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Study of Short Circuit and Inrush Current Impact on the Current-Limiting Reactor Operation in an Industrial Grid

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Abstract: Current-limiting reactors are widely used in industrial electrical grids to reduce the current amplitude in the equipment and stabilize the voltage on the busbar during short circuits. Their application is distinguished by high technical and economic efficiency. However, mechanical damage to the reactors has been observed within extensive industrial grids with many induction motors and internal synchronous generators. The article analyses a case study of the reactor damage in the true industrial grid during a short circuit. An analysis of the damaged reactor's previous operation had shown that there was a weakening of the fastenings in the reactor design, caused by the repeated starting currents of the grid motors and generators. A study of grid transients during short circuits was carried out by Matlab/Simulink software. The simulation results showed that the reactor could be damaged by a critical peak current in an unfavourable combination of the grid configuration and the short circuit location. The results of the study prove that, for industrial networks containing powerful induction motors and internal synchronous generators, the standardized procedure for selecting current-limiting reactors should additionally consider such factors as the localization in the grid, the effect of equipment-starting currents and possible grid configurations.

Keywords: current-limiting reactor; industrial grid; modeling transients; mechanical stress; short circuit current peak; generator energizing

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1. Introduction

The high levels of short circuit currents and high transient overvoltages in medium voltage grids require more and more knowledge of the methods for limiting short circuit currents and their effects on switchgear and other electrical equipment. Developers split the grid, introduce higher impedance transformers and series current-limiting reactors, or use complex strategies such as sequential grid tripping. However, these solutions may create other problems such as the loss of the security and reliability of the power system, high costs and increased power losses.

The issues of the application of current-limiting reactors, their design and their location in power industrial grids and transmission systems are still relevant and discussed in monographs, IEEE standards, technical handbooks and manuals as well as numerous publications. The use of current-limiting reactors (CLRs) in various connections and locations is the most popular solution for industrial power grids [1]. Their application is inexpensive and they significantly reduce short circuits. The IEEE Standard [2] provides general information about dry-type air-core reactors that are installed in transmission and distribution systems, their effect on steady-state power flow and short circuit current limitation. The IEEE [3] standard provides ANSI/IEEE recommendations for power grid designers on short circuit current calculation to select the appropriately sized air-core reactors for industrial and power grid applications. The IEC Standard [4] describes the methodology for the technical specification and testing of reactors for manufacturers. The available literature [5–9] presents a wide range of issues on the design and testing of air-core current-limiting reactors for various industrial applications in accordance with the above standards. The methods for optimizing the configuration of a grid equipped with reactors and reducing the cost of the power grid due to the appropriate limitation of short circuit currents for the used electrical equipment are discussed.

The location of the current-limiting reactor at the power grid must be analysed as well in terms of a total lumped inductance in an equivalent electric circuit of the power grid, which could lead to an increase in the severity of the transient recovery voltage across the circuit breaker contacts, associated with the interruption of the circuit current [10–12]. Thus, for each of these grids, it is necessary to carry out the proper design of the reactor. The optimization of a reactor mainly focuses on solving the contradiction between the fundamental properties, such as inductance, current carrying ability and the metal conductor materials' (copper or aluminium) cost. Several computational methods are used to improve the utilization ratio of the metal conductors of reactor coils and their electromagnetic and thermal characteristics. Several papers [13–17] present the calculations of electromagnetic and thermal fields for reactors to improve their thermal efficiency.

The basic installation of CLR units is a series reactor connected between source and loads and is designed mainly to protect feeders and electrical equipment and devices against the high magnitude of short circuit currents and their thermal action. The more complex applications with series current-limiting reactors are designed as circuits where these units are installed between busbar sections of each power supply system, in series with switchboards equipped with a large number of induction motors with rated power above 250 kW and characterized by direct start or in series with industrial small synchronous generators that are connected to the main industrial grid bus. In these applications, the CLR allows the main busbar voltage to be stabilized and, when there is a fault, reduces the amplitude of the short circuit current to ensure the correct operation of sensitive feeders.

Nevertheless, operational experience indicates that faults within complicated industrial power grids have caused damage to the current-limiting reactors due to the incorrect estimating of their sizing. Such cases are provoked by a change in the operating configuration of an industrial power grid with internal generators when several of them can be connected in parallel regarding the possible short circuit location. The transient analysis of the possible operating configurations of the MV industrial power grid under fault conditions can support the selection of appropriate CLR parameters to ensure its reliable and sustained operation. The literature review has shown little information on the impact of short circuit and inrush currents on the mechanical strength of current-limiting reactors in industrial electrical grids. The authors of this study carried out a detailed technical analysis of the operation of current-limiting reactors affected by multiple current pulses caused by short circuits and the switching on of motors and generators in a specific industrial grid. The analysis of the damage to one of the grid reactors and the results of the following grid simulations have supported the supposed thesis on declining the rated mechanical strength of the current-limiting reactor due to the specific operating conditions.

The article presents studies that were prompted by analysing CLR damage in the true industrial grid with the intensive use of powerful induction motors and local synchronous generators. This paper intends to analyse the case and causes of a current-limiting reactor failure due to a three-phase short circuit within the industrial grid. The CLR was connected via a cable line between a busbar fed from the power system and internal generators and a busbar where eleven induction motors with ratings of 320 kW up to 2000 kW were operated. As a result of energizing one of the induction motors, a three-phase short circuit occurred due to damage to the insulation of the cable supplying it.

The article has been essentially divided into two parts. The first part of the article discusses the operational issues of CLRs in various configurations of MV industrial power grids. The second part presents the results of experimental studies carried out by modelling transients under short circuits in the described industrial grid. To analyse transients occurring under short circuits and equipment switching, the authors developed a model of the grid using the Matlab/Simulink software package, which provides simulating transients for potential switching events and network configurations.

2. Current-Limiting Reactor Specification

2.1. Design

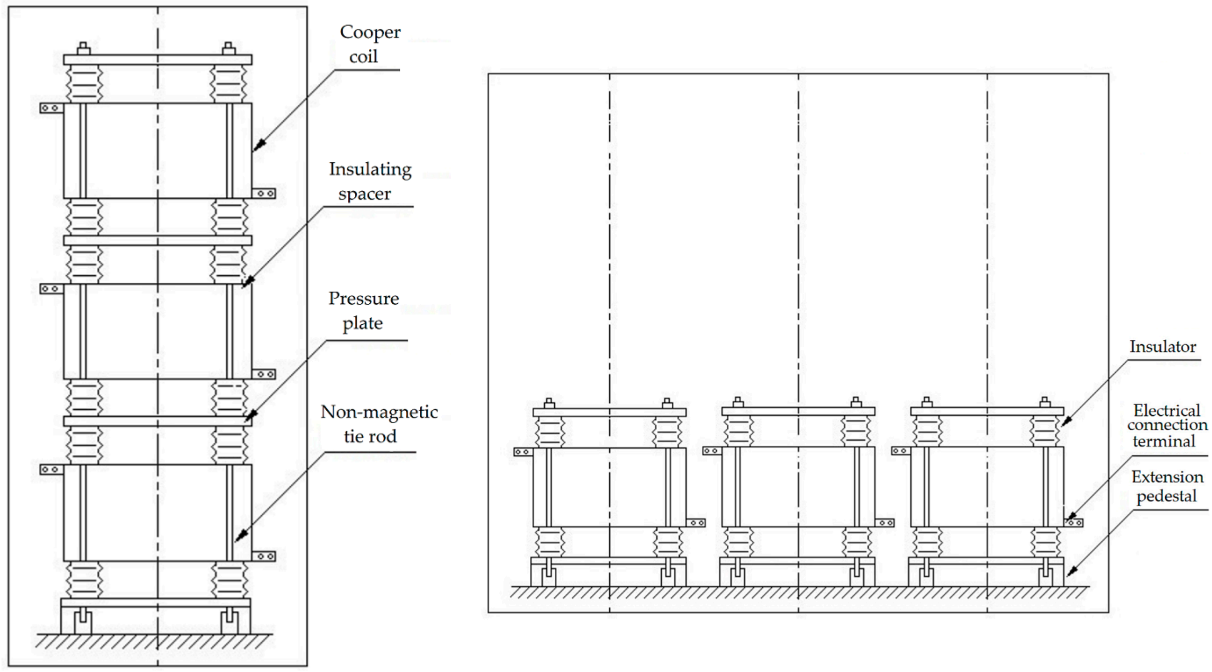
The current-limiting reactor unit, which is not equipped with an iron core magnetic material within the windings, is called an air-core current-limiting reactor. It consists of a circular coil wound around a nonmagnetic material for greater mechanical strength. Usually, in an industrial environment, the windings of current-limiting reactors are the air-cooled dry type or immersed in oil or a similar cooling fluid. Hence, there are different applications in the electrical field, where reactors improve the performance of a system or play a role in protecting it [1].

During a fault condition, the reactance of the current-limiting reactor should not diminish due to the saturation effect. This is an essential requirement to limit the short-time fault currents. Ideally, the current-limiting reactor must have a no-iron circuit and must be of the air core or coreless type. The iron core type provides non-linear saturating type characteristics, and during overcurrents tends to diminish their reactance due to the saturation effect, while the reactors are required to offer high impedances to limit the fault currents. The CLR type without a core will provide a near-constant reactance at all currents due to the absence of an iron core, hence their preference over other types for such applications. These reactors can be made of copper or aluminium winding without any core, similar to an air-cored solenoid. They are merely coils of wire wrapped around a non-metallic core. The cores are usually made of ceramics, concrete, fibreglass or glass polyester. In the absence of an iron core, there is a large amount of leakage flux (stray magnetic field) in the space, which may also infringe on the metallic tank housing of the reactor, and affect the reactance of the coil, in addition to heating the tank itself. It is therefore important to provide some kind of shielding between the winding of the reactor and the tank.

In cases without an iron core, there is no saturation of the core, so these reactors are more useful when they are required to be used as current-limiting devices for limiting the inrush currents during the switching of large inductive motors.

In the MV industrial power grid, the current-limiting reactors usually consist of three-phase coils stacked one above or next to the other with support insulators between them as shown in Figure 1.

In the first solution, which is a stacked three-phase reactor (Figure 1a), the gap between the two coils is maintained (>300 mm) such that each of them would fall nearly out of the inductive interference of the other. Moreover, that kind of construction of CLR unit will exhibit time-varying axial forces between the phase coils during a two-phase or three-phase short circuit. As the short circuit force depends on the distance between the coils, the force from the centre to the outward coils is much higher than between the two outward coils. Reversing the winding direction of the centre coil concerning the outward coils causes the neighbouring coils to be attracted to each other when the time-varying force reaches its maximum during a three-phase short circuit. This contraction force is absorbed by the supporting insulators between the coils. Further, the magnetic coupling between the coils increases the effective inductance of the centre coil. This effect can be compensated by reducing the self-inductance of the central phase due to a corresponding decrease in the number of turns. The second type of construction of the CLR unit is the location of three-phase coils next to each other (Figure 1b) with the dimension between the two coils as in the first solution to avoid the high inductive forces between them. The presented solution of the three-phase reactors, which are wound in the same direction and are placed with their axes parallel, causes the magnetic forces to be attractive if the current in one flows in the opposite direction to the current in the other, and repulsive if the current is in the same direction. In addition, setting three-phase reactor coils placed with axes parallel with braces between phases ensures better cooling conditions. Nevertheless, more busbars and operational areas are required in that case, which is associated with higher costs of preparing the electric room. In both cases, the foundation of the inductor coils must also be ensured to have no closed loops in the reinforcement concrete steel (RCS) [1].



(**a**) (**b**)

Figure 1. A typical solution for a three-phase unit of air-core current-limiting reactors for an MV industrial grid with non-magnetic shielding placed: (**a**) coaxially with provision for bracing against the compartment wall (stacked); (**b**) parallel with braces between phases.

The magnitude of the force between the adjacent reactors of a three-phase circuit is greater during a two-phase short circuit than it is during a three-phase short circuit, (although a two-phase short circuit current is only 86.6 per cent of the three-phase current) and therefore stresses caused by these forces should be based on two-phase short circuits. Forces due to two-phase short circuits are higher because the fluxes from adjacent reactors are in phase or 180 deg. out of phase during two-phase short circuits, while they are 120 deg. or 60 deg. out of phase during three-phase short circuits.

In the current-limiting reactor without an iron core a cylindrical shield of non-magnetic material, such as aluminium or copper, is provided around the inductor coil instead of a magnetic material. There is no iron path for the magnetic field, and the coil may not maintain a constant inductive reactance, as in the case of magnetic shielding. Instead of that, it can become reduced with an increase in the current due to a counter-field generated in the coil by the non-magnetic shielding. The effect is that there is no saturation of the non-magnetic core (inductor coil) and the reactor's V-I characteristic remains almost linear [1].

2.2. Short Circuit Current Rating

Referring to Standard [2], the short circuit current rating of the air-core current-limiting reactor should describe two impacts: mechanical and thermal. The mechanical short circuit current rating is based on the worst-case assumption of a simultaneous three-phase fault and the resulting offset peak current. The degree of offset is a function of system damping. The magnitude of the thermal short circuit current rating is obtained from system fault calculations and the duration is a function of the system operating policy including several "autorecloses" of the breaker, etc. (Section 5.6 in [2]).

The mechanical short circuit current rating is defined through the maximum peak value of the transient current during a three-phase short circuit, the so-called maximum asymmetrical current peak [3]. The maximum asymmetrical current peak can be obtained from industrial grid information and by calculating the reactor impedance. Unless specified, grid parameters estimating the maximum peak asymmetrical current I_{pk} shall be described as 2.55 times the RMS value of the symmetrical fault current:

$$I_{pk} = 2.55 I_{SC}. \tag{1}$$

The symmetrical RMS fault current of the reactor is calculated from a fault occurring at the load side terminals by using the system equivalent series reactance of an industrial grid:

$$I_{SC} = \frac{U_S}{\sqrt{3}(X_R + X_S)} \ , \tag{2}$$

where

I_{SC} - is the RMS short circuit current, [kA];

X_R - is the reactance of the series current-limiting reactor, [Ω];

X_S - is the total system equivalent series reactance, [Ω];

U_S - is the system line-to-line RMS voltage, [kV].

The reactances in Formulae (2) are calculated as follows:

$$X_S = \frac{U_s^2}{S_{SCs}} \ , \tag{3}$$

and

$$X_R = U_S^2 \left(\frac{1}{S_{SCl}} - \frac{1}{S_{SCs}} \right) , \tag{4}$$

where

S_{SCs} - is the three-phase fault level on the source side of the reactor, [MVA];

S_{SCl} - is the three-phase fault level on the load side of the reactor, [MVA].

The thermal short circuit current rating of a current-limiting reactor is defined as the RMS symmetrical fault current specified by (2). The duration should be specified by the user and should typically take into consideration system protection practices such as breaker interrupting time, breaker auto reclose sequence, etc. Typical values for the duration of the thermal short circuit current rating are 1, 2 or 3 s. If not specified by the user, the duration of the thermal short circuit current shall be considered to be 3 s [2,4].

2.3. Concern about Repetitive High Inrush Currents

Short circuit currents and motor inrush currents cause the electromagnetic forces in the reactor windings and auxiliary components that can be tens and hundreds of times higher than the values in steady-state operation. These forces are proportional to the square of the short circuit current amplitude value. The windings are subjected to the simultaneous action of circumferential and compressive forces. The mechanical clamping structure and the supporting elements of the reactor are subject to direct action forces and reaction forces. Current-limiting reactors in MV industrial grids containing powerful induction motors and local synchronous generators are exposed to repetitive inrush currents [5]. Hence, the CLR unit should be designed and verified by calculation so that its coils do not have mechanical resonances close to twice the inrush current frequency [2,13,14]. On the other hand, these repetitive currents cause the mechanical fatigue of the CLR construction.

The problem of considering the impact of repetitive transient currents when choosing the parameters of air reactors for medium voltage harmonic filters is well-known and described in various publications [18–21]. Its essence lies in the requirements to analyse the operating conditions of the air-core filter reactor within a specific power supply system, considering such impact factors as the transient current amplitudes and their repetition rate over a specific time interval. Depending on these data, the requirements for the mechanical strengthening of the air-core filter reactor design are established. Energizing the filter circuit or a powerful transformer is a typical repetitive event in industrial grids that causes high current magnitudes in the filter harmonic reactor. The number of such dynamic overcurrents per year is critical for the design of the filter reactor. The IEEE Standard [2] establishes that, if transient currents of a magnitude close to the mechanical short circuit current rating are expected to be frequent more than 10 times a year, the number of such transient current peaks per year shall be specified.

Our experience has shown that the problem of repetitive inrush currents should also be taken into account for air-core limiting reactors installed in industrial grids. The designer and the manufacturer must verify the location and function of the reactor in the industrial network every time, especially when exposed to the grid synchronous generators and induction motors since they affect the operating conditions of the CLR during transient currents. Therefore, before installing CLR in the MV grid, it is necessary to carry out appropriate tests and calculations to confirm that each coil of the reactors can withstand the mechanical effect of short circuit currents after the repetitive operational inrush currents of the equipment that occurred during the previous operation of the reactor.

2.4. Typical Applications

In medium and high-voltage industrial grids, the amplitude of the short circuit current is a function of the nominal voltage and reactance of the power grid. To limit its value to the appropriate level of electrical devices and equipment at the same voltage rating, the primary method is to increase the inductance of the supply system seen at the fault location. This can be done by either increasing the reactance of the circuit or by removing grid elements from the fault path. The first is done by adding current-limiting reactors and the second by current limiters [10].

Current-limiting reactor units can be installed anywhere in the industrial grid to limit the short circuit currents. Since they are essentially a linear inductive reactance, their impedance will add arithmetically to the power system impedance, reducing the fault current's magnitude.

The current-limiting reactors may be introduced in the outgoing feeders, incoming feeders or between the bus sections, so there are different applications in power engineering where CLRs improve the performance of a system or play a role in protecting it [6,7,12,22]. Besides the aspects mentioned above, the position of the reactor at the substation busbar to meet better the needs of the specific case should be analysed [8]. Various methods are proposed to develop the reactor's optimal design in each specific case [9,23,24]. The main applications of CLR installation diagrams in industrial power systems are illustrated in the figures below: the connection of the bus sections (see Figure 2a), the series connection with the incoming feeder (see Figure 2b) and the series connection with the outgoing feeder (see Figure 2c).

In the industrial power grid, which is characterized by the high value of the system fault level or based on more than one section of buses, the current-limiting reactor is installed between the sections to reduce the total short circuit current, Figure 2a. In case of a fault, the CLR reduces the total short circuit current in each section, allows the better sharing of transformer loading and reduces the required equipment short circuit rating of the industrial grid. In transient conditions, the CLR mechanically withstands the short circuit current peak amplitudes from incoming and outgoing feeders. Therefore, its rating parameters should be calculated considering the operational characteristics of the loads that are connected to each section of the substation between which it was installed. Moreover, in that application, CLRs are responsible for limiting fault currents from internal synchronous generators by effectively increasing their resultant impedance relative to the fault location through the bus tie. To the disadvantages of that kind of diagram, the CLR does not impact incoming feeder contribution and transients.

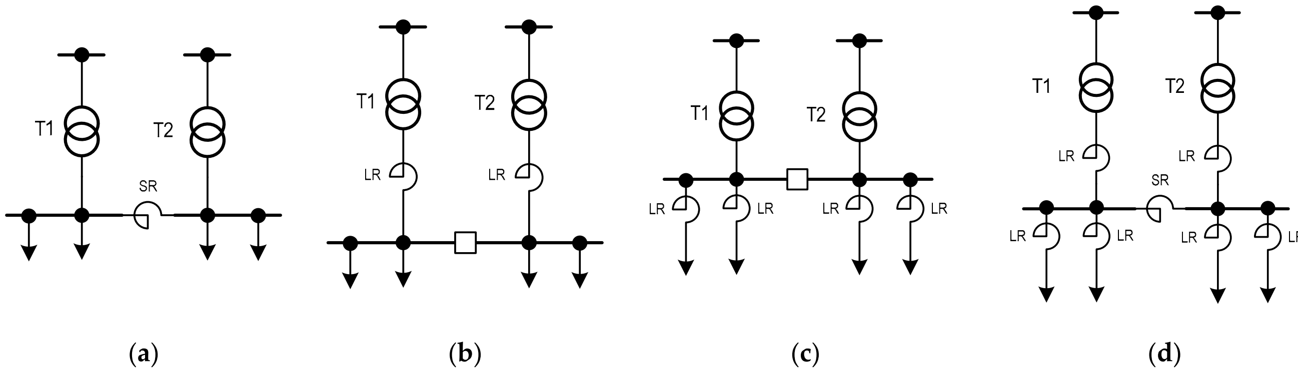


Figure 2. Typical diagrams of air-core current-limiting reactor applications for an MV industrial grid: (**a**) Connection of the bus sections; (**b**) Series connection with the incoming feeder; (**c**) Series connection with the outgoing feeder; (**d**) Mixed type of connection with bus sections and feeders.

In industrial power grids containing a large number of high-capacity induction motors, the series current-limiting reactors are installed in the incoming feeders, Figure 2b. Also, if a fault occurs, each CLR reduces the short circuit current amplitude at the first current rise. The reactor implementation in series with incoming feeders makes it possible to individually reduce the short circuit currents in the grid, but at the same time, in such a diagram, power losses increase, and there is a problem with voltage control on each busbar section.

Further, CLR can be installed in each outgoing feeder, Figure 2c. In this application, in the event of a fault, each current-limiting reactor reduces the amplitude of the short circuit current at the very first current increase, but with low power losses and better voltage control at each load at the end of the power cables during normal operation. The disadvantage of this case is the switching conditions of asynchronous motors. The amplitude of the starting current is 2–10 of the rated current, so the voltage drop across the reactor is in phase with the load voltage and causes large voltage drops, which can cause serious problems when starting large drives directly. As practice shows, to avoid a large voltage drop when starting motors, the main busbars of switchboards should be operated with a voltage higher than the nominal voltage, with a voltage factor from 1.05 to 1.1 of the rated voltage of the power system. In such a scheme, the reactors are not installed directly in the inrush current path of large feeders or loads with heavy starting. The motor starting reactor is connected in series with a motor to limit the inrush current during the motor starting operation. After the motor is started, the reactor is typically bypassed to limit power losses in continuous operation. That solution is frequently used in industrial power grids where cable lines are connected in series with high-capacity loads: at steel, coking and mining plants. In this case, a CLR limits the current under system fault conditions to a level that is compatible with the system equipment ratings.

In some MV industrial electrical grids, current-limiting reactors are installed in various parts of the network to improve their operational functionality and reliability of the power supply and prevent equipment damage at high short circuit transient currents, Figure 2d.

That type of application is a very cost-effective solution, as it eliminates the need for upgrading the entire switching and protection system when the short circuit power of the system is increased. Such a reactor is designed to withstand the rated and short-period transient fault currents, giving the total power supply system a specified impedance value.

The examined industrial grid in the presented article uses a mixed configuration of CLR units as in Figure 2d. In a further study, we describe the peculiarities of the CLR operation within true grid conditions.

3. Case Study

3.1. The Analysed Industrial Grid

The following methodology was adopted in the studies:

- the detailed analysis of the examined reactor failure;
- the analysis of the repeatability of the short circuits and switching currents of motors and generators in the industrial grid, which the reactor was subjected to during operation;
- the development of the grid model for studying transients affecting the reactor;
- the discussion of the simulation results to confirm the thesis about the decrease in the mechanical strength of the reactor due to the impact of multiple transient current pulses;
- suggesting a possible solution to the problem.

The analysis of short circuit currents and their impact on the current-limiting reactor was carried out on the example of an MV industrial cable grid shown in Figure 3. The 6 kV power grid under consideration is powered by an external 110/6 kV substation and contains two 6 kV synchronous generators, G1 and G2, with a rating of 25 MW.

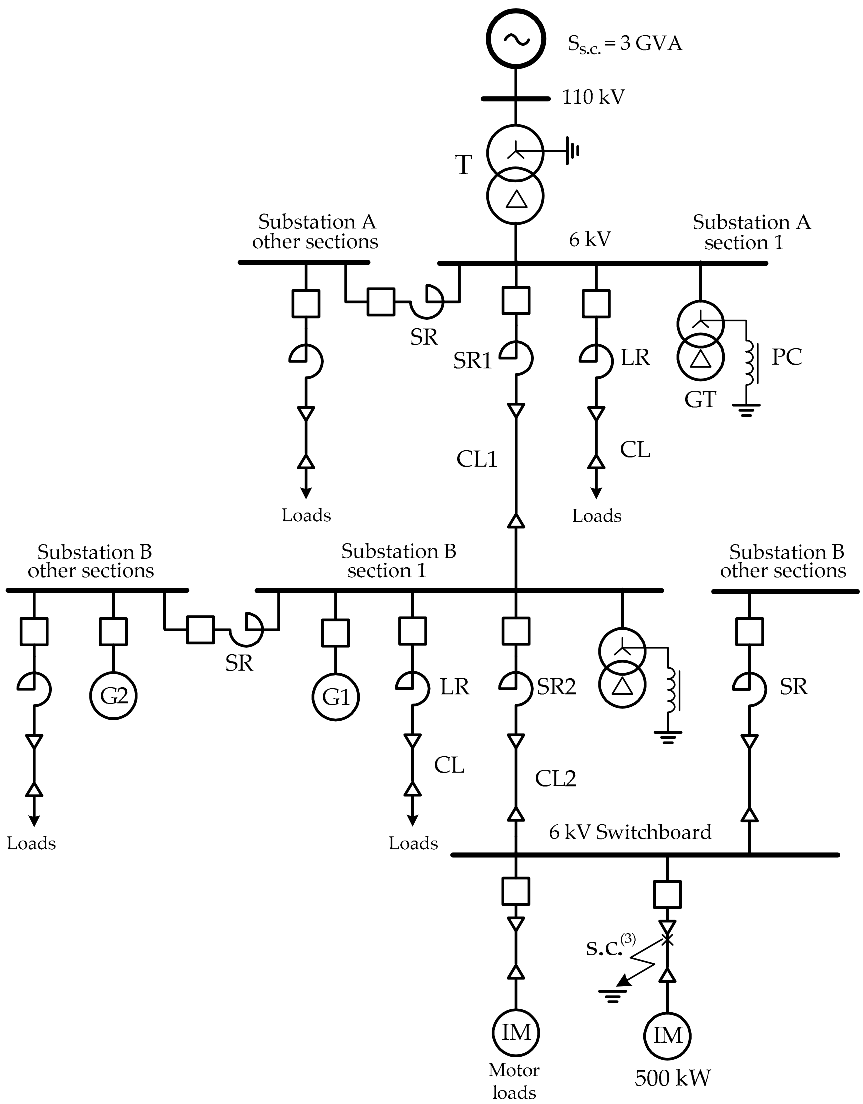


Figure 3. Single-line diagram of the industrial grid.

The industrial grid under study contains two substations, A and B, connected by cable CL1 and reactor SR1. The sections of these substations are connected by intersectional reactors SR. The feeders in all the sections are supplied through cables CL and current-limiting reactors LR. Two Petersen coils (PC) to compensate for capacitive single-line-to-ground fault currents are connected to the busbars of substations A and B by grounding transformers (GT) with a total rating of 690 kVA.

The examined grid is a highly extensive cable industrial grid with various powering configurations of substation B and thereby all loads are connected to the bus sections of the substation. The power supply of substation B in the typical configuration of the presented grid is provided by synchronous generators and by substation A. However, several topologies are strictly dedicated to the emergency operation of the industrial grid or have been applied during the technical inspection or routine maintenance of the electrical equipment and substation cell devices. Table 1, respectively, presents the rating data of the electrical equipment and the synchronous generators of the examined industrial grid.

Table 1. Catalogue data of the industrial grid.

Grid Component	Parameter	Unit	Value
Supply system	Transformer rated voltage, U_n	kV/kV	110/6
	Transformer capacity, S_n	MVA	31.50
	Short circuit power, S_{sc}	GVA	3.00
Cable lines, CL and SCL	Rated voltage, U_n	kV	6.00
	Specific resistance, R_0	Ω/km	0.16
	Specific inductance, L_0	mH/km	0.34
	Specific capacitance, C_0	μF/km	0.44
Line reactor, LR	Rated current, I_n	kA	0.60
	Resistance, R	Ω	0.35
	Inductance, L	mH	0.45
	Rated short circuit current peak, I_p	kA	32.00
Intersection reactor, SR1	Rated current, I_n	kA	1.00
	Resistance, R	Ω	0.27
	Inductance, L	mH	1.10
	Rated short circuit current peak, I_p	kA	37.00
Intersection reactor, SR2	Rated current, I_n	kA	1.60
	Resistance, R	Ω	0.13
	Inductance, L	mH	0.22
	Rated short circuit current peak, I_p	kA	52.00
Synchronous generators, G1 and G2	Rated active power, P_n	MW	25.00
	Rated voltage, U_n	kV	6.30
	Rated current, I_n	kA	2.29
	Power factor, cos φ	-	0.80
	Stator resistance, R_s	mΩ	5.22
	Subtransient reactance, X''_d	%	14.30
	Transient reactance, X'_d	%	24.00
	Synchronous reactance: X_d	%	245.00
	Mechanical time constant, T_m	s	9.32

In the examined industrial grid, the studies focus on the SR2 unit located in the electric room of substation B, which was connected in series with an aluminium cable line CL2 to power a 6 kV switchboard. It supplies the eleven MV induction motors with ratings from 320 kW to 2000 kW. The analysed current-limiting reactor SR2 was designed for rated current 1600 A to limit the current amplitude during the frequent starting of MV induction motors. The repetitive high current amplitudes during MV motor switching operations have similar negative impacts on the SR2 coils and their flexible connections to substation busbars, such as transient conditions that occur during short circuits. Therefore, the analysed current-limiting reactor is operated under the most severe conditions compared to the other reactors (SR or LR) installed in the industrial grid. The rated data of the current-limiting reactor SR2 are presented in Table 1.

The 6 kV switchboard is implemented as 14 bays that supply the auxiliaries for the industrial grid and is equipped with an Automatic Transfer Switch unit (ATS) with digital protections on each feeder. The automatic switching on of the reserve power supply of the MV switchboard is realized between two sections of substation B. Moreover, its electric devices and equipment have been designed for a voltage rating of 12 kV and transient overvoltage equal to 75 kV. The 6 kV bus can withstand a 1-s RMS short circuit current of 31.5 kA. The switchboard busbars feed eight induction boiler motors, four with a power rating of 320 kW, the rest 500 kW and three induction pump motors with power ratings of 630 kW, 900 kW and 2000 kW, respectively. The total power rating installed and supplied by the MV switchboard amounts to 6810 kW.

3.2. System Configuration Analysis during Fault

The deep analysis of the current-limiting reactor SR2 mechanical damage proved that the event was a result of the high peak current impact due to a three-phase short circuit (S.C.$^{(3)}$) on the cable connection of a 500 kW induction motor to the 6 kV switchboard (see Figure 3). At the time of the failure, the power industrial grid was supplied by two synchronous generators, G1 and G2, and additionally there was a power supply from the substation of 110/6 kV. The settings of the digital protection devices that were located in the relay section of the switchboard bays are presented in Table 2.

Table 2. Protection settings of digital protection devices.

Localization of Digital Protection Devices	Protection Settings			
	Overcurrent Protection		Ground Fault Protection	
	I [kA]	t [s]	I [kA]	t [s]
Bays of 6 kV Switchboard	30.50	0.12	-	signalling
Bay of 500 kW induction motor	0.71	0.08	2.18	0.02

Due to long service life (about 30 years), the considered industrial power grid and its electrical equipment are characterized by a significant accident rate. All the current-limiting reactors of the grid were subjected to short circuit currents and inrush currents from internal generators and motors. The average estimations summarized by operational personnel showed that each of the current-limiting reactors in this grid was subject to about 1–4 short circuits per year. At the same time, the analysed reactor, which was operated for about 15 years, was subjected to about 30 boiler motor starts and 5–10 pump motor starts per quarter. Before the failure, it withstood (without any damage) an average of about 5–8 short circuits per year. The damaged current-limiting reactor was regularly and properly serviced following the manufacturer's instructions and manual. Periodic inspections were carried out at least once a year and included the following operational activities: the inspection of reactor corrosion and dust, checking the screw connections and the condition of the terminals, as well as checking protection operation and the resistance insulation measurement of the reactor coils.

During the switching-on operation of the induction motor, the arcing single-line-to-ground fault on the cable connection was initiated. The fault lasted a time because the ground fault protection module for the current after 80 ms was not activated and the circuit breaker of the induction motor was still closed under the fault. Next, the fault turned into a three-phase current with high amplitude and the time delay overcurrent protection tripped the circuit breaker of the primary supply of the 6 kV switchboard after 120 ms from Section 1 of substation B. At the same time, the ATS system switched on the circuit breaker of the reserve power supply from the other section of substation B to prevent a shutdown of all the feeders and loads that were operated from the 6 kV switchboard. The detailed analysis showed that the main cause of the non-activated time delay over-current protection module of the induction motor was a too high measurement error from the input current transformers and analogue-to-digital converter of digital protection [25]. The detailed analysis of the protection settings showed that, during ground fault tests, the digital criterion of protection detected the disturbances only 40 ms after their occurrence. Therefore, after the failure, the settings of the ground fault protection module of the digital protection of the induction motor were changed, reducing the time delays of the decision to 5 ms and thus increasing the signal sampling frequency to 200 Hz.

The inspection of the current-limiting reactor SR2 in the electric room of substation B by operating personnel showed that its coils were faulty in all phases. Figure 4 presents a damaged coil of the current-limiting reactor SR2.

Figure 4. A faulty coil of the intersection current-limiting reactor SR2.

The detailed analysis of the current-limiting reactor failure showed that each phase coil was damaged due to the loosening of the screws of the elastomer springs on each turn of the reactor coil and the inappropriate number of epoxy isolate spacers between the turns of the reactor coil. Reducing the thickness of the insulating spacers led to the bending and indentation of the coil turns between themselves as a result of severe forces due to the high pulse of the short circuit transient current. Thus, it can be stated that the main reason for the failure of the considered current-limiting reactor was the incorrect mechanical calculation of its design and the subsequent choice of epoxy isolate spacers between the reactor coil turns, which led to the mentioned consequences.

3.3. Modelling the Industrial Grid

Figure 5 shows a block diagram of the industrial grid model developed by the SimPowerSystem and Electric Drives libraries of the Matlab software package. The following model blocks are used here: 110 kV external power supply system and step-down transformer T; G1 and G2—synchronous generators; CL and SCL—cables; arc suppression devices on the base of transformers GT and reactors PC, SR and CLR—short circuit current-limiting reactors; IM—induction motors; CB—power circuit breakers. The synchronous generator equivalent was implemented as a three-phase machine block, modelled in the *d*-*q* rotor reference frame. The external power supply system operates with a direct grounded neutral, and the examined industrial grid with an ungrounded one. Limiting the high ground fault current, arising due to the significant equivalent ground capacitance of the grid cables, is carried out by the arcing devices. The equivalent parameters of all the grid reactors are modelled using *R*-*L* elements. The effect of increasing cable resistance due to escalating transient frequency under short circuit faults in the industrial cable grid has negligible impacts on the transient behaviours. Therefore, it is reasonable to present the grid cable equivalent as a π-model with equivalent resistance and inductance series-connected and shunt capacitances. The three-phase induction motor in the discussion was implemented by a three-phase induction machine model with a squirrel cage and was loaded by mechanical torque modelled by a Step block. The remaining three-phase induction motors were implemented as one block with appropriate equivalent parameters.

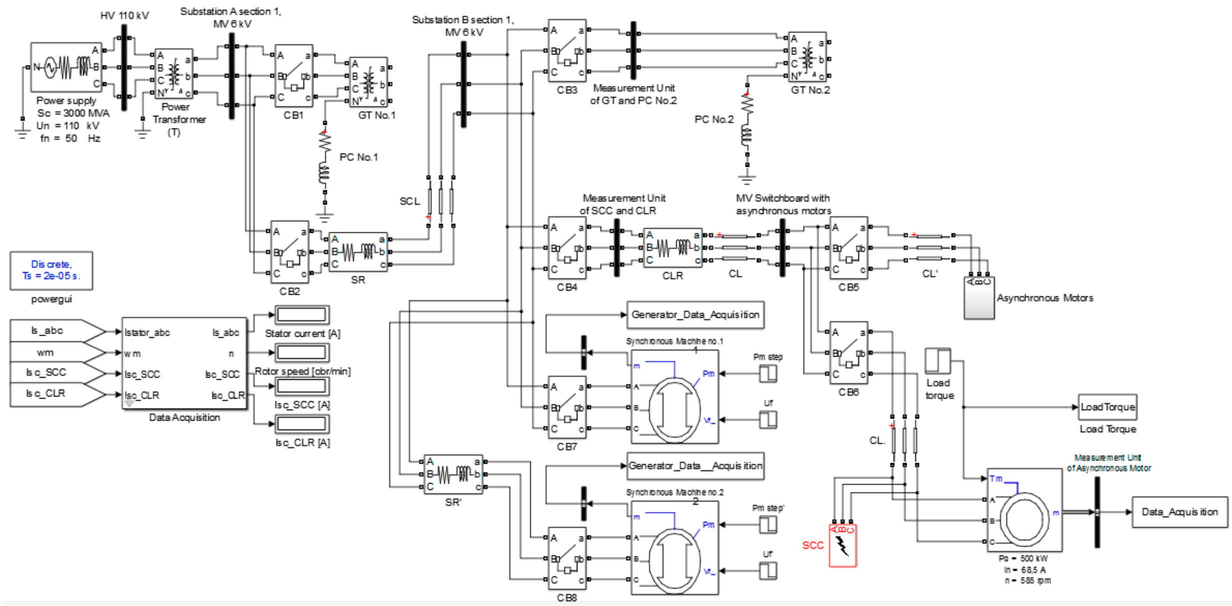


Figure 5. Block diagram of the industrial grid model.

During a short circuit that occurred on the cable feeder of the 500 kW induction motor, the total operational active power of the other induction motors was equal to 2910 kW. The three-phase short circuit on the cable connection was implemented by a three-phase fault block SCC from the SimPowerSystem library by two parameters: fault resistance $R_{on} = 0.04\ \Omega$ and ground resistance $R_g = 1.0\ \Omega$.

Transients caused by switching on motors and short circuits in the industrial grid under study are characterized by significant variations in the time constants and natural frequencies of the equivalent circuit loops. Therefore, automatic step recalculation by the ode23t solver was implemented to solve the model differential equations. The initial value of the step was taken as 20 µs. Using this solver makes it possible to provide the required accuracy and optimize the time for solving model equations. The equivalent circuit of the examined grid was built following the diagram in Figure 3, and the parameters of the model blocks are calculated by equipment catalogue data from Tables 1 and 2.

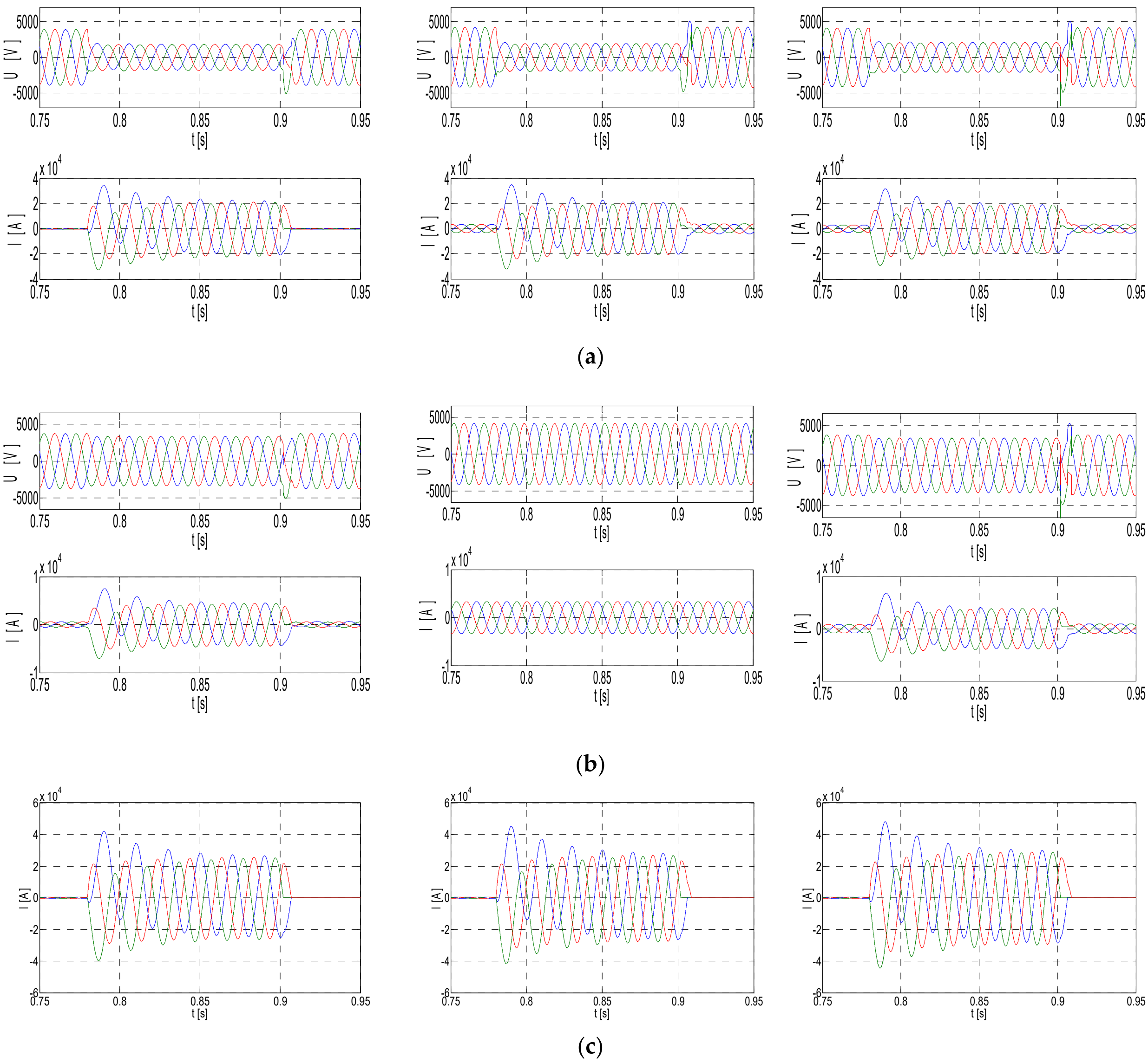
3.4. Results of Simulations and Discussion

The damage to the examined reactor selected according to the standard methodology initiated detailed simulations to determine the causes of such an event. Therefore, the simulations can give precise answers to the points about the actual short circuit current peak at the time of the accident, and the short circuit current peaks and motor starting currents that occurred in other grid configurations.

Several operation configurations can be used during the examined industrial grid's operating conditions. In the basic configuration, the power supply of the substation B sections is provided by generators G1, G2 and the external power system. Nevertheless, several configurations are predicted for technical inspection or emergency conditions where the substation sections are powered by one generator or just an external substation.

Hence, the article discusses only configurations of the industrial power grid that have a practical interest considering the analysed current-limiting reactor SR2 failure. The analysis was carried out for two types of industrial grid configurations. The first describes only one source to supply the substation B sections: the power supply system or synchronous generator G1 or G2. The second type describes a combination of the power sources connected to the industrial grid.

The main task of simulations is to obtain the short circuit current peaks in the examined reactor SR2 coils and compare their values under the considered industrial grid configurations. Figure 6 shows the transient voltages and currents in the grid components of interest during a three-phase short circuit at the motor cable feeder of the 6 kV switchboard (see Figure 3) when various power sources are connected to Section 1 of substation B, following the second type of configuration described above. Within these industrial network configurations, the highest current peaks in the coils of the SR2 reactor will occur during the considered short circuit.



Generators G1 and G2 are on **System and generator G1 are on** **System and generators G1 and G2 are on**

Figure 6. The transients in the grid components (phase A - blue, phase B - green, phase C - red): (**a**) Bus phase voltages and currents of synchronous generator G1; (**b**) Bus phase voltages and currents of synchronous generator G2; (**c**) Currents of the reactor SR2.

The comparison of short circuit current peaks on the fault point and in the reactor SR2 coil was carried out for all studied industrial grid configurations, and the results are presented in Table 3. Comparing the simulation results, one can note the following: the most impact on the transient short circuit current peak in the reactor winding is exerted by the synchronous generator G1, located "electrically closest" to the short circuit point.

Table 3. Maximum current peaks in the reactor SR2 coils (I_{Rp}) and at the short circuit point I_{SCp}.

Connected Power Sources	I_{Rp} [kA]	I_{SCp} [kA]
The first type of the grid configurations		
System	17.50	24.86
Synchronous generator G1	38.01	53.88
Synchronous generator G2	12.74	18.22
The second type of the grid configurations		
Synchronous generators G1 and G2	42.00	59.49
System and synchronous generator G1	45.17	63.98
System and synchronous generators G1 and G2	48.14	68.28

During the examined industrial grid short circuit, the induction motors operating on the 6 kV switchboard do not have an impact on the transient current of the SR2 reactor. They only increase the total transient currents in the fault location.

In the case of configurations of the first type, where only one power source is connected to Section 1 of substation B, the fault currents are not dangerous for this reactor.

The most severe fault conditions for the SR2 current-limiting reactor are observed for the second type of grid configurations, while different combinations of power sources are connected to Section 1 of substation B, and high current peaks through the analysed SR2 reactor cause significant mechanical stress on its windings.

The worst-case scenario is when all power sources are connected to Section 1 of Substation B, both the internal synchronous generators and the external power system. Analysing the values of current peaks in the SR2 current-limiting reactor coils, obtained by simulating for this type of grid configuration and presented in Table 3 and Figure 6, it can be seen that these values are close to the reactor rating short circuit current peak value. Such current peaks, as shown by operating experience, can cause damage to the reactor structure due to its mechanical fatigue caused by inrush currents of lower amplitude through the repeated starts of the induction motors and generators in the industrial grid during the previous operation of the reactor.

The example given in the article is intended to draw the attention of operating and design institutions to the problem of sizing current-limiting reactors in specific operating conditions. The requirement for transient analysis aiming for the correct definition of critical current peaks is especially relevant for industrial grids containing powerful asynchronous motors and generators. In our opinion, at the design stage calculations, it is also necessary to account for the number of repeated peaks of inrush currents of a given amplitude to ensure the reliable operation of the reactor at the declared rating values. Such an approach has been adopted, for example, for air-core filter reactors, as discussed in detail in [18,19,21]. Once the values of the transient peaks and their expected number are determined, the methodology recommended in the Standard [2] can be used to calculate the required mechanical short circuit current rating. The essence of this methodology is the use of weighting factors [2] when calculating the mechanical strength of a reactor designed to operate under conditions of repetitive inrush currents. The result is a more robust reactor design, electrically represented as a higher short circuit current rating than that derived from standard requirements for limiting short circuit current and busbar voltage drop.

4. Conclusions

The article describes the concern of operating current-limiting reactors in industrial power grids containing powerful induction motors and internal synchronous generators. During long-term operation, certain reactors of the grids are subjected to frequently repeated inrush currents under energizing induction motors and generators. Although these inrush currents have a lower amplitude than the reactor mechanical short circuit current rating, they cause a gradual weakening of the mechanical design. Repetitive electrodynamic blows during long-term operations cause a well-known phenomenon, which is commonly called "mechanical fatigue" in the reactor design. As a result of the following short circuit in the grid with a transient current peak amplitude close to the rating one, the reactor can be damaged. It can be claimed that the previous operation of the reactor under the described operating conditions caused a certain derating (decreasing) of such a parameter as the mechanical short circuit current rating.

To support the described statement on the possible impact of the previous operation of the air-core limiting reactor, the authors carried out a detailed simulation of a true industrial grid and its operating conditions during a short circuit that caused damage to the reactor. Compared with other reactors of the power system, the analysed reactor has run under specific (the most severe) operating conditions, as it was subjected to the frequent starting currents of powerful induction motors. The simulation results showed that, under these conditions, the short circuit current peak that caused damage to the reactor was lower than the nameplate rating one, which confirms the thesis about the mechanical fatigue of the reactor design. In other words, damage to the reactor by a short circuit current with a peak current lower than specified on the nameplate denotes that, at the time of the accident, the mechanical strength of the reactor was significantly weakened due to the previous inrush current blows and did not meet the declared guarantees.

The studies in this paper indicate that, for industrial grids containing powerful induction motors and internal synchronous generators, the sizing of current-limiting reactors should be carried out not only by the standard requirements for limiting short circuit currents and ensuring residual voltage on busbars but also considering their location in the network, the number of motor and generator starts and the possible number of faults and grid configurations that provoke the highest amplitudes of short circuit currents. Transient analysis should be used to identify critical current peaks in such industrial grids correctly.

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