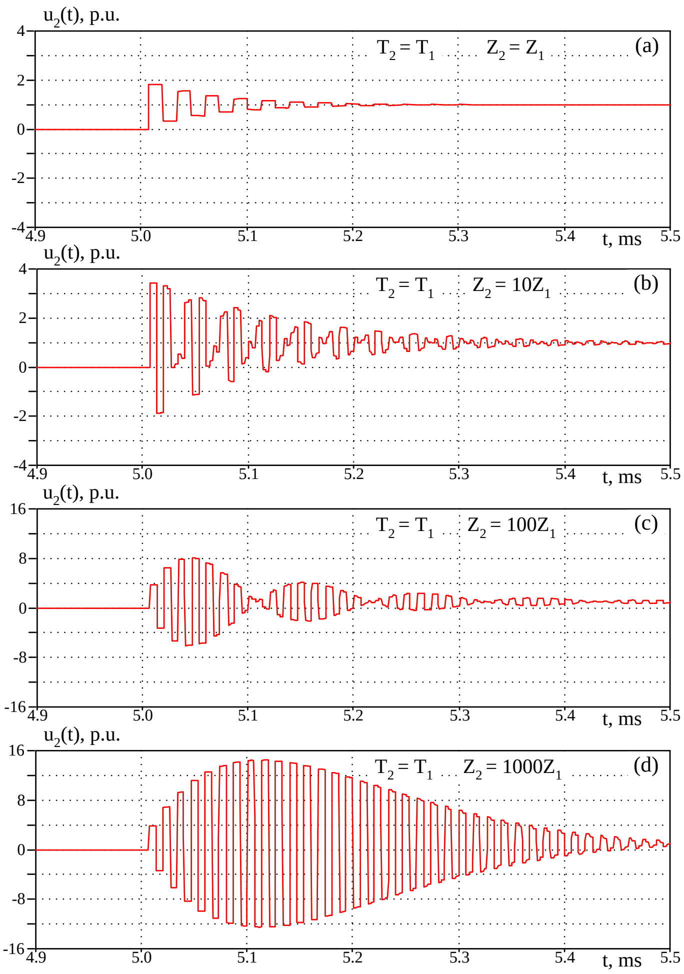

Fig.7. Voltage at the open end of two serial lines when they are switched on (scheme Fig.6), depending on the ratio of surge impedances Z_1 and Z_2.

By simple reasoning, it was shown that in circuits with two lines connected in series, there are two main requirements for the occurrence of resonant overvoltages:

– significant difference of surge impedances $Z_1 << Z_2$;

– coincidence of frequencies $f_1 = f_2$ (it means that periods $T_1 = T_2$, run time $\tau_1 = \tau_2$).

Examples of voltage calculations at the open end of the two in series lines are shown in Fig.7. It can be seen that the more the surge impedances of the lines differ (provided that the periods are equal), the more dangerous overvoltages can be. At this stage, we don't take into account the effect of gapless/gapped metal oxide surge arresters (MOA, [4-6]).

Two-frequency circuits were considered earlier, for example, in one of the chapters of the scientific work [7], but there it was about network elements with lumped inductance and capacitance, and not at all about lines with distributed parameters characterized by one or another wave travelling time. Also, in [7], no simple explanation of the essence of the observed phenomenon was given.

The described case of resonant voltage rise at the open end of the series lines allows us to assume for what reason and under what conditions equipment may be damaged in power networks with modern cables. It is in the schemes of the form of Fig.2b and Fig.2c, when voltage is supplied to a network element with a large surge impedance through a cable with a small surge impedance, the resonance conditions indicated above can be fulfilled.

For example, the surge impedance of a cable with XLPE insulation is only no more than 30 Ω (Fig.5), but for ordinary overhead line it is already about 10 times higher and for transformer it is about 100÷1000 times higher than for the cable. This provides $Z_1 << Z_2$.

Of particular danger are the cases $T_1 \approx T_2$ ($\tau_1 \approx \tau_2$), characteristic for circuits where the length of the cable section is of the same order with the length of the overhead line or with the length of the transformer winding.

IV. MIXED CABLE AND OVERHEAD LINES

There is a whole range of issues for mixed cable and overhead lines, including:

requirements for the list of the equipment of connection points (CP);

requirements for the grounding resistance of CP;

organization of line automatic reclosure (LAR);

organization of protection against lightning overvoltages.

The optimal list of the CP equipment (that is, the need to install disconnectors and measuring transformers on the CP), is a problem that has not yet found a single solution [8]. Also, there are no final requirements for CP grounding resistance.

Proposals for LAR were made in [9,10] and consisted in equipping the cable screen groundings points with special measuring current transformers, allowing in case of damage on the cable section to form a command to ban LAR.

Considerations for protection against overvoltage were expressed in [11], where it was assumed that the main danger is not switching, but lightning processes. In particular, [11] noted the inaccuracy of requirements, allowing not to put MOA at the ends of cable sections longer than 1.5 km. The absence of these MOA has already led to significant damage at a number of facilities, and therefore, at all connection points, regardless of the CL length, MOA should be placed (#1 in Fig.8a). Also, according to [11], the MOA is also needed at the input of the CL to the switchgear (#2 in Fig.8a) to its protection from lightning overvoltages.

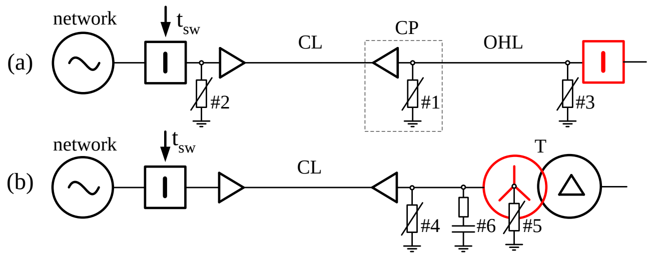

Fig.8. Protection schemes of cable and overhead lines (a) and transformers (b).

New research has given grounds to believe that not only lightning processes, but even switching overvoltages (namely, the phenomenon of transient resonance), can pose a serious danger for cable and overhead lines. To combat these overvoltages, which may occur at the end of the overhead line during switching, a MOA should be installed at the end of the line before line breaker (#3 in Fig.8a). Also, MOA #3 is very useful for protecting the insulation of the switchgear from lightning waves coming from the line. If these MOAs do not exist, then it is possible to reduce the impact on the equipment by another solution – to power up the line with network voltage 50 Hz not from its cable section, but from the overhead (the levels of lightning overvoltages will not change, but transient resonance will be excluded).

Only the presence of MOA on any CP, as well as on all the inputs of CL and overhead lines to switchgear, will fully protect the cable and overhead lines from overvoltages of both lightning and switching nature (including transient resonance).

V. POWER TRANSFORMERS

It is believed that the surge impedance can be characterized only by those lines that are located along a grounded surface (ground, screen etc.). In this case, the linear parameters (inductance and capacitance) are unchanged along the line route. However, for example, in the world literature, surge impedance is also introduced for overhead line towers (pylons), although they are perpendicular to the ground, and the capacitance to the ground differs significantly for the upper and lower elements of the tower. Also, the surge impedance is introduced for the lightning channel in the area between the cloud and the ground, and even for the windings of the power transformer. The use of a wave model of transformer windings is partly controversial, but it allows us to make new assumptions about the possible causes of insulation damage, which may be useful, since according to [12] many accidents have not yet been explained.

If we consider the transformer winding as a line with distributed parameters, then its surge impedance can be estimated in thousands of Ω, the wave propagation speed is at the level of 150÷200 m/mks (both for windings in oil and for dry transformers). The length of the transformer windings can reach several kilometers, as well as the length of cable lines.

The surge impedances of the cable and the transformer windings meet the resonance condition $Z_1 << Z_2$ much better than it was for the cable and the overhead line. Also, the second resonance condition $T_1 = T_2$ is most often feasible for cables and transformer windings, since the wave velocities and lengths can be comparable (whereas the length of the overhead line, as a rule, is several times longer than the length of the cable sections). Thus, the most dangerous consequences from the phenomenon of transient resonance should be expected for circuits with cables and transformers, and not at all for cable-overhead lines.

When a power transformer is turned on under voltage through a cable line (Fig.2c), the processes in it will depend on the connection scheme of the windings (star, triangle), as well as on the state of the transformer's neutral:

when connecting the windings to a star with an ungrounded neutral, the most dangerous voltages are expected near the neutral end of the winding, reaching maximum values under the condition $T_1 = T_2$ (if $\upsilon_1 \approx \upsilon_2$, it means cable and winding are of equal length);

when the windings are connected to a star with a grounded neutral or when connected to a triangle, the most dangerous voltages are expected in the middle part of the winding, reaching maximum values under the condition $T_1 = T_2/2$ (if $\upsilon_1 \approx \upsilon_2$, it means the cable is 2 times shorter than the winding).

For example, if the transformer winding has a length of 2000 m and is connected to a star with an ungrounded neutral, then it will be dangerous to turn it on under voltage through a cable about 2000 m long, and if the neutral is grounded, then it would be dangerous to turn it on through a cable about 1000 m long. The authors know several cases of insulation breakdown of the windings connected to the star at the time they are switched on through cables with XLPE insulation. Among these cases:

windings of 6-35 kV dry transformers with an ungrounded neutral with cable lengths of 6-35 kV in the range of 1000÷2000 m;

windings of 500 kV block transformers with grounded neutral at hydroelectric power plants and nuclear power plants in the territory of USSR and China with 500 kV cable lengths in the range of 500÷1000 m (there were a number of accidents when a 500 kV SF6 gas insulated line was used instead of a cable, also having a low surge impedance).

Additionally, we explain that the windings connection scheme (star or triangle) of a particular transformer and its neutral state (grounded or not grounded) are fundamental. At the same time, the network neutral grounding method (isolated, grounded) and the voltage class of the windings (6-35 kV, 110 kV, 220-500 kV) do not matter much here.

Also note that for the ungrounded neutral of the transformer, there is no voltage in it when the three phases of the switch (Fig.8b) work synchronously. If one of the phases, due to the available spread, turns on a little earlier than the other two (say, only 0.1 ms earlier), then this is already enough for dangerous overvoltages to occur in the ungrounded neutral of the transformer during this time and cause insulation damage.

If it was enough to place MOA in the necessary places to protect cable and overhead lines, then it is not always possible to do this with transformers in cable networks. For example, a MOA at the transformer bushings (#4 in Fig.8b) will not affect the overvoltage of the transient resonance inside transformer in the middle of the winding or near the neutral. Or with ungrounded neutral, it is not always possible to connect a MOA to it (#5 in Fig.8b), since for some transformers there is no special bushing for neural and neutral is kept inside.

In these cases, when the use of MOA is impossible, it is necessary to avoid switching schemes of the transformer through a cable of dangerous length. Also here it can be proposed to install special RC-circuits on the transformer bushings (# 6 in Fig.8b), the resistance of which is close to the surge impedance of the cable, but of course we can only talk about 6-20 kV networks, where the dimensions of such RC-circuits are still reasonable.

VI. CONCLUTIONS

Modeling of transients in lines and transformers is a very difficult task, to which many detailed studies are devoted. Without questioning their results, the article suggests an easy-to-understand mechanism that allows us to assume for what reason damage to various equipment is possible in networks with XLPE insulation cables.

1. Modern 6-500 kV cables with XLPE insulation have increased electrical capacity and reduced surge impedance.
2. Due to the low surge impedance, these cables, when switching together with overhead lines or power transformers, may provoke a phenomenon of transient resonance.
3. The danger of transient resonance in mixed cable and overhead lines is eliminated by placing protective MOA at the input of the overhead line into the switchgear (this MOA is needed for lightning protection too). As for the MOAs at the ends of the cable section, they also need to be installed, but only under the conditions of protection against lightning overvoltages (even if the cable section is short or, on the contrary, more than 1.5 km long).
4. The danger of transient resonance in circuits with power transformers is manifested in cases when the length of the cable line is close to 0.5÷1.0 of the length of the transformer winding. To protect transformers, it can be recommended to exclude dangerous circuits by rationally choosing the voltage source and cable length. If this is not possible, at least one of the following is recommended:
   - to place protective MOA to the transformer neutral (if ungrounded);
   - to install RC-devices close to the transformer bushings (only for classes of 6-20 kV);
   - to be more careful when choose the connection scheme of the transformer windings.

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