# An Optimal Strategy for Three-Phase Intelligent Auto-Reclosing of Power Lines with Shunt Reactors

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**Abstract— Intelligent auto-reclosing technology is an effective method for mitigation of switching overvoltages that occur during reclosing of power lines with shunt reactors. The idea of this technology is to precision control the moment when the power line is energized to reduce the intensity of electromagnetic transients that induce overvoltages. In this paper, we consider the application features of the theory of intelligent auto-reclosing of long transmission lines with shunt reactors in a three-phase auto-reclosing cycle. The principles of choosing line phases energizing moments are investigated and the optimal strategy of three-phase intelligent auto-reclosing is proposed. In contrast to the known strategy, the new strategy takes into account both the inter-phase coupling effect and the influence of the spread of circuit breaker operation time on. The modeling proved better efficiency of the new strategy compared with a known strategy of intelligent auto-reclosing and significant advantages over traditional metal-oxide surge arresters, even if a spread of circuit breaker operation time exists.**

***Keywords— intelligent automatic reclosing, controlled switching, switching overvoltage, power lines, shunt reactor***

## I. INTRODUCTION

During the dead time of reclosing cycle of a long power line equipped with shunt reactors (SRs), a high-Q oscillating circuit is formed. In it, at the time of reclosing, the oscillatory discharge of the distributed capacity of the power transmission line through SRs is still continuing. Reclosing of the "charged" line at a random moment can lead to dangerous switching overvoltages in a network.

A danger of switching overvoltages for isolation during the auto-reclosing cycle was detected in the mid-1950s when developing ultra-high voltage transmission lines [1]. Research has shown that just this type of overvoltage is the most severe and determines the requirements for the insulation of power lines, significantly affecting the cost of its construction [2]. Various technical measures were proposed to limit the overvoltage caused by auto-reclosing: installation of metal-oxide surge arresters (MOSA) at the ends of power lines, the use of special circuit breakers (CB) with pre-insertion resistors and controlled switching [1, 3].

MOSA reduce the level of overvoltages at the installation point to the required level, dissipating the electromagnetic transient energy on its active resistance. However, their effective range is limited in principle, so overvoltage protection of long power lines requires the installation of MOSA along the line, which is not always acceptable [1].

Special CBs with pre-insertion resistors have been widely used as a means of limiting switching surges since the early 1960s [4, 5]. The power line is energized with 2 stages: first, using the first group of CB contacts, the line is connected to the power source via a resistor with a resistance of 250÷600 Ohms, and after 4÷20 ms, the resistor is shunted by the second group of CB contacts. The reduction of switching overvoltage occurs both by reducing the amplitude of the electromagnetic wave that occurs in the line when switched on and by reducing the reflection coefficient of the wave from the supply end of the line. Long-term experience of operation of such special CBs has shown their insufficient reliability and significant operating costs [1]. In this regard, preference is given to intelligent auto-reclosing technology [6, 7].

The reduction of overvoltage during auto-reclosing of uncompensated power line using control of energizing moment was proposed by E. Maury in 1966 [8]. This principle was named controlled or synchronous switching.

The principle of controlled switching prescribes energizing of power line at the moment when the voltage between CB contacts is zero or minimal [8]. The line voltage of uncompensated power line during the dead time of auto-reclose cycle has an aperiodic nature with small damping. Therefore, the zero-crossing points of voltage curve across CB contacts or minimum points (when there are no zero-crossing points) are easily predicted, and implementation of the principle of controlled switching of uncompensated line does not cause difficulties.

The voltage across CB during the dead time of auto-reclosing cycle of power line with SRs has a beat nature. The location of zero-crossing points of voltage curve is not periodic and complex to predict. The development of principle of controlled switching for power line with SRs was proposed by A. Clerici [9]. The proposed principle prescribed energizing of power line at the minimum of voltage beat.

The first controlled switching devices for power lines with SRs could not predict the moments of voltage beat

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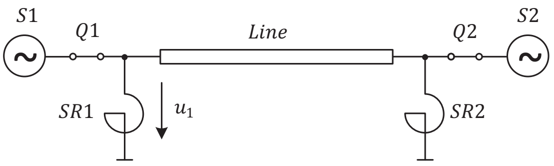


Fig. 1. Electrical network scheme with a power line, equipped by shunt reactors

minimum. So, the duration of dead time was set in advance based on a preliminary calculation of the most likely scenario of the reclosing cycle [10]. The efficiency of such devices depended on the degree of compliance of the calculated parameters of transient process with actual ones.

The development of microprocessor technology and digital signal processing algorithms in the early 1990s made it possible to implement intelligent controlled switching algorithms that can predict the optimal switching moment [6, 11]. Such algorithms called intelligent auto-reclosing algorithms [7, 12].

Theoretical issues of intelligent auto-reclosing are discussed in detail in [13] on the base of a two-wire power line with SRs. This report develops the ideas of [13] concerning a strategy of three-phase intelligent auto-reclosing of power lines with SRs.

## II. FUNDAMENTALS OF INTELLIGENT AUTO-RECLOSING

The principles of electromagnetic transient management by control of power line reclosing moment are considered on the example of a two-wire line.

Switching overvoltages during auto-reclosing are caused by high-frequency components of the electromagnetic transient process. According to the statements of [13], the transient components in a power line with SRs (Fig. 1) can be considered as the result of power line energizing by EMF source *e* with internal inductance $L_{s1}$ (Fig. 2). The EMF value in the computation scheme is numerically equal to the voltage at the CB contacts at the time of reclose. It is known that at the time of line reclosing high-frequency transient components in the line voltage $u_1(t)$ completely decay, and only one low-frequency (close to the nominal frequency) damped component remains [14]. Therefore, the EMF source $\underline{E}(t)$ in the computation scheme (Fig. 2) will be equal to the difference between the sinusoidal EMF of the supply system $\underline{E}_{s1}(t)$ and the damped oscillatory line voltage $\underline{U}_1(t)$ :

$$\underline{E}(t) = \underline{E}_{s1}(t) - \underline{U}_1(t) = E_{s1} e^{j\psi_{s1}} e^{p_{s1} t} - U_1 e^{j\psi_L} e^{p_L t}. \quad (1)$$

Here $\psi_{s1}$ and $\psi_L$, $p_{s1} = j\omega_0$ and $p_L = -\alpha_L + j\omega_L$ – the initial phases and complex frequencies of the power system EMF and line voltage respectively, $\omega_0$ – the frequency of the EMF system, $\alpha_L$, and $\omega_L$ – the damping coefficient and the frequency of the low-frequency transient component of power line voltage.

The complex amplitudes of the high-frequency voltage transient components

$$\underline{U}_q = \frac{1}{p_q A'(p_q)} \left[ \frac{E_{s1} e^{j\psi_{s1}} - U_1 e^{j\psi_L}}{1 - \underset{*}{p}} - \frac{E_{s1} e^{-j\psi_{s1}} - U_1 e^{-j\psi_L}}{1 + \underset{*}{p}} \right], \quad (2)$$

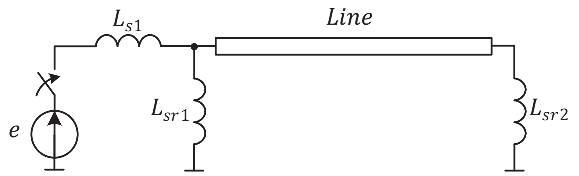


Fig. 2. Equivalent scheme for computation of electromagnetic transients during power line with shunt reactors auto-reclosing

are determined by the voltages values of the supply system and power line at the moment of switching on and the value of the characteristic function *A*(*p*), which depends on the position of the observation point on the line. Here $p_q$ is the zero of the polynomial *A*(*p*) with serial number *q*, $A'(p_q)$ – the value of the derivative of characteristic function *A*(*p*) at $p = p_q$,

$$\underset{*}{p} = \frac{p_L}{p_q} \approx \frac{p_{s1}}{p_q}, \quad \left| \underset{*}{p} \right| << 1. \quad (3)$$

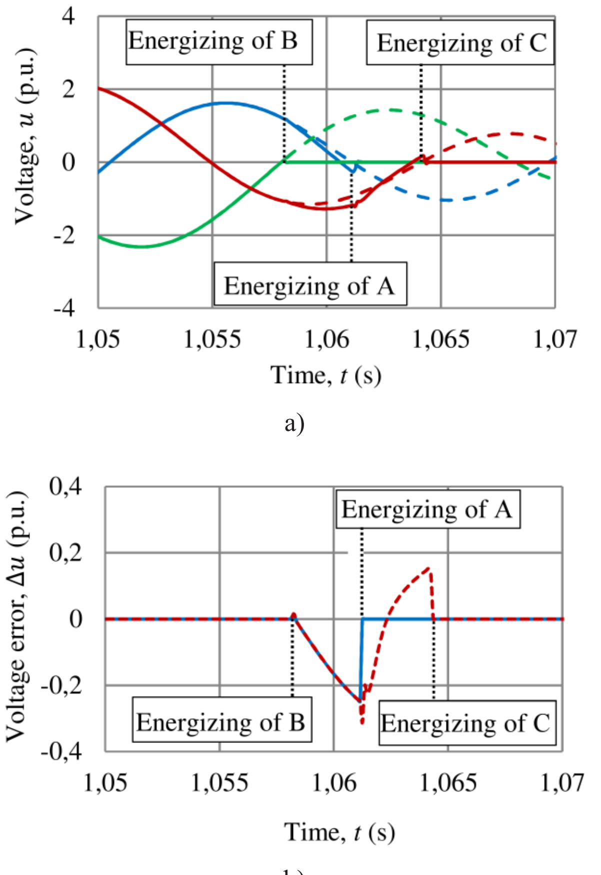
The amplitude $\underline{U}_q$ in (2) determines the intensity of the electromagnetic transient, and, consequently, the level of switching overvoltages during auto-reclosing. Precision control of reclosing moment can mitigate switching overvoltages due to reducing the value of the numerator of the expression (2). There are two possibilities to reduce the intensity of electromagnetic transient: energizing of the line near the minimum of a beat (envelop) of voltage across CB (when $\psi_{s1} = \psi_L$) and energizing of a line in the vicinity of voltage zero-crossing (when $E_{s1}\sin\psi_{s1} = U_1\sin\psi_L$). The most effective strategy for mitigation of commutation overvoltage corresponds to combination of these two possibilities: reclosing in the vicinity of CB voltage zero-crossing near the minimum of its envelope. From the traveling wave's point of view, this is explained, first, by a decrease of the front of voltage traveling wave, produced by commutation, and secondly, by a decrease of wave amplitude.

## III. THE SPECIFICITY OF THREE-PHASE AUTOMATIC RECLOSING

Although the optimal reclosing strategy is known – reclosing of each phase when the voltage across CB's contacts pass through zero near the minimum of the voltage envelope – there is a specificity of three-phase auto-reclosing, that makes such a strategy unrealizable. It is related to the processes that occur during the previous tripping of the power line.

Discharge of distributed capacity of power line trough shunt reactors often begins with an asymmetry of initial conditions if line tripping is preceded by an asymmetric mode of the line (for example, an asymmetric fault). In this case, the discharge of capacitances occurs simultaneously in all sequences circuits. Since the circuit parameters of the positive and negative sequences being identical and differ from the zero-sequence circuit parameters, mainly due to the difference in distributed capacitance of the line, then complex frequencies of transient components of these circuits also differ: frequency of transient component in the zero-sequence circuit is 4-13% higher than this in positive sequence circuit [10].

Due to the asymmetry of line voltage at reclosing time, the minimum of the envelope of voltage across CB's



a)

b)

Fig. 3. Predicted (dotted lines) and actual (solid lines) voltage curves across CB contacts (a) and prediction errors for phase A (solid line) and C (dotted line) caused by inter-phase coupling effect (b). Energizing sequence is B-A-C

contacts is not reached simultaneously in all phases, and the time interval between them can be hundreds of milliseconds. Such delay between reclosing of line phases is unacceptable due to power system dynamic stability conditions and risk of resonant overvoltage in incomplete-phase modes of a power line.

There is another argument for reclosing of remaining phases of the power line immediately after the first phase is enabled. The transient process in the line that begins due to reclosing of any phase distorts the power line voltage curves in the remaining phases. It causes shifting of actual zero crossings of voltages across CB's contacts from moments predicted during the auto-reclosing dead time (Fig. 3). This phenomenon is known as an inter-phase coupling effect [15]. Prediction error rises with increasing time interval between phase reclosing moments. Attempt to consider the impact of the inter-phase coupling effect when predicting voltage curves of the second and third phases is ineffective since the transient parameters are volatile due to some random spread of the CB action time. A reasonable strategy for three-phase auto-reclosing is to reclose the second and third phases as close as possible to the moment of reclosing the first phase [11].

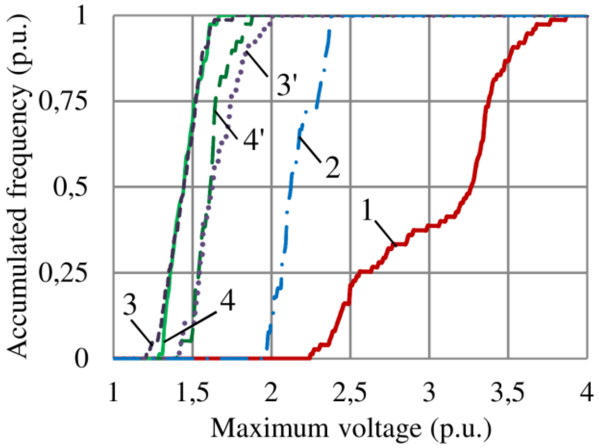


Fig. 4. Cumulative curves of maximum voltages for a three-phase automatic reclosing of a power line with shunt reactors (rated voltage 500 kV, length 432 km): at the maximum voltage across CB contacts (curve 1) on a power line without MOSA; on a power line with MOSA with a protective level of 2,0 p.u. (curve 2); for a three-phase intelligent auto-reclosing using the strategy [11] (curves 3 and 3') and a new strategy (curves 4' and 4) taking into account the spread of the CB operation time 1 ms and without spread respectively

## IV. THREE-PHASE INTELLIGENT AUTO-RECLOSING STRATEGY

The well-known strategy of intelligent auto-reclosing [11] is based on choosing the sequence of phase reclosing using a special approach. This strategy takes into account that, on the one hand, the maximal deviation of reclosing conditions from optimality will be in the third phase, and on the other hand, the minimum overvoltage, even if the switching moment deviates from the optimal one, will be in the phase with the lowest level envelope of voltage across CB contacts. Therefore, first, form the curves of predicted phase voltage across CB contacts, the zero-crossing point corresponding to the smallest value of envelope compared with other phases is found, and this point is selected as the moment of reclosing of the third phase. Nearest zero-crossings of voltage curves in other phases lies on the left of selected moment are taken as reclosing moments of first and second phases.

Although the described strategy allows reducing the inter-phase coupling effect, it does not take into account the envelope values in the first and second reclosing phases. At the same time, the envelope values can be significant, and, according to [13], even switching on the first and second phases strictly at voltage zero-crossing point an intensive transient process and overvoltages can still occur.

Further increase in the efficiency of intelligent auto-reclosing is impossible without simultaneously taking into account the inter-phase coupling effect and the voltage envelope in each phase. In the improved three-phase intelligent auto-reclosing strategy, due to the consideration of envelope values, it is possible to significantly reduce the maximum level of overvoltage, especially when there is a spread of CB operation time.

The effectiveness of the new strategy was studied on a model of a real 500 kV 432 km transmission line using PSCAD software. The model parameters are given in tables. The degree of compensation of line capacity power was varied from 0.25 to 1.5, and all types of short circuits were modeled.

TABLE I. POWER SYSTEM PARAMETERS

| **Substation** | **EMF, kV** | **Impedance at nominal frequency, Ohm** | | |
|---|---|---|---|---|
| | | ***Positive sequence*** | ***Negative sequence*** | ***Zero sequence*** |
| S1 | 515 | $0.909 + j16.784$ | | $0.254 + j10.35$ |
| S2 | 515 | $10.884 + j97.905$ | | $5.385 + j74.727$ |

TABLE II. POWER LINE PARAMETERS

| **Parameter** | **Value** |
|---|---|
| Line length | 432 km |
| Phase wire type | 3xAS-330/43 |
| Sub-wire spacing distance | 0.4 m |
| Tower type | PB500-7H |
| Ground wire type | 2xAJS-70/39 |
| Wire sag | 7.4 m |

TABLE III. SHUNT REACTOR PARAMETERS

| **Parameter** | **Value** |
|---|---|
| Type | RODC 500 kV |
| Winding connection scheme | star with grounded neutral |
| Nominal reactive power | variable, according to degree of compensation of line capacity power |
| Nominal power loss | 0.3% of nominal reactive power |

On a power line that is not equipped with a MOSA, the level of switching overvoltage reaches to 3.87 p.u. (curve 1 in Fig. 4; 1 p.u. corresponds to the nominal voltage), significantly exceeding the permissible level of switching overvoltage of network equipment. Surge arrester with a protection level of 2.0 p.u., installed at both line ends, allows limiting the overvoltage to 2.38 p.u. (curve 2 in Fig. 4).

Intelligent auto-reclosing technology demonstrates the best efficiency of surge mitigation on the line in comparison with the use of MOSA for the same purposes, even in conditions of a spread of CB operation time (curves 3, 3', 4 and 4'). The new strategy is more effective than the strategy [11] both in the case of an ideal switch (maximum overvoltage 1.67 p.u. vs. 1.75 p.u., curves 3 and 4 in Fig. 4) and in the case of a reclosing with a spread of CB operation time (maximum overvoltage 1.88 p.u. and 2.0 p.u. respectively, curves 3' and 4').

## V. CONCLUSIONS

Theoretically, the best strategy for an intelligent three-phase automatic reclosing of power line with shunt reactors is to close phases in the vicinity of zero-crossing of voltage curve across CB contacts. However, the reclosing of the first phase already leads to a violation of the optimal conditions for the reclosing of the remaining phases due to the inter-phase coupling effect. Therefore, when choosing the phase reclosing moments during the intelligent three-phase auto-reclosing cycle, the inter-phase coupling effect must be taken into account. The proposed strategy of three-phase intelligent auto-reclosing eliminates the influence of the inter-phase coupling effect by choosing the moment of the line phase reclosed, taking into account the levels of voltage envelopes in all phases, ensuring better overvoltage mitigation efficiency even if circuit breaker operation time has significant spread.

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