A Damage Prevention of Circuit Breaker During Energizing of Low-loaded Line with Shunt Reactors

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***Abstract*—Energizing current of low-loaded highly-compensated power lines with shunt reactors mainly consists of an aperiodic component, and for a long time has not zero-crossing points. The modern SF6 circuit breaker fails to trip such power line immediately after energizing if unexpected fault or protection relay malfunction occurs because of commutation inability of aperiodic current. This leads to a long arc burning, and eventually to the breaker damage. The paper studies the transients during the commutation of the low-loaded power line and conditions when the amplitude of aperiodic component exceeds a safe level. The study shows that effective prevention of circuit breaker failure may be achieved using controlled switching technology assuming precision control a line energizing moment. The optimal reclosing moment is located near a beat minimum of the circuit breaker voltage and corresponds to the phase of supply voltage, at which the initial amplitude of the energizing current aperiodic component does not exceed the amplitude of the fundamental component. Reclosing of power line at the proposed optimal moment guarantees the safety of commutation for the circuit breaker and ensures mitigation of switching overvoltages.**

Keywords—controlled switching, power lines, shunt reactor, circuit breaker damage, switching overvoltage

I. INTRODUCTION

The energizing mode of low-load power line with shunt reactors (SRs) of EHV transmissions is characterized by two significant features of energizing current. First, the forced component level of the current is relatively small due to the low loading of the line, and secondly, a significant part of its free process is the aperiodic component of the current of the SR with a small damping factor. Therefore, the energizing current flowing through the circuit breaker (CB) consists mainly of the aperiodic component, and its curve does not have zero-crossing points for a long time. This complicates the operating conditions of the CB when line forced tripping by an unexpected short circuit or a relay protection maloperation immediately after line energizing occurs.

At the same time, the forced de-energizing of the power line is also affected by CB type mainly due to the nature of the arc extinguishing process.

For example, in traditional air CBs, the intensity of the blowing off the arc does not depend on the current. Air CBs are characterized by a significant cut-off current, due to then, they can disconnect currents that do not contain zero-crossing points. However, when the inductive load circuit is disconnected, this feature of the air CBs creates dangerous overvoltage for isolation. Often, such overvoltages cause multiple restrikes of arc between separated contacts and followed by damage of CB [1, 2].

The intensity of arc quenching in SF6 CBs is directly dependent on the current. Therefore, when SF6 CB trips a small load the blowing in the chamber will be weak, so that they trip small sinusoidal inductive currents without cut-off and, consequently, overvoltage. But in case of tripping a low-loaded power line with SRs, this property of SF6 CBs becomes the main drawback: breaker cannot extinguish arc current with dominant aperiodic component, and the arc burns until essential zero-crossings appear in the current curve [2, 3]. Prolonged arc burning leads to contact melting and causes overheating of the SF6 and catastrophic increase of pressure in the arc-extinguishing chamber of CB. Typical examples of such accidents are those on 1150 kV Altayskaya Substation (26.02.2007) and 750 kV Novobrianskaya Substation (13.07.2011).

One of the ways to prevent CB damage is the use of special pre-insertion resistors [4]. This technical measure provides fast damping of the aperiodic component in the energizing current. However, the operation experience of CB with pre-insertion resistors shows that this approach is associated with the high cost and is not reliable [3, 5].

Another way for prevention of CB damage is tripping of SRs during the auto-reclose cycle [2, 3]. This measure eliminates the resonance between SR and power line capacity and leads to an increase of the fundamental component amplitude of energizing current. However, this requires a large number of switching operations during reclose cycle that reduces reliability of whole system [2].

The effective measure for prevention of CB damage is controlled switching technology [3, 6]. The main idea of the method is to control the line energizing moment to reduce the amplitude of current aperiodic component to a safe level. This controlled switching technology requires highly stable operation time of CBs (spread does not exceed 1.0–2.0 ms). A typical spread of modern design SF6 CBs is about 0.4–0.5 ms [7] and so this technology is widely applicable.

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The principles of safe controlled switching of a circuit with a shunt reactor are discussed in detail in [8]. However, these works consider modes when the reactor is in a balanced electromagnetic state before commutation (there is no transition process). In this paper, we develop principles for preventing dangerous modes for CB when the power line is forced tripped immediately after energizing [9].

II. FACTORS AFFECTING THE LEVEL OF APERIODIC COMPONENT

We are interested in factors that lead to an increase of aperiodic component amplitude relative to the amplitude of the forced component of current through CB when energizing a low-loaded two-wire line with shunt reactors (Fig. 1a). Considering the processes in the network, we suppose that CB on the remote end is opened (there is no load current in the line).

The internal impedance of supply system is usually small compared to reactor impedance ($\omega_0 L_S \ll \omega_0 L_{SR}$) and the input impedance of the entire circuit (Fig. 1b) at industrial frequency $\underline{Z}_{in}(\omega_0)=z_{in}(\omega_0)\angle\varphi(\omega_0)$. Therefore the voltage at the line input and the reactor SR is almost equal to the EMF of the system

$$e_S(t) = u_S(t) = U_S \sin(\omega_0 t + \psi_S)\,. \tag{1}$$

This feature of the circuit when a power line with a shunt reactor is energized allows us to consider the processes in the reactor and the power line independently, although both components of energizing current – reactor current and line current – flow through the CB.

Energizing current

$$i_Q(t) = i_f(t) + i_a(t) + \sum_{q=1}^{\infty} i_{d,q}(t), \tag{2}$$

consists of a forced component $i_f(t)$ and components of the free process – an aperiodic component $i_a(t)$ in reactor SR and a sum of high-frequency power line damping components (the last term of the equation). The aperiodic current component flowing through CB is completely determined by the shunt reactor's circuit. If energizing of power line occurs without residual charge (for example, energizing by the operator) aperiodic component is proportional to the amplitude of supply voltage

$$i_a(t) = \frac{U_S \cos\psi_S}{\omega_0 L_{SR}} e^{-t/\tau}, \tag{3}$$

where $\tau = L_{SR}/R_{SR}$ is a time constant determined by losses in reactor, U_S is supply voltage amplitude, ω_0 and ψ_S is the frequency and initial phase respectively. Contrariwise, if power line has a residual charge (for example, when energizing occurs during the auto-reclose cycle) an oscillatory discharge of line distributed capacity through reactor occurs at the energizing time and current aperiodic component is proportional to the amplitude of voltage between breaker contacts U_Q

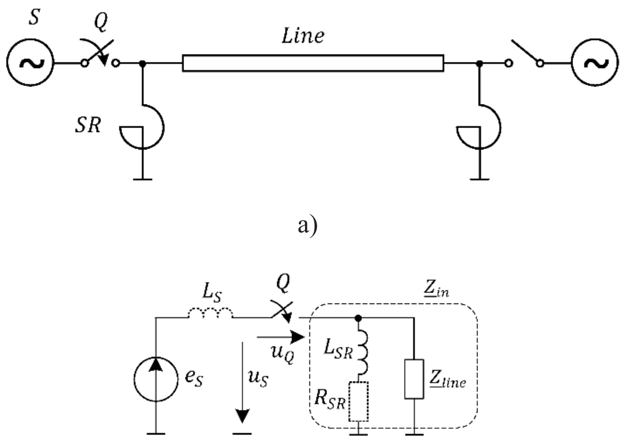
$$i_a(t) = \frac{U_Q \cos\psi_S}{\omega_0 L_{SR}} e^{-t/\tau}. \tag{4}$$

The last formula can be considered as a general form of the formula (3) which takes into account a transient in power line at the energizing time (when there isn't residual charge $U_Q = U_S$).

Although the forced current component $i_f(t)$ includes eponymous components of reactor and line currents, it is convenient to determine it through input impedance of entire circuit $\underline{Z}_{in}(\omega_0)$:

$$i_f(t) = \frac{U_S}{z_{in}(\omega_0)} \sin\left[\omega_0 t + \psi_S - \varphi(\omega_0)\right]. \tag{5}$$

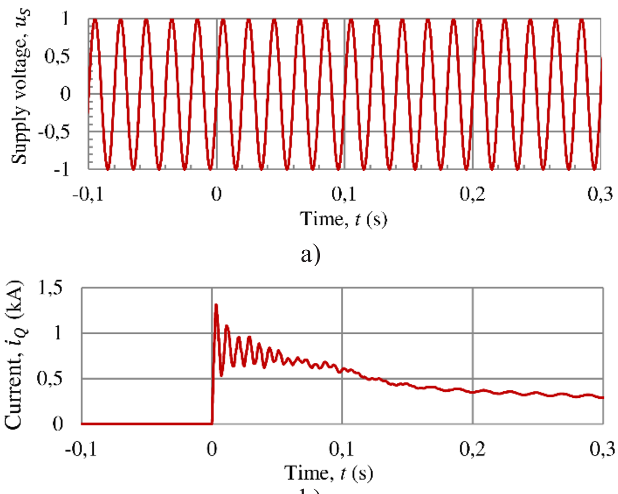
This representation is convenient when analyzing the dependence of forced component amplitude on compensation degree of power line capacitive power k_c and evaluating the multiplicity of initial value of the reactor current aperiodic



a)

b)

Fig. 1. Scheme of energizing of power line with shunt reactors (a) and equivalent circuit (b)



a)

b)

Fig. 2. Supply voltage curve (a) and current through CB when power line energized in the vicinity of voltage zero-crossing (b). Line rated voltage 500 kV, length 432 km, compensation degree of capacitive power k_c = 0.95

component relative to the amplitude of CB current forced component.

When a compensation degree of power line capacitive power

$$k_c = \frac{2}{\omega_0^2 L_{SR} C_0 D},$$

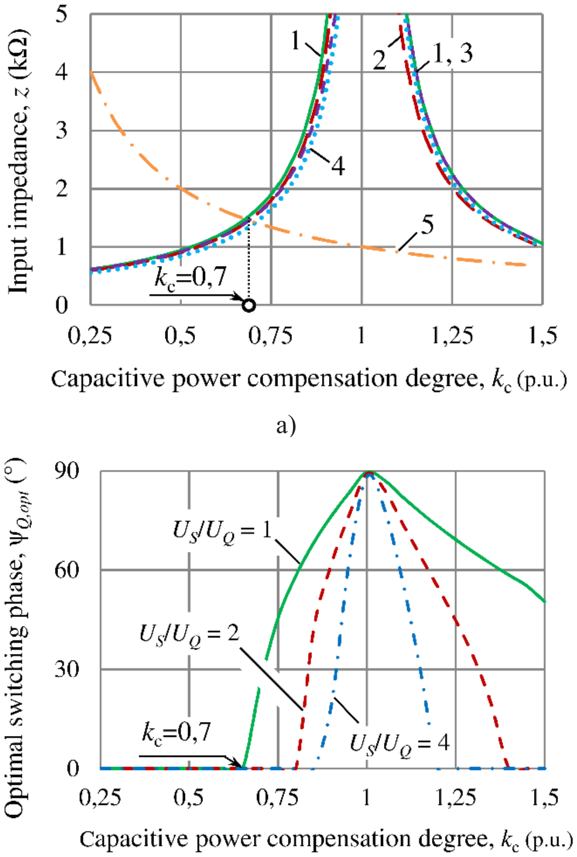
approaching to unit, resonance conditions at the frequency of forced component are emerging, and therefore input impedance of overall circuit increases [$z_{in}(\omega_0)\to\infty$] and amplitude of the forced current is reduced ($i_f(t)\to 0$, where D is length of the line, C_0 – capacitance of line per km). Hence, the energizing current of such a highly compensated line practically consists of the aperiodic component only, since the high-frequency current terms [$i_{d,q}(t)$ in (2)] usually quickly decay and have a significantly lower amplitude compared to the aperiodic component. Besides, a share of the CB current aperiodic component becomes prevalent if line energizing moment is in the vicinity of voltage curve zero-crossing. In this regard, the curve of current through CB for a long time does not have zero-crossings (Fig. 2), causing a prolonged arcing during CB tripping. There are examples when an arc burned between separated contacts of CB for about 50 seconds, causing damage to CB.

III. OPTIMAL CONTROL OF ENERGIZING MOMENT OF THE POWER LINE TO PREVENT CIRCUIT BREAKER DAMAGE

Guaranteed prevention of CB damage during commutation of shunt-compensated power lines is provided if the initial amplitude of aperiodic current component is less than the amplitude of the forced component. Equations (3) and (4) shows that this can be achieved when choosing the moment for power line energizing as close as possible to the maximum point of supplying voltage $u_S(t)$ (when energizing by the operator) or voltage on CB's contacts $u_Q(t)$ (when energizing carried out during the auto-reclose cycle) [3, 6]. However, this requirement conflicts with the requirement for ensuring a permissible level of overvoltage on the power line, because its energizing in vicinity of the voltage curve maximum leads to an increase of commutation overvoltages [9]. Therefore, when choosing the moment energizing power lines requires a compromise: energizing must be carried out between voltage curve zero-crossing and maximum so that neither commutation overvoltages nor an aperiodic component of current is not a danger to power equipment [6].

Energizing of power line in optimal phase $\psi_{S,opt}$ should, on the one hand, prevent damage of CB, and on the other hand, ensure the maximum possible reduction of switching overvoltage level under these restrictions. Therefore, it is proposed to consider the problem of selecting the switching moment as a problem of optimizing of switching overvoltage level, taking into account the restriction caused by the safety requirement for CB. So, the overvoltage level optimization implies minimizing the voltage phase at energizing moment ($\psi_S\to 0$) [9], and CB safety requirement implies selection of energizing phase $\psi_{S,opt}$ that ensures the appearance of a CB current zero-crossing already at the first period of its forced component.

For the optimal switching phase, the condition must be met



a)

b)

Fig. 3. The input impedance of the unfaulted phase of power line with shunt reactors $z_{in}(\omega_0)$ (a) and optimal switching phase $\psi_{S,opt}$ (b) as the functions of capacitive power compensation degree k_c. The character of impedance changes only slightly dependent on the fault type [single-phase (curve 1), double-phase (curve 2) and double-phase-to-ground (curve 3) faults] and similar to the impedance of healthy line (curve 4).

$$\max\left|i_a(t)\right| \le \max\left|i_f(t)\right|,$$

which, taking into account (4) and (5), can be written as an inequality

$$\psi_{Q,opt} \ge \arccos\left[\frac{U_S}{U_Q}\frac{\omega_0 L_{SR}}{z_{in}(\omega_0)}\right]. \qquad (6)$$

As can be seen from (6), the optimal switching phase depends on the ratio between amplitudes of supply U_S and breaker U_Q voltages and ratio between impedances of shunt reactor $\omega_0 L_{SR}$ and power line unfaulted phase $z_{in}(\omega_0)$ at the frequency of supply voltage ω_0. If the arccosine argument is equal or greater than 1, the amplitude of the forced component will be greater than the initial value of the aperiodic term for any energizing phase. Therefore, the switching phase of the power line should be selected based on the requirement of limiting overvoltage, i.e. $\psi_{S,opt} = 0$.

The impedance $z_{in}(\omega_0)$ of unfaulted phases of the power line mainly depends on the degree of capacity power compensation k_c and this dependence has a distinct resonant character (Fig. 3b). At the same time, the presence of fault on the line, fault type, and location practically haven't influence on impedance $z_{in}(\omega_0)$ (curves 1-4 practically coincide).

The voltage ratio U_S / U_Q in formula (6) depends on the line commutation type. When the line is energized by an operator there is no residual charge on the line and $U_Q = U_S$.

During the auto-reclose cycle, an oscillatory discharge of line distributed capacity through reactor occurs with frequency ω close to frequency ω_0 of the supply voltage. The voltage across breaker $u_Q(t)$ has low-frequency beat nature and on the beat cycle's one-half $U_Q > U_S$, and on the other half – $U_Q < U_S$. To mitigate commutation overvoltages controlled switching technology implies breaker closing in the vicinity of beat minimum when $U_Q < U_S$ [9]. This leads to a significant reduction of aperiodic component and decreases a range of compensation coefficient k_c, in which line energizing is potentially dangerous for CB and energizing moment must be shifted from voltage zero-crossing (Fig. 3).

The change in the optimal switching phase $\psi_{S,opt}$ with an increase of compensation power of shunt reactors depends on the compensation coefficient k_c: up to the resonant value ($k_c = 1$) the optimal phase increases, reaching π/2 at resonance in «power lines – shunt reactor» circuit, and at $k_c \geq 1$ – decreases (Fig. 3b).

IV. CONCLUSIONS

The risk of CB damage during forced tripping of power lines with shunt reactors immediately after its energizing is caused by the prevalent level of an aperiodic component of energizing current that leads to the absence of CB current curve's zero-crossing for a long time.

Proper reduction of aperiodic component level in energizing current is possible by control of the energizing phase of the line. Research shows that controlled switching is mandatory for power lines with a compensation degree above 0.7. It is shown that the choice of switching phase which optimizes switching overvoltage level and the aperiodic component of switching current should take into account the ratio of reactor impedance to the power line impedance.

Energizing of the line during the auto-reclose cycle near a beat minimum of the CB voltage, on the one hand, can significantly reduce the probability of breaker damage, and on the other hand, mitigates switching overvoltage.

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