Switching Capacitor bank Back-to-Back to Underground Cables

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Abstract—The paper addresses the capacitor bank switching back-to-back to underground cables. The high currents recorded during the capacitor bank-switching occur due to the traveling waves in the underground cables. The detailed analytical study of the capacitive inrush currents is done. The closed-form expressions of the inrush current waveforms due to the initial current surges as well as due to the superposition of the initial and reflected current waves are derived. The formulas for the peak inrush current and its maximum rate of rise are obtained. The case study of the 24 kV capacitor bank switching back-to-back to the underground cables is described. The results of the field measurements are compared with the results of EMTP simulation. The dependence of the inrush current peak on the number of the cables, the equivalent inductance between the capacitor bank and the substation busbar as well as on the cable length is analyzed. The inrush currents caused failures of the capacitor bank circuit breakers. Since the described capacitor inrush current significantly exceeds the "inrush current of isolated capacitor bank" it should taken into account in the selection of the capacitor bank switchgear.

***Index Terms*—capacitor switching, inrush current, traveling waves, underground cables.**

I. INTRODUCTION

The growth of the urban areas all over the world, the increased requirements to the reliability and quality of power supply as well as the struggle against visual pollution caused by the overhead lines result in undergrounding transmission and distribution power lines [1]-[3]. The gradual replacement of overhead lines with underground cables leads to changing many fundamental characteristics of electrical power systems. Since the majority of existing approaches to studying the electrical phenomena is based in the assumption that the transmission and distribution networks include primarily overhead lines, the power line undergrounding invites revising the present ways of calculation of the short-circuit currents, the temporary overvoltages and the electromagnetic transients.

This paper addresses influence of undergrounding overhead lines on the capacitor bank inrush currents.

Shunt capacitor banks are widely used on power systems for reactive power compensation to achieve the power and energy loss reduction, the system capacity release and the voltage regulation [4]-[5].

Application of shunt capacitor banks requires proper selection of their switchgear, which should be capable of the capacitor bank switching without any damage both to the switchgear and to the capacitor bank itself .Selection of an appropriate circuit breaker (CB) for a capacitor bank requires taking into consideration the following limitations imposed by the capacitor inrush currents [5]-[13]:

- The inrush current peak I_{peak}
- The maximum rate of change of the inrush current (di/dt).

A circuit breaker properly chosen for the capacitor switching duty shall be capable to withstand the I_{peak} and di/dt without any damage during the CB switching life.

The existing approach to the capacitive inrush currents recognizes the inrush currents resulting from switching overhead lines/cables and the inrush currents due to switching capacitor banks.[6]-[10]. During the energization of overhead lines/cables I_{peak} is limited by their surge impedance. Thus, in spite of high di/dt that may occur, energization of cables and lines is not considered to be a severe stress to the switching device [1], [6]-[12].

According to the general theory of capacitive current switching, the most severe duty for CBs results from energization of capacitor banks. The existing standards recognize the inrush current of single (isolated) capacitor bank as well as the back-to-back inrush current [8]-[11].

Consider energization of isolated capacitor bank to the secondary side of HV/MV substation transformer (Fig.1)

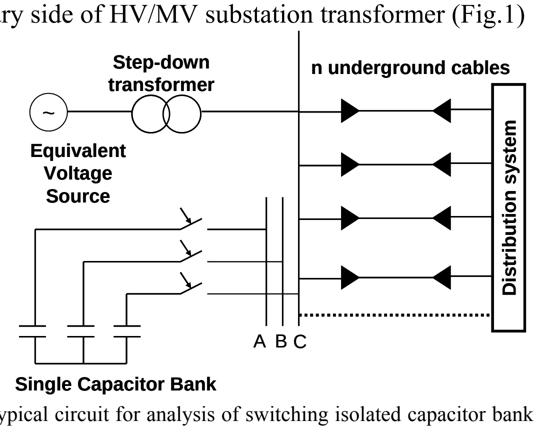

Fig. 1. Typical circuit for analysis of switching isolated capacitor bank back-to-back to underground cables

According to the general theory of capacitive current switching, the peak inrush current I_{peak} is limited by the characteristic impedance formed by the inductance of the substation transformer L_S and the capacitance of the capacitor bank C. The value of di/dt is limited by L_S. The inrush current and its rate of rise are maximal in a phase, where the

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voltage waveform of the voltage source reaches its peak value V_m at the instant, at which the switching device closes the circuit:

$$I_{peak} = \frac{V_0}{\sqrt{L_S / C}}, \qquad \frac{di}{dt} = \frac{V_0}{L_S} \tag{1}$$

In (1) V_0 is the peak value of the steady-state voltage on the substation busbar after energizing the bank

$$V_0 = \frac{\beta^2}{\beta^2 - \omega^2} V_m \tag{2}$$

In (2) ω - angular frequency of the voltage source; β - natural angular frequency of the loop composed of the inductance L_S the capacitance C

$$\beta = \frac{1}{\sqrt{C\ L_S}} \tag{3}$$

The values of I_{peak} and di/dt for the inrush current of a capacitor bank installed on the secondary side of a substation transformer are, as it follows from (1), limited by the inductance of the transformer. It is assumed that for the real-world systems the inrush current of an isolated capacitor bank does not pose any problem neither to the capacitor CB nor to the capacitor bank. The "inrush current of isolated capacitor bank", according to the IEEE standard [11], can be handled by a General Purpose (class C0) circuit breaker, which is not designed for back-to-back switching duty.

The field tests done in the Israel Electric Corporation (IECo) revealed that the inrush current peak of 9 MVAR, 24 kV isolated capacitor bank can reach 7 kA, while its di/dt is about 3000 kA/ms [14].

It was suggested that those high inrush currents result from the traveling waves in the underground cables connected to the same busbar (see Fig.1) [15]. At the instant, when the capacitor circuit breaker closes energizing the capacitor bank, the voltage at the substation busbar collapses to zero. Then transient process of the voltage recovery takes place. The busbar voltage change initiates the voltage surges traveling down the cables connected to the same busbar (Fig.1). These voltage surges generate current surges in the cables. Since the amplitudes of the current traveling waves are limited by small surge impedance of the cables, they can reach significant values. According to this approach, the capacitor inrush current is a sum of the current traveling waves. The more cables are connected alongside the capacitor bank, the higher value of the inrush current should be expected.

In spite of the study conducted in [15], the origin of the inrush currents recorded in [14] is still not clear. It can be ascribed either to the traveling waves in the cables [15] or to the back-to-back inrush current of the capacitor bank switched in parallel to the equivalent capacitance of the cables [1].

Since those capacitive inrush currents significantly exceed the "inrush current of isolated capacitor bank", their detailed research is necessary for selection of the capacitor bank switchgear.

II. Analytical Study

Consider energization of a capacitor bank connected to the secondary side of a substation transformer alongside n underground cables (Fig.1) using the single-phase circuit shown in Fig. 2. The inductance L_S and resistance R_S represent the short-circuit impedance of the transmission system and the utility transformer; C is the capacitance of the switched utility capacitor bank; L is the equivalent inductance between the capacitor bank and the substation busbar; Z_{CW} is the equivalent surge impedance of n underground cable; Z_{LW} represents some equivalent impedance at the termination of the cable at the remote end. The single-phase circuit can be used to analyze the maximum phase inrush current that takes place during the three-phase switching of the capacitor bank [10].

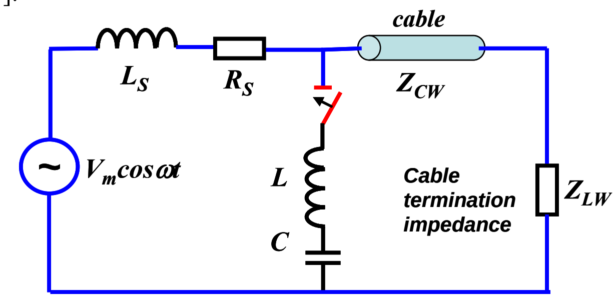


Fig. 2. Single phase circuit for analysis the capacitor inrush current

The maximum inrush current takes place, if the CB closes the circuit at the time instant $t = 0$, when the voltage waveform reaches its peak value V_m.

The transient inrush current can be obtained from Fig.3 using the principle of superposition [16]:

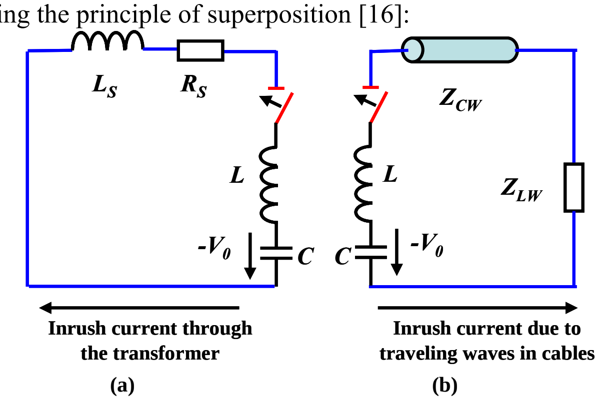


Fig. 3 Circuits for analytical study of the inrush current. (a) Inrush current through the substation transformer. (b) Inrush current due to the traveling waves in the alongside cables

The component of the capacitive inrush current generally referred to as the "inrush current of isolated capacitor bank", can be determined from the circuit in Fig. 3a. The current waveform $i_{tr}(t)$ is

$$i_{tr}(t) = I_{peak} e^{-\frac{R_S}{2L_S}t} \sin \beta t \tag{4}$$

If the inductance L is negligibly small in comparison to the inductance L_S, the peak inrush current I_{peak} and its frequency β are obtained using (1) and (3) accordingly.

The component of the capacitive inrush current that appears due to traveling waves in the alongside cables can be determined from the circuit in Fig. 3.b.

Consider a general case, when the distribution network is connected to the substation busbar through n underground cables having different lengths [15]. In this study the cable length is understood as a distance between the substation busbar and some junction (terminal) that causes the reflection of the wave traveling along the cable. Assume that all the cables have the same specific parameters. In that case, the equivalent cable surge impedance Z_{CW} will be determined as follows

$$Z_{CW} = \frac{Z_C}{n} = \frac{1}{n}\sqrt{\frac{L_o}{C_0}} \tag{5}$$

In (5) Z_C is a cable surge impedance determined by the cable specific inductance L_0 and specific capacitance C_0.

The capacitor bank energization results in appearance of the current waves traveling along the cables with propagation velocity $v = 1/\sqrt{L_0 C_0}$. The waves reflect at the terminations on the opposite ends of the cables. Since the cables have different lengths, the reflected waves arrive to the capacitor bank busbar at different time instances. Therefore, the reflected waves reduce the inrush current. This is why the inrush current reaches its maximum value until the reflected waves arrive at the substation busbar.

The capacitor inrush current produced by the initial current waves in n alongside cables can be determined from Fig. 3b, while the cable termination impedance Z_{LW} is short-circuited. The current in the Laplace domain $i(p)$ is as follows

$$i(p) = \frac{V_0 C}{LCp^2 + Z_{CW}Cp + 1} \tag{6}$$

Expression of the inrush current waveform depends on the relationship between the equivalent cable surge impedance Z_{CW} and the characteristic impedance Z_W of the circuit formed by the inductance L and capacitance C:

$$Z_W = \sqrt{\frac{L}{C}} \tag{7}$$

A value of the characteristic impedance Z_W depends on the size of inductance L. The equivalent inductance L includes the inherent inductance of the capacitor bank, the inductance of the connections between the bank and the substation busbar as well as the inductance of a damping (current limiting) reactor. If the damping reactor is not installed, L varies from 5 to 15 μH [10]. Application of the damping reactor may increase the inductance to hundreds of μH.

If the damping reactor is not installed, the following relationship takes place:

$$Z_{CW} \geq 2Z_W \tag{8}$$

Under condition (8), the capacitive inrush current $i(t)$ can be derived from (6) and expressed similar to (4)

$$i(t) = 2Ie^{-\delta t}\sinh \alpha t \tag{9}$$

In distribution systems including 6-12 cables alongside the substation capacitor bank with damping reactor, the relationship between impedances Z_W and Z_{CW} is

$$Z_{CW} \prec 2Z_W \tag{10}$$

Under the condition (10), the inrush current becomes oscillatory. Its waveform is given by

$$i(t) = 2Ie^{-\delta t}\sin \alpha t \tag{11}$$

The constants I, α and δ are given by

$$I = \frac{V_0}{\sqrt{\left|Z_{CW}{}^2 - 4Z_W{}^2\right|}},$$
$$\delta = \frac{Z_{CW}}{2L}, \quad \alpha = \frac{\sqrt{\left|Z_{CW}{}^2 - 4Z_W{}^2\right|}}{2L} \tag{12}$$

The time instant t_m, when the inrush current waveform $i(t)$ reaches its peak value, can be determined from the condition

$$\frac{di(t)}{dt} = 0 \tag{13}$$

and presented as follows

$$t_m = \frac{1}{2\alpha}\ln\frac{\delta+\alpha}{\delta-\alpha} \tag{14}$$

Substitution of (14) into (9) enables to obtain the peak value I_{peak} of current waveform $i(t)$

$$I_{peak} = \frac{2I\alpha}{\sqrt{\delta^2-\alpha^2}\left(\dfrac{\sqrt{\delta^2-\alpha^2}}{\delta-\alpha}\right)^{\frac{\delta}{\alpha}}} \tag{15}$$

The inrush current peak depends on the inductance L. If the value of stray inductance tends to zero, the expression of I_{peak} is as follows

$$I_{peak} = n\frac{V_0}{Z_C} \tag{16}$$

For that limiting case, the peak inrush current is proportional to the product of the number of underground cables and the system voltage peak and inversely proportional to the cable surge impedance.

For a circuit, where due to application of the damping reactor with high value of L, the characteristic impedance Z_W obtained by (7) is significantly bigger than the equivalent surge impedance of n cables Z_{CW} (see (5)), the inrush current peak is limited only by the characteristic impedance Z_W:

$$I_{peak} = \frac{V_0}{Z_W} \tag{17}$$

The rate of rise of the inrush current can be obtained by differentiation of $i(t)$ (see (9)). The maximum rate of rise is achieved at the time instant $t = 0$; its value is given by [15]

$$\frac{di}{dt} = \frac{V_0}{L} \tag{18}$$

The maximum rate of rise of the inrush current (as it follows from (18)) is limited only by the equivalent inductance L. If L includes only stray inductance (damping reactor is not applied) the maximum value of di/dt can be extremely high.

The capacitor bank inrush current $i(t)$ that occurs due to the traveling waves is not oscillatory in the usual frequency related sense, but the initial slope of its waveform can be used to determine an equivalent frequency f_{eq}, which can be compared with the rated inrush current frequency defined in the circuit breaker standards[8], [10], [11]:

$$f_{eq} = \frac{di/dt}{2\pi I_{\max}} = \frac{1}{2\pi}\sqrt{\delta^2-\alpha^2}\left(\frac{\sqrt{\delta^2-\alpha^2}}{\delta-\alpha}\right)^{\frac{\delta}{\alpha}} \tag{19}$$

Consider some particular case, when the distribution network is connected to the substation busbar through n underground cables having equal length l_C [15]. Assume that all the cables at their opposite ends are terminated in overhead feeders having the same surge impedance Z_L. That case may take place in realworld power utilities, when a new indoor substation with GIS switchgear is connected by cable sections to the existing overhead lines, which ends are located at the same distance from the substation busbar.

Since the cables have equal length, the initial voltage surges traveling along the cables with propagation velocity ν reflect at the remote ends of the cables and arrive to the capacitor bank busbar simultaneously at the time instant $t_0 = 2l_C/\nu$. After their reflection at the capacitor termination those waves generate the 1st reflected current surges propagating away the busbar. Those reflected current waves superimposing on the incident current waves change the bank inrush current. Then, at the time instant $2t_0$ the second reflected current waves start traveling along the cables causing a new change in the inrush current.

It was suggested that in the networks composed of n cables of the same length the inrush current may achieve its peak value due to superposition of the initial and reflected current surges in the alongside cables [15].

The inrush current as a superposition of the current waves in the cables in the Laplace domain may be derived using the circuit in Fig.3b:

$$\begin{aligned} i_S(p) &= \frac{V_0 C}{LCp^2 + Z_{CW}Cp + 1}\times \\ &\times\left[1 - 4\delta\sum_{k=1}^{\infty}\frac{a_L^k[(p+p1)(p+p2)]^{k-1}}{[(p-p1)(p-p2)]^k}\right] \end{aligned} \tag{20}$$

In (20) a_L is a reflection coefficient at the remote end of the cables

$$a_L = \frac{Z_{LW} - Z_{CW}}{Z_{LW} + Z_{CW}} \tag{21}$$

where

$$Z_{LW} = Z_L / n \tag{22}$$

The constants $p1$ and $p2$ are given by

$$p1 = -\delta + \alpha, \qquad p2 = -\delta - \alpha \tag{23}$$

According to the results of our numerical study, for the realworld cable lengths the inrush current peak is obtained as superposition of the initial current wave and the 1st, the 2nd and the 3rd reflected current waves:

$$i_S(t) = i(t) + i_1(t_1) + i_2(t_2) + i_3(t_3) \tag{24}$$

In (24) $i(t)$ is the initial inrush current given by (9) or (11); $i_1(t_1)$ is the component of the inrush current due to the 1st reflected waves from the capacitor termination

$$\begin{aligned} i_1(t_1) &= 2Ie^{-\delta t_1}[a_{11}\sinh(\alpha t_1) + a_{12}\alpha t_1\sinh(\alpha t_1) - \\ &-a_{12}\delta t_1\cosh(\alpha t_1)] \end{aligned} \tag{25}$$

where

$$\begin{aligned} t_1 &= t - t_0, \qquad a_{11} = -2\frac{Z_{CW}^2 a_L}{Z_{CW}^2 - 4Z_W^2}, \\ a_{12} &= -2\frac{Z_{CW} a_L}{\sqrt{Z_{CW}^2 - 4Z_W^2}} \end{aligned} \tag{26}$$

In (24) $i_2(t_2)$ is the component of the inrush current that appears due to the 2nd reflected waves in the cables

$$\begin{aligned} i_2(t_2) &= 2Ie^{-\delta t_2}[a_{21}\sinh(\alpha t_2) + a_{22}\delta t_2\sinh(\alpha t_2) - \\ &-a_{21}\alpha t_2\cosh(\alpha t_2) + a_{23}\delta^2 t_2^{\,2}\sinh(\alpha t_2) - \\ &-a_{24}\delta^2 t_2^{\,2}\cosh(\alpha t_2)] \end{aligned} \tag{27}$$

where

$$\begin{aligned} t_2 &= t - 2t_0, \quad a_{21} = 2\frac{Z_{CW}^2\left(Z_{CW}^2 + 8Z_W^2\right)a_L^{\,2}}{\left(Z_{CW}^2 - 4Z_W^2\right)^2}, \\ a_{22} &= 2\frac{(Z_{CW}^2 + 4Z_W^2)a_L^{\,2}}{Z_{CW}^2 - 4Z_W^2}, \\ a_{23} &= 4\frac{(Z_{CW}^2 - 2Z_W^2)a_L^{\,2}}{Z_{CW}^2 - 4Z_W^2}, \quad a_{24} = 4\frac{Z_{CW} a_L^{\,2}}{\sqrt{Z_{CW}^2 - 4Z_W^2}} \end{aligned} \tag{28}$$

The component of the inrush current caused by the 3rd reflection from the capacitor bank termination $i_3(t_3)$ is given by

$$\begin{aligned} i_3(t_3) &= 2Ie^{-\delta t_3}[a_{31}\sinh(\alpha t_3) + a_{32}\delta t_3\sinh(\alpha t_3) - \\ &-a_{31}\alpha t_3\cosh(\alpha t_3) + a_{33}\delta^2 t_3^{\,2}\sinh(\alpha t_3) - \\ &-a_{34}\delta^2 t_3^{\,2}\cosh(\alpha t_3) + a_{35}\delta^3 t_3^{\,3}\sinh(\alpha t_3) - \\ &-a_{36}\delta^3 t_3^{\,3}\cosh(\alpha t_3)] \end{aligned} \tag{29}$$

In (29) t_3 is time starting at the time instant, when the 3rd reflected waves start propagating away from the capacitor termination:

$$t_3 = t - 3t_0 \tag{30}$$

The constants $a_{31} - a_{36}$ are given by

$$a_{31} = -2\frac{Z_{CW}^2\left(Z_{CW}^4 + 24Z_{CW}^2 Z_W^2 + 48Z_W^4\right)a_L^{\,3}}{\left(Z_{CW}^2 - 4Z_W^2\right)^3} \tag{31}$$

$$a_{32} = -2\frac{\left(Z_{CW}^4 + 16Z_{CW}^2 Z_W^2 + 16Z_W^4\right)a_L^{\,3}}{\left(Z_{CW}^2 - 4Z_W^2\right)^2} \tag{32}$$

$$a_{33} = -16\frac{(3Z_{CW}^2 - 4Z_W^2)Z_W^2 a_L{}^3}{\left(Z_{CW}^2 - 4Z_W^2\right)^2} \quad (33)$$

$$a_{34} = -48\frac{Z_{CW}Z_W^2 a_L{}^3}{\left(Z_{CW}^2 - 4Z_W^2\right)^{\frac{3}{2}}} \quad (34)$$

$$a_{35} = -\frac{16}{3}\frac{\left(Z_{CW}^2 - Z_W^2\right)a_L{}^3}{Z_{CW}^2 - 4Z_W^2} \quad (35)$$

$$a_{36} = -\frac{16}{3}\frac{Z_{CW}\left(Z_{CW}^2 - 3Z_W^2\right)a_L{}^3}{\left(Z_{CW}^2 - 4Z_W^2\right)^{\frac{3}{2}}} \quad (36)$$

Using (24) one can obtain the inrush current waveform from the time instant of closing the capacitor circuit breaker (***t***=0) to the time instant, when the 3rd reflected waves return to the substation busbar (***t*** = 4***t₀***).

III. CASE STUDY

A. Circuit description

Consider switching 24 kV capacitor bank back-to-back to ***n*** underground cables (Fig.1). The circuit parameters are similar to the typical parameters of the 24 kV distribution systems in IECo.

The utility is represented by the step-down transformer fed from an infinite HV busbar. The equivalent parameters of the transformer are: MVA rating-45 MVA; short–circuit impedance -18%; pu copper losses - 0.00375. The System Source Strength at the MV utility busbar is 250 MVA.

The following two types of 24 kV capacitor banks are considered: single step 9 MVAR capacitor bank and multi-step capacitor bank including 3 steps of 5 MVAR each. The study deals with switching 1st step of the multi-step bank. The capacitors are connected into Y or double Y with isolated neutral (see Fig.1). A damping reactor is not applied to 9 MVAR capacitor bank. Each 5 MVAR capacitor bank step includes 100 μH damping reactor designed to limit the back-to back inrush currents. Since IECo future 24 kV capacitor banks will use damping reactors of various sizes, detailed study on the influence of the size of damping reactor on the inrush current is conducted.

The number of underground cables ***n*** that connect the distribution system to the substation busbar (see Fig.1) varies from 2 to 12. A detailed study is carried out for the most common case in the urban areas, when ***n*** = 8. Each phase of the 24 kV cable is a single-core coaxial type cable with copper conductor/sheath cross-sections 300/25 and XLPE insulation. The cables are laid in trefoil formation. The cable sheaths are bonded and grounded at both ends of the cable sections.

Switching capacitor bank with floating neutral causes traveling waves in the alongside cables propagating in a mode, which parameters correspond to the positive-sequence cable parameters. Specific parameters of the underground cables in IECo are calculated using a Cable Constant routine based on analytical expressions detailed in [17].

Cable specific parameters seen by the traveling waves are calculated taking into account that the cable specific resistance R_0 and specific inductance L_0 are frequency dependant [18].

According to our calculations, the traveling waves in the cables resemble oscillatory transients with frequencies lying in the range of 20-100 kHz. Taking into account that R_0 and L_0 do not change greatly in that range, their values were selected corresponding to the frequency of 40 kHz: R_0 - 1.6 Ω/km; L_0 - 128 μH/km. These values differ greatly from the cable parameters calculated for 50 Hz: R_0 - 0.06 Ω/km; L_0 - 334μH/km. The cable specific capacitance C_0 is 0.251μF/km.

The distribution network under consideration also includes overhead lines at the remote end of the underground cables. The typical positive-sequence parameters of IECo overhead lines for 40 kHz are as follows: R_{0L} - 0.94 Ω/km; L_{0L} - 1030 μH/km, C_{0L} - 0.011μF/km.

B. Results of field tests versus EMTP simulation

The capacitor inrush currents that significantly exceed the "inrush current of isolated capacitor bank" were discovered for the first time in EMTP simulations [15]. In order to verify the phenomenon, IECo did field tests of switching 9 MVAR, 24 kV capacitor bank [14]. The tested capacitor bank is installed at the secondary side of 45 MVA, 161/24 kV transformer alongside eight underground cables used for power delivery to the loads in the distribution network. Lengths of the underground cables vary from 1 km to 9 km. In addition to the 8 cables used for power delivery, the outgoing cables also include two short cable sections (each one is shorter than 200 m) connecting the grounding transformer and the auxiliary need transformer to the busbar.

The capacitor bank CB is of indoor metal-clad GIS type. The length of the cable between the capacitor bank circuit breaker and the capacitor bank isolator is 20m.

The capacitor bank phase currents were measured using protective cores of the current transformers.

The peaks of the inrush currents measured in the capacitor bank phases during 4 switching tests are given in Table 1.

TABLE I
PEAK INRUSH CURRENTS MEASURED IN FIELD TESTS

Test Number	Peak inrush currents [kA, peak]		
	I_R	I_S	I_T
1	4.8	5.0	5.0
2	5.7	4.6	7.1
3	5.6	4.5	7.2
4	6.1	3.2	6.6

The maximum values of ***di/dt*** measured during the tests varied from 1000 to 3300 kA/ms.

The measured values significantly exceed the corresponding parameters of the "inrush current of isolated capacitor bank" determined according to the existing theory of the capacitive switching: I_{peak} = 1.6 kA, ***di/dt*** = 2.67 kA/ms [10].

The results of the field tests were compared with the simulations done using the Electromagnetic Transient

Program (EMTP) [18]. In the EMTP model all the underground cables and overhead lines were presented as elements with distributed, frequency-dependent parameters. The waveform of the maximum phase inrush current obtained in the simulations is shown in Fig.4.

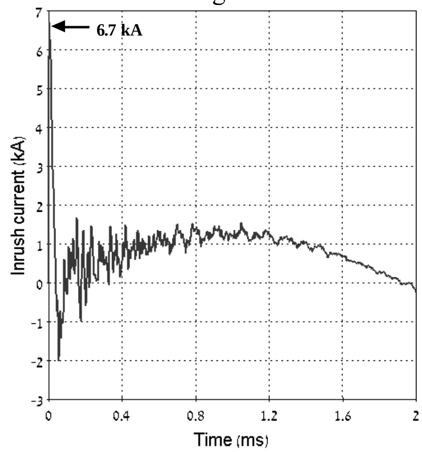


Fig. 4. Inrush current waveform obtained in EMTP simulation

In the phase, where the voltage waveform of the voltage source reaches its peak value at the instant of the CB closing, the inrush current peak is 6.7 kA, while its maximum rate of rise is 3600 kA/ms. These values are in good agreement with the results of field tests.

One can see that the inrush current component that can be ascribed to the traveling waves decays in some hundreds of microseconds. After the wave attenuation, the waveform is close to the waveform of the "inrush current of the isolated capacitor bank" described by the general theory of capacitive switching [10].

C. Parametric study of inrush current peak

The aim of the study is to identify the network parameters that influence the inrush current peak.

First, consider the capacitor switching back-to-back to n underground cables having unequal lengths. In that case the peak inrush current I_{peak} as a function of network parameters is given by (15).

Obtain dependence of I_{peak} on the number of underground cables. The curves of I_{peak} resulting from switching 5 MVAR and 9 MVAR capacitor banks versus n are presented in Fig. 5. The curves are calculated for the following values of the equivalent inductance between the capacitor bank and the substation busbar: L = 5μH, L = 100 μH and L = 1000μH.

It is evident that if L = 5μH (L includes only a stray inductance), the I_{peak} is proportional to n. Change of n from 2 to 12 results in the increase of I_{peak} from 1.7 kA to 9 kA. The curve corresponding to switching 9 MVAR capacitor bank (the solid curve) practically coincides with the curve for switching 5 MVAR capacitor bank (the dotted curve). The independence of the inrush current peak on the capacitance of the switched capacitor bank proves that the inrush current is a sum of traveling waves in the alongside cables, which is proportional only to the number of cables, as it follows from (16).

Adding damping reactor in series with the capacitor bank reduces the dependence of the inrush current peak on the cable number. It is evident that if L = 1000μH (L includes a big current–limiting reactor), the I_{peak} is practically independent of n. In that case, the I_{peak} is limited primarily by the characteristic impedance Z_W formed by L and the capacitance C of the switched capacitor bank (see (17)).

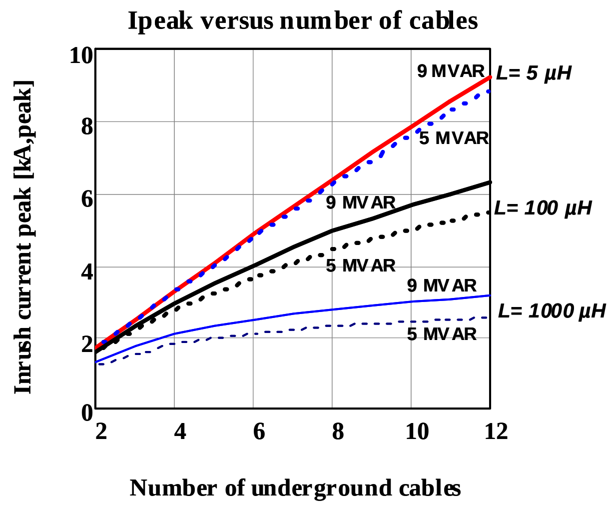


Fig. 5. Inrush current peak versus the number of underground cables

Obtain dependence of I_{peak} on equivalent inductance between the capacitor bank and the substation busbar L. The curves of I_{peak} versus L corresponding to switching 5 MVAR and 9 MVAR capacitor banks back-to back to 8 underground cables are presented in Fig. 6.

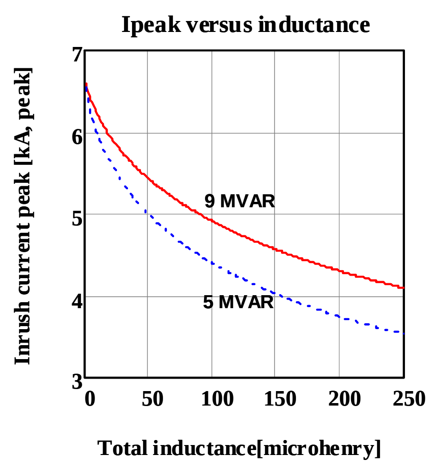


Fig.6 Curves of the inrush current peak versus equivalent inductance L

It is evident that increase of the equivalent inductance L leads to reduction of I_{peak} .

The inrush current reaches its peak value I_{peak} at the time instant $t=tm$ determined by (14).Since the waves travel along the cables with the propagation velocity $v = 1/\sqrt{L_0 C_0}$, the cables should be long enough so that at the time instant $t=tm$ no reflected waves arrive at the capacitor bank termination.

Define the minimal length of cable l_{min} as the shortest cable length among n cables that makes it possible for the inrush current to reach its peak value I_{peak} determined from (15) before the reflected wave in that shortest cable arrives at the substation busbar. The value of l_{min} is given by

$$l_{\min} = \frac{1}{2} v t_m = \frac{1}{2} \frac{t_m}{\sqrt{L_0 C_0}} \qquad (37)$$

The minimal length of cable l_{min} is determined primarily by the capacitor bank equivalent inductance L.

The curves l_{min} corresponding to switching the capacitor banks without damping reactors back-to-back to 8 cables versus the equivalent stray inductance, are given in Fig. 7.

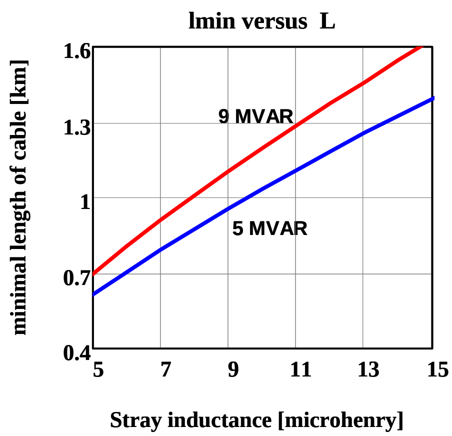


Fig.7 Curves of the minimal length of cable for the capacitor banks without damping reactors

For the capacitor banks without damping reactors the minimal length of cable varies from 600-700 m to 1.5-1.6 km. For the typical IECo substations located in urban areas, the average cable length between the substation busbar and some junction, where the traveling wave is reflected, generally exceeds 1-2 km. Therefore, switching a capacitor bank that does not include damping reactor generally results in the inrush current, which reaches its peak value I_{peak}.

Applying damping reactor to the capacitor bank significantly increases the minimal length of cable (see Fig. 8).

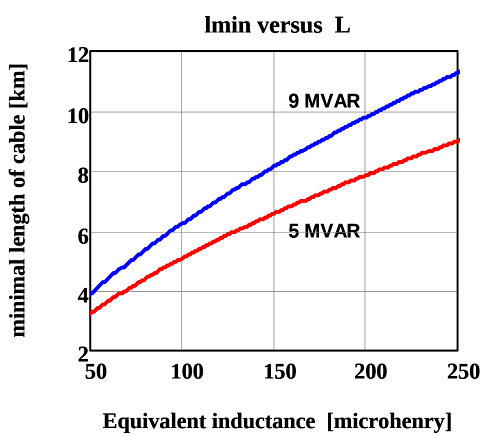


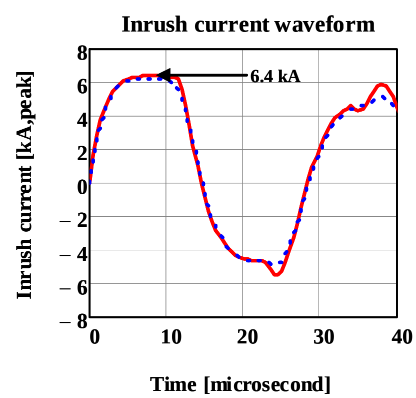
Fig.8 Curves of the minimal length of cable for the capacitor banks with damping reactors

The growth of l_{min} with L increase can be explained by the drastic reduction of the rate of rise of the inrush current due to adding the damping reactor.

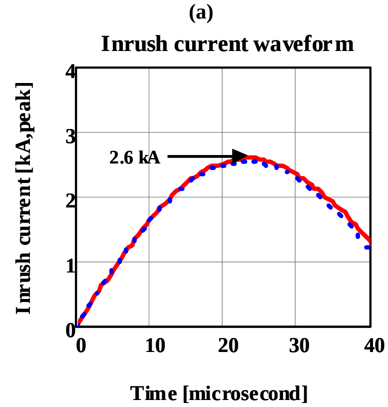
The inrush current due to switching the capacitor bank with damping reactor may reach its peak I_{peak} only if the minimal length of cable exceeds a number of km. For example, the inrush current due to switching 5 MVAR capacitor bank with damping reactor of 100 μH back-to-back to 8 underground cables may reach its peak value only if l_{min} exceeds 5 km (see Fig.8). For the typical IECo substations, the average cable length between the substation busbar and some junction, where the traveling wave is reflected, is smaller than 5 km. This is why the inrush current of the capacitor bank with damping reactor generally can not reach its peak value.

Consider now the particular case, when the distribution network is connected to the substation busbar through n underground cables having equal length l_C [15]. The calculations are performed for 8 identical cables connected to the busbar alongside the isolated capacitor bank. It is assumed that each cable is terminated in a long overhead line. All the lines have the same surge impedance.

In order to validate the derived analytical expressions, the analytical current waveforms calculated from (24)-(36) were compared with the waveforms obtained using EMTP simulations for the 3-phase model in Fig.1.



(a)



(b)

Fig.9 Back-to-back switching to 8 cables of 1 km length. (a) Capacitor bank of 9 MVAR, L = 5μH. (b) Capacitor bank of 5 MVAR, L = 100μH

The waveforms illustrating the inrush current due to switching 9 MVAR capacitor bank (L = 5μH) and 5 MVAR capacitor bank (L = 100μH) back-to-back to 8 identical, 1km long underground cables, are shown in Fig.9.

The analytical waveforms (the solid curves) practically coincide with the EMTP waveforms (the dotted curves). Very good agreement between the analytical waveforms and the EMTP waveforms enables to accept the hypothesis that the high values of the inrush currents recorded in the field tests (see Table I) occur due to the traveling waves in the alongside underground cables.

The maximum crest value of the inrush current waveform during switching 9 MVAR capacitor bank without damping reactor (see Fig. 9a) is the first current peak corresponding to the peak inrush current due to the initial traveling waves (15) (I_{peak} = 6.4 kA). The current reaches I_{peak} because the cable length (l_C = 1km) is bigger than the minimal cable length l_{min} (l_{min} =0.7 km).

The crest value of inrush current waveform during switching 5 MVAR capacitor bank with damping reactor is 2.6 kA (see Fig. 9b). The inrush current can not reach the value of the inrush current peak (I_{peak} = 4.4 kA), because the cable length l_C is smaller than the minimal cable length (l_{min} =5 km).

It is evident that adding damping reactor to the capacitor bank results in reduction of the inrush current due to the following reasons:

1. Adding the damping reactor reduces the inrush current peak I_{peak} (see the curves in Fig.6)
2. Adding the damping reactor significantly increases the minimal length of cable required to reach the I_{peak}. Since the required length of l_{min} exceeds the existing lengths of the underground cables, even the reduced value of I_{peak} can not be achieved.

The waveforms illustrating the inrush current due to switching 9 MVAR capacitor bank without damping reactor back-to-back to 8 identical, 5km long underground cables, are shown in Fig.10.

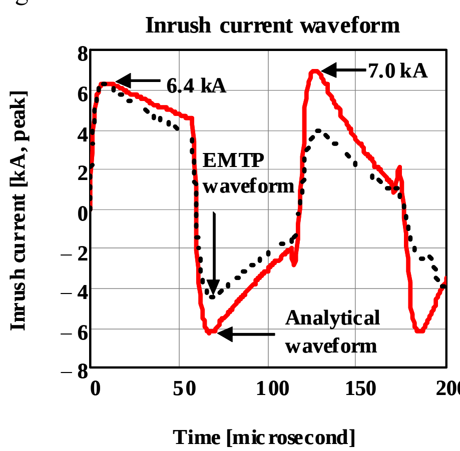


Fig.10 Inrush current waveforms for switching the capacitor bank (Q = 9 MVAR, L = 5μH) back-to-back to 8 cables of 5 km length.

The analytical waveform (the solid curve) is in good agreement with the EMTP waveform (the dotted curves) only in the first slope of the waveforms. The discrepancy between the current peaks that grows with time can be explained by disregard of the attenuation of the traveling waves in the cables in the analytical model. Because of the attenuation, the crest values of the numerical waveforms are smaller than the peaks of the analytical waveforms. For example, the maximum crest value of the analytical inrush current waveform) is the 3rd current peak. But according to the EMTP waveform, the maximum crest value is achieved at the 1st current peak. The 3rd current peak of the EMTP waveform is much smaller than the 3rd current peak of the analytical waveform due to the attenuation of the traveling waves.

The similar result was obtained in other simulations of the capacitor bank switching back-to-back to n identical long cables: the maximum value of the inrush current is always achieved at the first peak of the current waveform and is close to the inrush current peak I_{peak} determined by (15). The following crest values of the current waveform are smaller than the 1st peak because of the attenuation of the traveling waves.

For the bank switching back-to-back to n underground cables having the equal length, the maximum crest value of the inrush current can be obtained as a function of the cable length.

The maximum peak of the inrush current versus the cable length l_C for switching 9 MVAR capacitor bank alongside 8 identical cables is shown in Fig. 11.

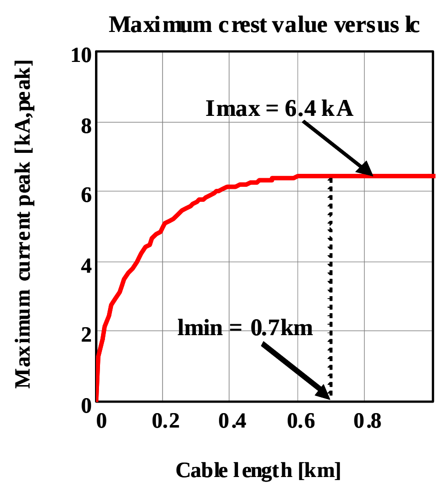


Fig.11 Maximum current peak versus the cable length in switching the capacitor bank (Q = 9 MVAR, L = 5μH) alongside 8 cables

Variation of the cable length from zero to the minimal length of cable l_{min} given by (37) results in increase of the maximum current peak from zero to the inrush current peak I_{peak}. The following growth of the cable length does not cause the increase of the maximum current peak because of the attenuation of the traveling waves in the cables.

To illustrate the influence of undergrounding the distribution power lines on the capacitor inrush current compare the waveforms of the inrush current, when 9 MVAR capacitor banks is switched back-to-back to 8 underground cables (Fig.12), with the waveforms of the inrush current, when the bank is switched back-to-back to 8 overhead lines (Fig. 13). The waveforms of the total inrush current are shown together with the waveform of the "inrush current of isolated capacitor bank" flowing between the substation transformer and the capacitor bank (see Fig.1).

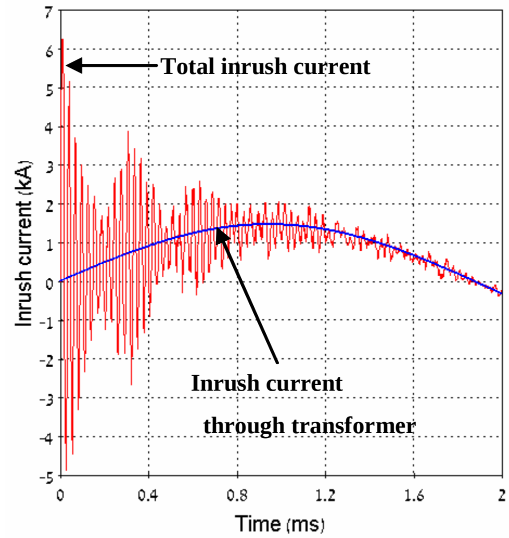


Fig.12 Inrush current waveforms, when the capacitor bank is switched back-to back to 8 underground cables.

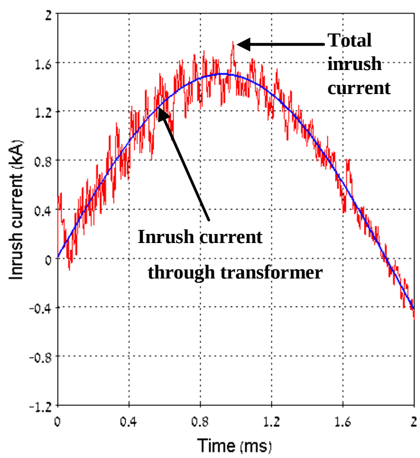


Fig.13 Inrush current waveforms, when the capacitor bank is switched back-to back to 8 overhead lines.

Switching the capacitor bank back-to-back to the underground cables results in the inrush current, which is significantly higher than the "inrush current of isolated capacitor bank" usually taken into account, when the capacitor bank switching is concerned (see Fig. 12). It is evident, that proper selection of the capacitor bank switchgear requires taking into consideration the inrush currents caused by the traveling waves in the underground cables.

It seems that switching capacitor bank back-to-back to the underground cables should be addressed in the standards concerning the capacitive current switching [7]-[10].

Taking into account the phenomenon of the capacitor bank switching back-to-back to the overhead lines does not result in significant change of the inrush current in comparison to the "inrush current of isolated capacitor bank" (see Fig.13). May be, this is the reason, why the traveling waves that occur during the capacitor bank switching were not addressed in technical literature.

IV. Operational Experience

During the last few years a number of failures of the minimum oil CBs used for switching isolated 6 and 9 MVAR, 24 kV capacitor banks were recorded in IECo. All the capacitor banks, where the breaker failed, are connected to the substation busbar alongside the underground cables that have replaced overhead lines. The capacitor CBs are installed inside indoor, metal-enclosed, 24 kV, switchgear busbar. Explosions of the minimum oil breaking units of CBs were accompanied by short-circuits on the busbars.

Examination of the failures revealed that the breakers had to handle the inrush currents having the inrush current peaks of 4-6 kA and the equivalent inrush current frequency (see (19)) of 40-60 kHz on daily basis. The above currents caused quick deterioration of the oil and various problems with CB mechanical system. As a result, openings of the breakers brought about numerous restrikes, when the inrush current peak could reach 8-12 kA. The inrush currents during the restrikes as well as the voltage escalation, resulting from the restrikes, led to the circuit breakers' failures and to the short-circuits on the substation busbar.

It should be noted that replacing the minimum-oil CBs with modern SF_6 CBs designed for back-to-back capacitor switching, enables normal operation of the capacitor banks switched alongside the underground cables.

V. Summary

The replacement of overhead lines with underground cables requires taking into consideration the capacitor bank switching back-to-back to the underground cables.

The field tests revealed high magnitude and high frequency inrush currents in the capacitor banks switched alongside the underground cables. It was assumed that those currents resulted from the traveling waves in the cables.

The detailed analytical study of the inrush currents caused by the traveling waves is done. The closed-form expressions of the inrush current waveforms due to the initial current surges as well due to the superposition of the initial and reflected current waves are derived. The formulas for the peak inrush current and its maximum rate of rise are obtained.

The results of 24 kV capacitor bank switching back-to-back to the underground cables are described. The peak inrush currents measured during the field tests of 24 kV, 9 MVAR capacitor bank switching are about 7 kA, while its maximum rate of rise exceeds 3000 kA/ms. The EMTP simulations are in good agreement with the results of field tests.

The developed analytical expressions enable to perform the parametric study of the inrush current peak. If damping reactor is not applied, I_{peak} is proportional to the number of the underground cables. For 24 kV capacitor banks, changing n from 2 to 12 results in I_{peak} increase from 1.7 kA to 9 kA.

Adding damping reactor to the capacitor bank leads to significant reduction of the inrush current due to the following reasons: increase of the equivalent capacitor bank inductance L reduces the inrush current peak I_{peak}; the grow of L results in the drastic increase of l_{min}, so that the minimal length of cable required to achieve I_{peak} exceeds the existing lengths of the underground cables.

The crest value of the inrush current waveform never exceeds the inrush current peak I_{peak} determined by (15).

The coincidence of the analytical waveform of the inrush current with the current waveform obtained by the EMTP simulation enables to accept the hypothesis that the high values of the inrush currents recorded in the field tests (see Table I) occur due to the traveling waves in the underground cables.

Since the inrush current during capacitor bank switching back-to-back to the underground cables significantly exceeds the "inrush current of isolated capacitor bank" it should taken into account in the selection of the capacitor bank switchgear.

Switching 24 kV capacitor banks back-to-back to the underground cables resulted in failures of minimum-oil CBs. Replacement of the minimum-oil CBs with modern SF_6 CBs designed for the back-to-back capacitor switching, enables normal operation of the capacitor banks switched alongside the underground cables.

According to the derived expressions (9)-(18), the peak inrush current I_{peak} as well as its maximum rate of change ***di/dt*** is proportional to the system voltage. This is why switching high voltage capacitor banks back-to-back to high voltage cables may result in magnitudes of I_{peak} and ***di/dt*** that are significantly higher that the corresponding values obtained due to the switching 24 kV capacitor banks.

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