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# Fundamentals of Intelligent Automatic Reclosing of Long-Distance Transmission Lines with Shunt Reactors

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**Abstract**—One effective overvoltage control method for the automatic reclosing cycle (ARC) of long-distance high-voltage transmission lines is intelligent automatic reclosing. The method is based on the selection of a reclosing time that is optimal for reducing the intensity of the transient process. The article investigates the basic transient process patterns in the ARC and analyzes various automatic reclosing methods. The principle of superposition is used for the analysis as well as the proposed universal electrical network model, which describes the processes at all ARC stages. It is shown that the intensity of the transient process at the automatic reclosing directly depends on the ratio of the supply voltage and line voltage at the reclosing time. It is shown that the overvoltage level can be reduced by line reclosing at the breaker contacts' voltage zero-crossing time or at the valley point of this voltage envelope, but the intelligent automatic reclosing is more effective, combining both approaches and performing reclosing at the zero-crossing time near the envelope valley. Computational experiments confirm that the reclosing time has a decisive influence on the overvoltage in the ARC, while the influence of the compensation degree and transmission angle is not so important.

*Keywords*: transmission line, automatic reclosing, switching overvoltage, controlled switching

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A long-distance transmission line equipped with shunt reactors (SRs) forms a high-Q oscillatory system during the three-phase automatic reclosing cycle (ARC). By the time of reclosing, the unfaulted phases retain a significant electric residual, therefore the line reclosing can be accompanied by an intensive wave process with dangerous overvoltage in the "charged" phases.

Controlling the switching moment to reduce the intensity of the transient process during the automatic reclosing of uncompensated transmission lines was proposed by E. Maury [1]. This is called "controlled" or "synchronous" switching.

During the ARC time of the lines with shunt reactors, the breaker contacts' voltage is pulse-shaped. A development of Maury's idea of controlled switching of such lines was proposed in [2], which proposed reclosing the line at the valley point of the breaker contacts' voltage envelope.

The first controlled switching devices of compensated transmission lines did not have the ability to predict the envelope valley point of time in the process. Therefore, the duration of the automatic reclosing time was set in advance based on a preliminary calculation of the most likely reclosing cycle scenario, which limited the effectiveness of such devices.

The development of the elemental base and digital signal processing algorithms made it possible to implement controlled switching algorithms that are able to predict the optimal switching time at the during the process—intelligent automatic reclosing algorithms. Their effectiveness has been confirmed by the results of numerous practical tests, as well as mathematical and physical simulation. However, there is still no theoretical description of the ARC transient process patterns or a mechanism for reducing the overvoltage that would underly intelligent automatic reclosing.

## ANALYTICAL CALCULATION OF THE ARC TRANSIENT PROCESS

For clarity, the model of the network under consideration is deliberately simplified to a single-phase one similarly to [3], which has, however, significant limitations preventing the application of the proposed method. This is due to the fact that in [3] the electric residual of the unfaulted phase of the compensated line is not taken into account and the design expressions are given only for the open circuit side of the transmission line, while automatic reclosing provides maximum voltage at other points of the line.

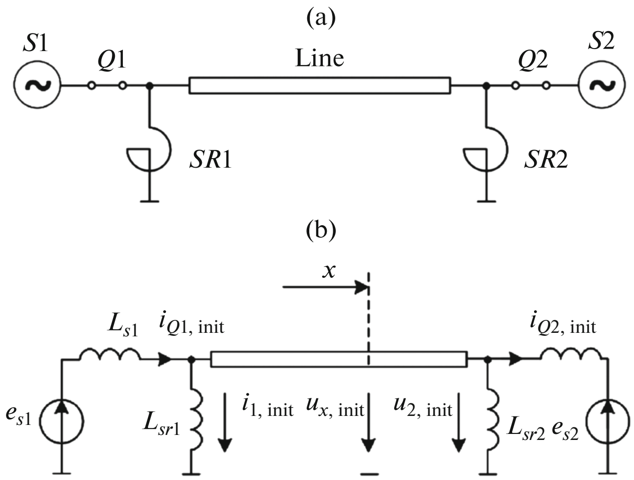


**Fig. 1.** (a) Network diagram and (b) its design scheme in the load mode

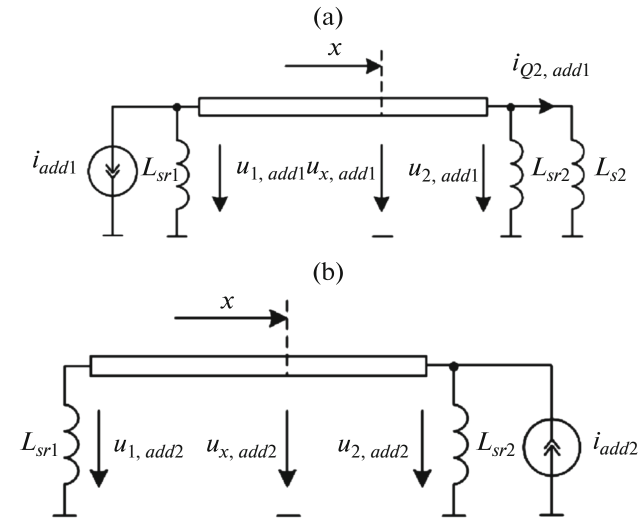


**Fig. 2.** Network equivalent circuit in auxiliary modes (a) 1 and (b) 2.

The following sequence of modes is considered that most closely corresponds to the modes in the unfaulted phase of the three-phase line in the automatic reclosing cycle: load mode → line disconnection from the first side → line disconnection from the second side → line reclosing from the first side → line reclosing from the second side (switching into transit).

To calculate the transient process, the method of reduction to zero initial conditions is used. At each time of the automatic reclosing cycle, the electrical values are calculated as the sum of the previous and auxiliary mode values.

## *Network Design in the ARC*

### *Load Mode*

The initial conditions of the ARC transient process are formed in the load circuit diagram (Fig. 1).

### *Line Disconnection from the First and Second Sides (Auxiliary Modes 1 and 2)*

The electric network in modes 1 and 2 is a passive circuit connected to the current source (Fig. 2). The source parameters are determined by the corresponding breaker current in the previous mode. For the mode 1 circuit, the previous mode is the initial mode; therefore,

$$i_{add1}(t) = i_{Q1,init}(t).$$

The current source parameters in the mode 2 circuit are determined by the breaker $Q2$ currents in the mode 1 and initial mode circuits as

$$i_{add2}(t) = i_{Q2,init}(t) + i_{Q2,add1}(t).$$

Since breakers $Q1$ and $Q2$ are connected in series with the inductance, it is assumed that the arc blowout upon the breakers opening occurs at the point of natural current zero-crossing.

### *Line Closing from the First Side and Switching into Transit (Auxiliary Modes 3 and 4)*

Network equivalent circuits in modes 3 and 4 are also passive circuits, but, unlike modes 1 and 2, each of them is connected to the EMF source (Fig. 3). The source voltage is determined by the breaker contacts' voltage in the previous mode:

In mode 3, as

$$e_{add3}(t) = e_{s1}(t) - u_{1,pr3}(t), \qquad (1)$$

where $u_{1,pr3}(t) = u_{1,init}(t) + u_{1,add1}(t) + u_{1,add2}(t)$;

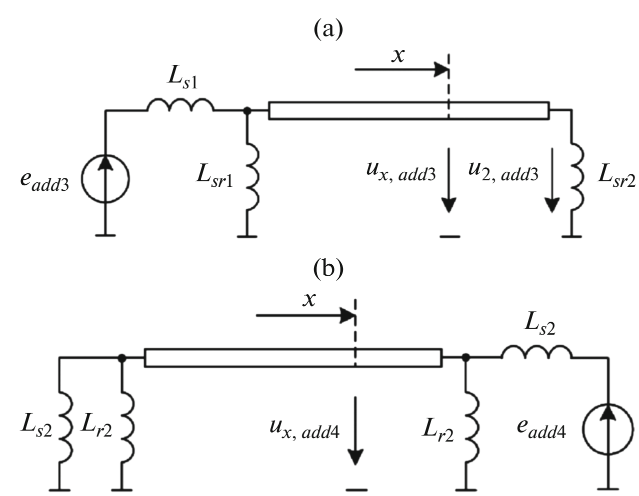


**Fig. 3.** Network equivalent circuit in auxiliary modes (a) 3 and (b) 4.

in mode, 4 as

$$e_{add4}(t) = e_{s2}(t) - u_{2,pr4}(t),$$

$$u_{2,pr4}(t) = u_{2,init}(t) + u_{2,add1}(t) + u_{2,add2}(t) + u_{2,add3}(t).$$

When assessing the overvoltage level, mode 4 should not be considered, since it is not accompanied by an intense transient process. This is because, first, the line is usually switched into transit with the presynchronization of system voltages $S2$ and line $u_2$ and, therefore, voltage $e_{add4}$ has a low amplitude, and, second, the reflection coefficient of the electromagnetic wave for both line ends is small due to the low resistance of power sources.

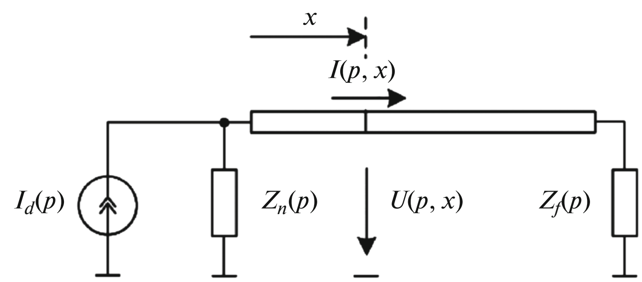


**Fig. 4.** Universal electrical network design scheme: $Z_n$ and $Z_f$ are the equivalent resistances of the left- and right-hand sides of the circuit.

## UNIVERSAL DESIGN SCHEME

All auxiliary modes are modes of switching on the source into the passive circuit with zero initial conditions. This feature consideration makes it possible to formalize the calculation and simplify its implementation in the computing environment by reducing the scheme of all auxiliary modes to a universal form (Fig. 4) [4]. The universal design scheme is applicable for the calculation of the initial mode, if the actions of power sources are considered separately.

The universal design topology remains unchanged in all modes, while the connection point of the current source, the position of the observation point, and the line current polarity may differ in the universal design scheme. For example, the mode 1 scheme corresponds exactly to the universal design scheme, and the mode 2 scheme is a mirror image of the universal scheme with corresponding changes in its parameters.

It is obvious that ARC switching overvoltage is caused by free components of the transient process. Therefore, they are the focus of the overvoltage analysis. The calculation involves an operator method in which electrical quantities are represented as a set of forced and free components.

Calculated expressions for describing current and voltage at an arbitrary line point in the universal circuit (hereinafter, if there is no ambiguity of interpretation, complex variable $p$ is omitted in the expressions) are as follows:

$$U(x) = I_d Z_n \frac{Z_f \cosh\gamma(l-x) + Z_w \sinh\gamma(l-x)}{D}; \quad (2)$$

$$I(x) = I_d Z_n \frac{\cosh\gamma(l-x) + \dfrac{Z_f}{Z_w}\sinh\gamma(l-x)}{D}; \quad (3)$$

Here, $\gamma = \sqrt{(R_0 + pL_0)(G_0 + pC_0)}$; is the wave distribution constant; $z_w = \sqrt{(R_0 + pL_0)/(G_0 + pC_0)}$ is the wave resistance; $R_0$, $L_0$, $G_0$, and $C_0$ are the specific resistance, inductance, active conductivity, and line capacity; $l$ is the length of the transmission line; and $x$ is the coordinate of the observation point measured from the termination point of the current source.

## COMPONENTS OF ELECTRICAL QUANTITIES IN THE TRANSIENT MODE

In general, the desired electrical quantity $v(t)$ in the universal network scheme (Fig. 4) can be represented as

$$V(p) = \frac{F(p)}{A(p)},$$

where $F(p)$ is the value of the electrical quantity of the disturbance source; $A(p)$ is a function defined by the scheme parameters. In our case, the network scheme contains a long-distance transmission line. Therefore, $A(p)$ has an infinite number of zeros and the desired value of $v(t)$ under the action of the disturbance source, in the form of a damped sinusoid,

$$f(t) = F_m e^{-\alpha_f t} \sin(\omega_f t + \psi_f),$$

will contain a forced component and infinite number of free terms:

$$v(t) = \operatorname{Im}\left[\underline{V}_e e^{p_f t} + \sum_{m=1}^{\infty} \underline{V}_{d,q} e^{p_m t}\right]. \quad (4)$$

The complex amplitude of the forced component and the initial value of the complex amplitude of the $m$th free term [5] are

$$\underline{V}_e = \frac{F_m e^{j\psi_f}}{A(p_f)}$$

and

$$\underline{V}_{d,q} = \begin{cases} \dfrac{F_m e^{j\psi_f}}{A'(p_q)(p_q - p_f)}, \text{ if } \operatorname{Im} p_q = 0, \\ \dfrac{F_m}{A'(p_q)}\left[\dfrac{e^{j\psi_f}}{p_q - p_f} - \dfrac{e^{-j\psi_f}}{p_q + p_f}\right], \text{ if } \operatorname{Im} p_q \neq 0. \end{cases} \quad (5)$$

Here, $p_f = -\alpha_f + j\omega_f$ is the complex frequency of the disturbance source and $p_q$ is the zero value of function $A(p)$ with sequence number $q$.

**Table 1**

| ARC conditions | Free component $\underline{V}_q$ complex amplitude | |
|---|---|---|
| | in the general case | maximum value |
| Random closing | $\frac{1}{p_q A'(p_q)}\left[\frac{E_{s1}e^{j\psi_{s1}} - U_1 e^{j\psi_L}}{1-\underset{*}{p}} - \frac{E_{s1}e^{-j\psi_{s1}} - U_1 e^{-j\psi_L}}{1+\underset{*}{p}}\right]$ (8) | For $\psi_{s1} = \psi_L + \pi$, $\psi_L = \pm\pi/2$ $(E_{s1} + U_1)\,B\left(p_q, \underset{*}{p}\right)$, (9) where $B\left(p_q, \underset{*}{p}\right) = \frac{2}{p_q A'(p_q)\left(1-\underset{*}{p}\right)\left(1+\underset{*}{p}\right)}$ |
| Closing at the breaker contacts' voltage zero-crossing time: $E_{s1}\sin\psi_{s1} = U_1\sin\psi_L$ | $\frac{E_{s1}\cos\psi_{s1} - U_1\cos\psi_L}{p_q A'(p_q)}\left[\frac{1}{1-\underset{*}{p}} - \frac{1}{1+\underset{*}{p}}\right]$ | For $\psi_{s1} = \pi n$, $\psi_L = \pi(n+1)$, $n \in Z$ $\underset{*}{p}(E_{s1} + U_1)\,B\left(p_q, \underset{*}{p}\right)$ (10) |
| Closing at the breaker contacts' voltage envelope valley point: $\psi_{s1} = \psi_L = \psi$ | $\frac{E_{s1} - U_1}{p_q A'(p_q)}\left[\frac{e^{j\psi}}{1-\underset{*}{p}} - \frac{e^{-j\psi}}{1+\underset{*}{p}}\right]$ | For $\psi = \pm\pi/2$ $(E_{s1} - U_1)\,B\left(p_q, \underset{*}{p}\right)$ (11) |
| Closing at the breaker contacts' voltage zero-crossing time near the envelope valley point: $E_{s1}\sin\psi_{s1} = U_1\sin\psi_L$ $\psi_{s1} \approx \psi_L = \psi$ | $\frac{E_{s1} - U_1}{p_q A'(p_q)}\left[\frac{1}{1-\underset{*}{p}} - \frac{1}{1+\underset{*}{p}}\right]\cos\psi$ | For $\psi = \pm\pi$ $\underset{*}{p}(E_{s1} - U_1)\,B\left(p_q, \underset{*}{p}\right)$ (12) |

The electrical quantities in the transient mode of the network with the long-distance transmission line theoretically contain an infinite number of free terms, but their amplitude rapidly decreases with increasing frequency. Therefore, the choice of the optimal conditions for the controlled transmission line closing depends only on the first three or four terms of the free process.

## OVERVOLTAGE DECREASE MECHANISM WITH THE INTELLIGENT AUTOMATIC RECLOSING CYCLE

The transient process at the reclosing proceeds in auxiliary mode 3 (Fig. 3a) and is caused by the connection of EMF source $e_{add3}$ (1) to the electrical network. By this time, all transmission line voltage high-frequency free components have already attenuated and only the low-frequency damping component remains [6]. Therefore, in mode 3, EMF source voltage $e_{add3}$ is

$$\underline{E}_{add3}(t) = \underline{E}_{s1}(t) - \underline{U}_1(t) = \underline{E}_{s1}e^{j\psi_{s1}}e^{p_{s1}t} - U_1 e^{j\psi_L}e^{p_L t}, \qquad (6)$$
$$p_{s1} = j\omega_0, \quad p_L = -\alpha_L + j\omega_L,$$

where $\psi_{s1}$ and $\psi_L$ are the initial EMF phases of the system and line voltage, $\omega_0$ is the system EMF frequency, and $\alpha_L$ and $\omega_L$ is the attenuation coefficient and voltage frequency of the transmission line. Usually, transmission line voltage frequency $\omega_L$ is close to nominal network frequency $\omega_0$ and attenuation coefficient $\alpha_L$ is small and does not exceed 2 $s^{-1}$ [7]. Therefore, $p_L \approx j\omega_L$.

For a transmission line with a length of much shorter electromagnetic wavelength, the frequency of all free components in a transient mode is many times higher than the system EMF frequency ($\omega_q \gg \omega_0$) and the transmission line voltage frequency ($\omega_q \gg \omega_L$). Therefore, it is conceivable that

$$p_q - p_{s1} \approx p_q - p_L = p_q\left(1 - \underset{*}{p}\right),$$
$$p_q + p_{s1} \approx p_q + p_L = p_q\left(1 + \underset{*}{p}\right), \qquad (7)$$
$$\underset{*}{p} = p_L/p_q \approx p_{s1}/p_q, \quad \left|\underset{*}{p}\right| \ll 1.$$

At the same time, a compensation degree of long-distance transmission lines is close to unity [8]. Such lines are characterized by $\omega_L \approx \omega_{s1}$. Therefore, $p_L \approx p_{s1}$, and assumption (7) is also applicable to them.

Taking into account expressions (5)–(7), the initial value of the $q$th free component complex amplitude can be represented in a more convenient form for analysis—in the form of expression (8) (see Table 1), from analysis of which it follows that the ARC overvoltage intensity depends on the amplitude–phase ratio of the supply system and the line. Consequently, there are several possible intelligent automatic reclosing methods.

The most intense overvoltage occurs when the transmission line is reclosed at the time of the maximum

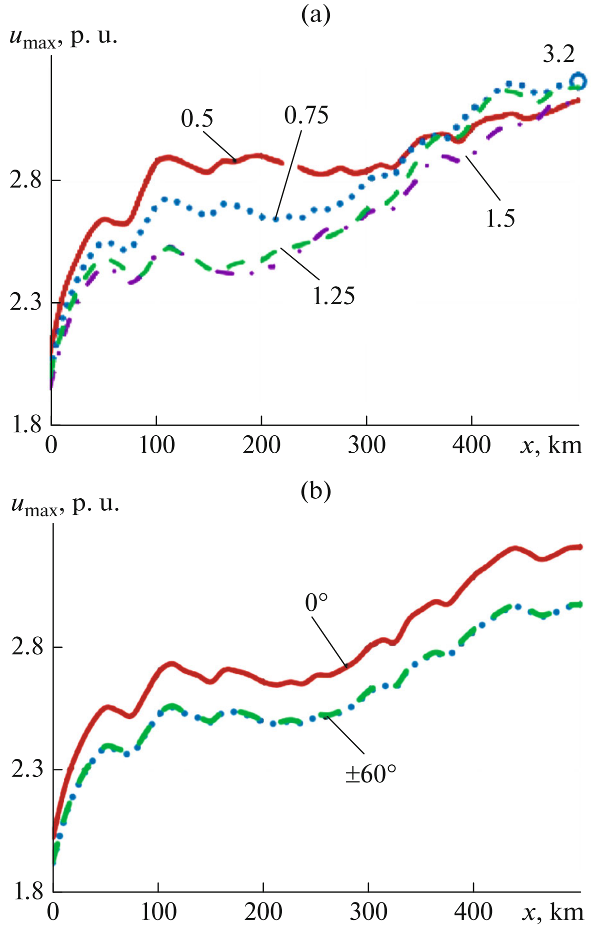


**Fig. 5.** Maximum transmission line voltage profile at the reclosing at breaker contacts $Q1$ maximum voltage time for (a) $\delta = 0$ and $k_c = 0.5, 0.75, 1.25$, and 1.5 and (b) for $k_c = 0.75$ and $\delta = 0$ and $\pm 60°$. Designations are the same as in Fig. 5.

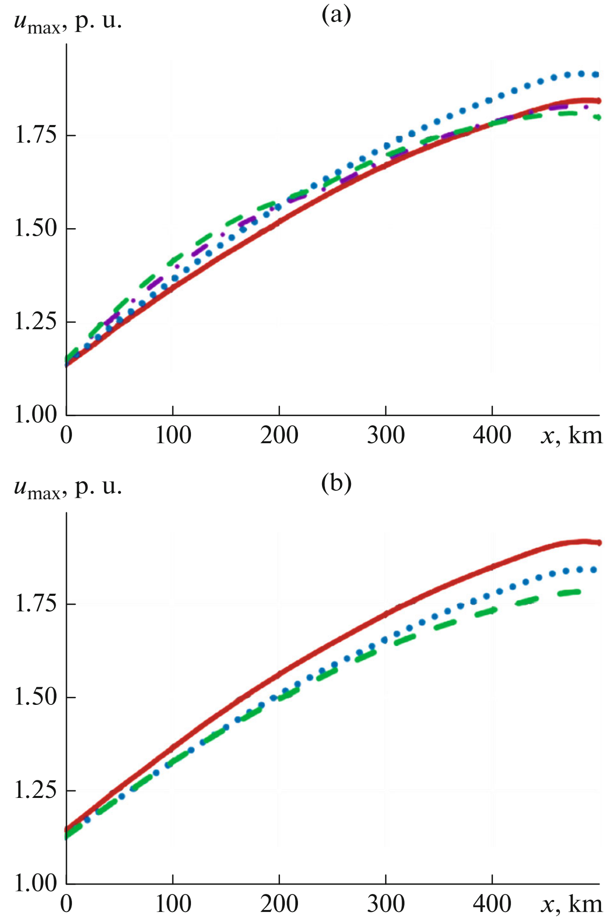


**Fig. 6.** Profile of maximum voltage on power lines upon reclosing at time of voltage transition on the contacts of switch $Q1$ through zero: (a) $\delta = 0°$; (b) $k_c = 0.75$.

breaker contacts' voltage (expression (9), Table 1). This case is typical of common automatic reclosing.

The line reclosing at the time of breaker contacts' voltage zero-crossing [1, 9] allows for a decrease in overvoltage by $1/p$ times compared to the worst case (9) and at the valley point of the voltage envelope [10, 11] by $(E_{s1} + U_1)/(E_{s1} - U_1)$ times. This follows from comparison of expressions (10) and (11) with expression (9).

The most effective decrease of overvoltage is achieved using the intelligent automatic reclosing algorithm ensuring the reclosing at the breaker contacts' voltage zero-crossing time near the envelope valley point. This provides the overvoltage reduction $(E_{s1} + U_1)/[\underset{*}{p}(E_{s1} - U_1)]$ times compared to the common automatic reclosing (expression (12), Table 1).

## COMPUTATIONAL EXPERIMENT

The purpose of the computational experiment is to investigate the effect of the scheme parameters and reclosing conditions on the overvoltage level. An overvoltage rating is based on maximum voltage profiles along the entire line. The experiment program includes the study of processes during reclosing as follows.

(A) At maximum breaker contacts $Q1$ voltage time.

(B) At breaker contacts $Q1$ voltage zero-crossing time.

(C) At the valley point of breaker contacts $Q1$ voltage envelope.

(D) At breaker contacts $Q1$ voltage zero-crossing time near the valley point of this voltage envelope.

The influence of dischargers and surge arresters is not taken into account.

## SCHEME PARAMETERS

A transmission line is analyzed with length $l = 500$ km with specific parameters $R_0 = 0.0296\ \Omega$/km, $L_0 =$

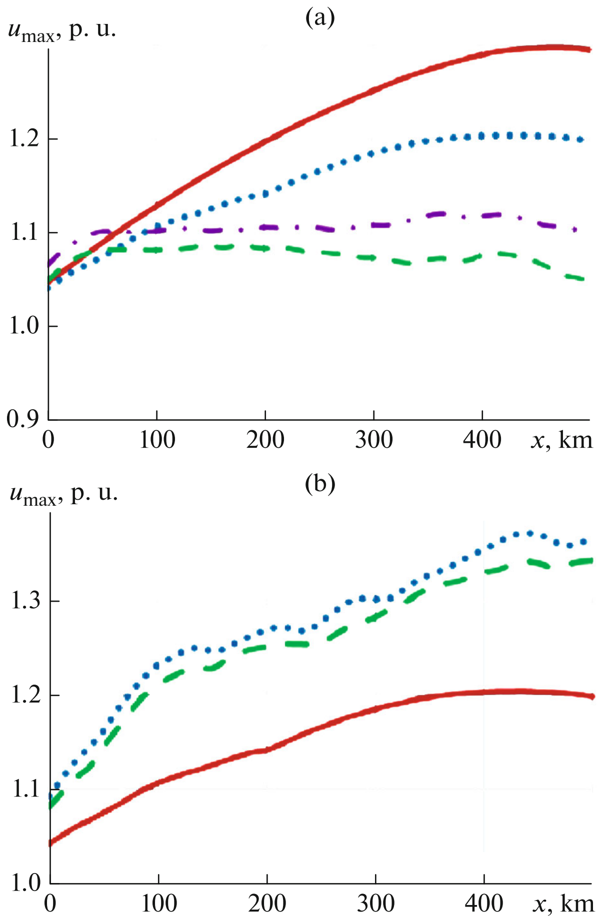


**Fig. 7.** Maximum voltage profile on the transmission line at breaker contacts $Q1$ voltage envelope valley point: (a) $\delta = 0°$; (b) $k_c = 0.75$ (b). Designations are the same as in Fig. 5.

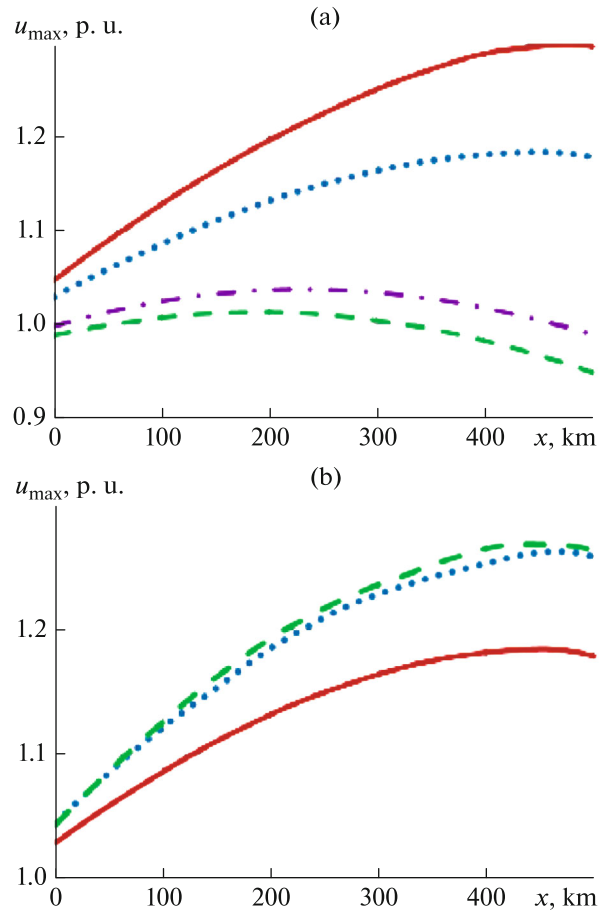


**Fig. 8.** Maximum transmission line voltage profile at the reclosing when breaker contacts $Q1$ voltage zero-crossing near the voltage envelope valley point: (a) $\delta = 0°$; (b) $k_c = 0.75$. Notations are the same as in Fig. 5.

0.98 mH/km, and $C_0 = 11.6$ nF/km equipped with two reactors with inductance

$$L_{sr1} = L_{sr2} = \frac{2}{k_c \omega^2 l C_0},$$

where $k_c$ is the compensation coefficient of the line charge capacity. Left- and right-hand power systems are represented by EMF sources $E_1 = 1 < \delta$ p. u. and $E_2 = 1 < 0°$ p. u. with internal inductance of $L_{s1} = L_{s2} = 0.064$ H. Compensation coefficient $k_c = 0.5–1.5$, and transmission angle $\delta = –60°...60°$. The minimum duration of the reclosing time is taken to be 0.35 s [12].

### *Line Reclosing at the Breaker Contacts' Voltage Maximum Time*

The maximum voltage is observed near the open line end and reaches 3.2 p. u. (Fig. 5). This significantly exceeds the level of permissible switching overvoltage for the isolation of the EHV network equipment (2.2 p. u. for the 330-kV network, 1.65 p. u. for the 1150-kV network).

The overvoltage level is almost independent of the degree of compensation of the transmission line charge capacity. This is due to the fact that the free components of the transient process, causing overvoltage, are of a high frequency and almost do not flow through the shunt reactors.

A change in the transmission angle weakly affects the overvoltage level, although with an increase in the absolute value of the transmission angle, the amplitude of the line residual voltage decreases during the reclosing time.

### *Line Reclosing at the Breaker Contacts' Voltage Zero-Crossing Time*

The maximum voltage is reduced by more than 41% compared with the previous case and is equal to 1.9 p. u. (Fig. 6). Since, in this case again, the overvoltage level is mainly determined by the free components, the influence of other factors on it is weak.

*Line Reclosing at the Voltage Envelope Valley Point or at the Breaker Contacts' Voltage Zero-Crossing Near the Envelope Valley Point*

Both methods are equally effective on a low-loss line: the maximum voltage does not exceed 1.36 p. u. (Figs. 7 and 8), which is explained by the small value of the breaker contacts' voltage envelope at the closing time that is characteristic of such lines.

The advantage of reclosing at the breaker contacts' voltage zero-crossing near the envelope valley point becomes apparent when line losses increase—for example, due to bad weather conditions. In this case, the voltage at the envelope valley point is high.

Both methods are characterized by a decrease in overvoltage with an increase in compensation due to a decrease in the amplitude of the line voltage forced component (Figs. 7a, 8a), but this circumstance is not decisive in terms of overvoltage. A change in the transmission angle leads to an increase in the overvoltage level due to an increase in the envelope value at the valley point (Figs. 7b, 8b).

## CONCLUSIONS

The closing time exerts a decisive influence on the overvoltage level during the ARC. The influence of the line charge capacity compensation and the transmission angle is relatively small.

The theoretical analysis and computational experiment confirm that the transmission line ARC algorithm has an advantage at the breaker contacts' voltage curve zero-crossing near the envelope valley point over other algorithms.

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