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NEW METHOD OF SHORT-CIRCUIT CURRENT LIMITING

Nowa metoda ograniczania prądów zwarciowych

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***Summary*: A new method of short-circuit current limiting in AC power systems and an inductive short-circuit current limiter realizing the method has been presented in the paper. The inductive short-circuit current limiter operation depends on the fact that at the instant of a short-circuit beginning the limiter switches automatically impedance into the short-circuit system, without any measurement or a control system action. During the normal operation the limiter "is not seen" by the network—there is no voltage drop so the limiter reactors' inductances can be multiple of those of normal short-circuit reactor which could have been applied in the same conditions. A very large reactors' inductance during the short-circuit separates efficiently the short-circuit loop from the remaining part of a power system. The principle of the inductive short-circuit current limiter operation and the simulation results of the most characteristic modes of its operation as well as the expected effects if its application have been presented in the paper.**

***Streszczenie*: W artykule przedstawiono nową metodę ograniczania prądów zwarciowych w sieciach napięcia przemiennego i indukcyjny ogranicznik prądów zwarciowych, realizujący tę metodę [1]. Działanie indukcyjnego ogranicznika prądów zwarciowych polega na tym, że w chwili początku zwarcia włącza do obwodu zwarciowego samoczynnie, bez udziału układów pomiaru i sterowania, impedancje dławików. W czasie normalnej pracy ogranicznik jest dla sieci „niewidoczny" — nie ma na nim spadku napięcia, więc indukcyjności dławików ogranicznika mogą być wielokrotnie większe od indukcyjności dławików zwarciowych, które można by zastosować w tych samych warunkach. W stanie zwarcia bardzo duża impedancja dławików skutecznie separuje miejsce zwarcia od reszty sieci . W artykule przedstawiono zasadę działania indukcyjnego ogranicznika prądów zwarciowych, wyniki badań symulacyjnych charakterystycznych stanów jego działania i spodziewane efekty zastosowania.**

Key words: short-circuit current limitting, electrical energy quality
Słowa kluczowe: ograniczanie prądów zwarciowych, jakość energii elektrycznej

1. INTRODUCTION

The presently used passive methods of short-circuit current limiting depending on a network impedance increase (special network configuration, sectionalization of bus-bars, high values of transformers' short-circuit voltage, short-circuit reactors) lead to the quality decrease of an electric power in the power system. The selection of the deciding, of a power system impedance, factors has to be a result of a compromise between the required effect—limitation of short-circuit currents, and the unwanted effect—decrease of the electric power quality. The new method of a short-circuit current limiting, the subject of the paper, allows to avoid the necessity of looking for the above mentioned compromise and to obtain the short-circuit current limitation being much more efficient than that obtained with a help of the presently used methods. Any desired limitation of a short-circuit current can be achieved in case of the proposed method application, the price of the limiter production is the only one constraint.

2. PRINCIPLE OF OPERATION OF THE INDUCTIVE SHORT-CIRCIT CURRENT LIMITER

The principle of the new method depends on the fact that the two in series connected reactors are connected into each phase of the power system in such a way that during the normal operation the cumulative voltage drop is negligible,

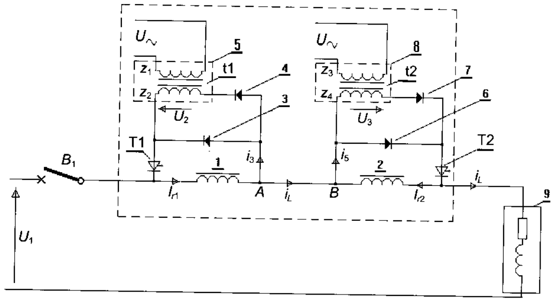

Fig. 1. Circuit diagram of one phase of the short-circuit current limiter; 9—impedance representing the remaining part of the power system with loads; B_1—circuit breaker in the power system behind the limiter

therefore the reactors' inductances can assume large values. Only at the beginning of the short-circuit a substantial voltage drop (on them) arises.

An example of the method realization is shown in fig. 1, which presents one phase of a 3-phase inductive short-circuit current limiter. The limiter contains two connected in series reactors (1;2). A circuit branch containing a diode and a thyristor (3, T1; 6, T2) has been connected in parallel with each of the reactors and the direction of the thyristor and the diode connection in the circuit branch parallel to the second reactor is opposite to that in the circuit branch parallel to the first reactor. The application of the two reactors with parallel circuit branches in necessary in order to obtain a rapid and instant limiter operation when a short-circuit begins during the positive or negative half-wave of an alternating sinusoidal voltage.

Constant currents I_r flow in the reactors and are maintained by peak parts of positive half-waves of an alternating sinusoidal voltage fed from ordinary auxiliary power transformers of a low rated power (t1; t2) and passed by smaller diodes (4; 7). The voltage value is being adjusted in such a way that the current I_r flowing in reactors is bigger than the peak value of the rated load current I_{Lm}. During the time period between these voltage pulses the reactor's current flows through the bigger diode (3, 6) and the thyristor (T1, T2). The voltage drop on the reactor is equal to the voltage on the circuit branch containing the bigger diode and a thyristor, which is almost constant and practically independent from the current flowing through these elements so the voltage drop on the limiter equal to the sum of voltage drops on both the reactor is almost equal to zero. When the voltages U_2 and U_3 on secondary windings of auxiliary transformers are equal to each other and are in conformable phase, the diodes 4 and 7 are conducting current simultaneously so that also during their conduction the voltage drop on the limiter is close to zero.

When the value of the load current i_L varies, even small changes in the value of the current in the reactor lead to the formation of an EMF in the reactor, which is sufficient to cause such a big change of the current in the branch containing the diode and the thyristor that the reactor's current remains almost unchanged. It can be assumed that the changes in the value and direction of the load current cause only changes in the values of current flowing in the circuit branches containing diodes and thyristors and do not influence value of the current flowing in reactors. From the Kirchoff's equations for the nods A and B (fig. 1.) the following relations can be stated:

$$i_3 = I_{r1} - i_L \quad \text{and} \quad i_5 = I_{r2} + i_L \tag{1}$$

As long as the following inequality is true:

$$-I_{r2} < i_L < I_{r1} \tag{2}$$

the currents i_3 and i_5 are different from zero and positive, the thyristors T1 and T2 are conducting and the reactors 1 and 2 are shunted with the branches D3 – T1 and D6 – T2 respectively. Voltage drops on the reactors assume values of about 3–4V and are in counter phase so the total voltage drop on both the reactors is approximately equal zero.

This happens only then when the actual values of the load current i_L are less than the currents I_r in the reactors. When the load current i_L rises and during eg. positive half-wave of its sinusoidal shape reaches the value equal to the current I_{r1} in the reactor, the current i_3 in the circuit branch containing the thyristor T1 stops flowing, the thyristor starts electrical interlocking and the branch shunting the reactor stops conducting. Since this instant on the whole load current flows through the reactor and the reactor's impedance is permanently switched on into the circuit.

The description of the operation has been illustrated with the figures 2a–2c which show a circuit diagram of one phase of the limiter in which color Sankey diagrams representing values of the currents have been also included. The supply voltage is a peak value (amplitude) of a phase network voltage 3 x 6 kV.

The first two figures illustrate the limiter operation at the low value of the load current i_L and in case of its both directions, the next two figures—at the high value of the load current but still less than the currents I_r flowing in reactors. Changes of the load current result only in changes of the current flowing in circuit branches containing diodes and thyristors (Fig. 2a–2d). The currents in reactors remain almost constant and the voltage drop on the reactors is negligible.

When the load current, being positive, increases above the value of the currents flowing through reactors, the current flowing through the branch shunting the left reactor stops flowing, the thyristor in this branch switches off and the left reactor switches on into the short-circuit system. (Fig. 2e). After the current reverse—the second thyristor is being switched off and the second reactor is being switched on into the system (Fig. 2f). The thyristors have been switched off permanently and in order to set them into the conduction mode ignition signals should be delivered to their gates.

In such a way the two connected in series rectors have been switched on automatically into the short-circuit system, at the beginning of the short-circuit occurrence, limiting radically the short-circuit current. No measurement system detecting a short-circuit and no control system of the thyristors switch off, are required,

During the normal operation of the protected by the limiter objects, constant currents flowing through the reactors contain a very small alternating component so the reactors

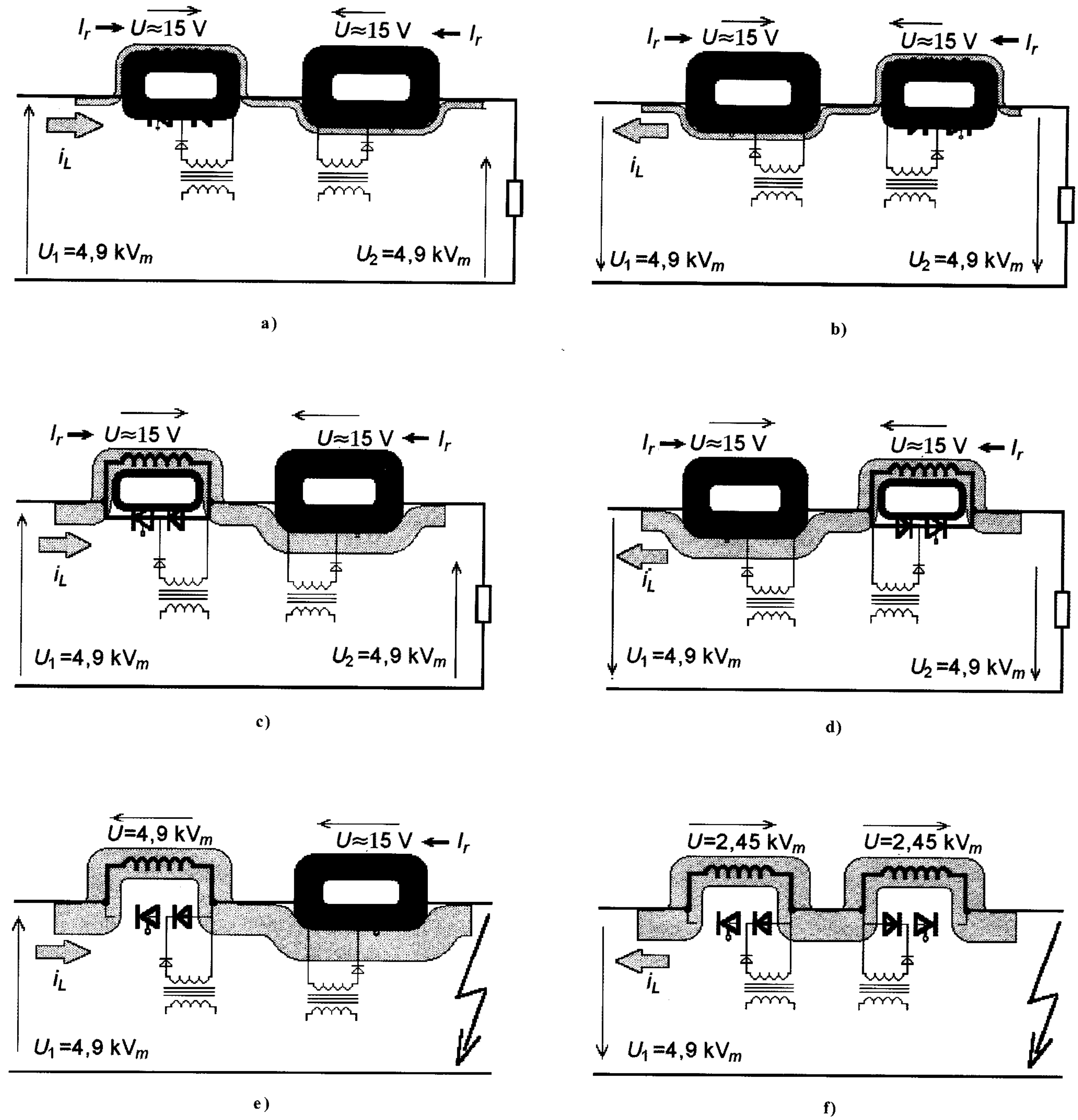

Fig. 2. Illustration of the principle of operation of an inductive short-circuit current limiter.

can be of a core type, usually much cheaper than those of an air-core type. Switching on the limiter's reactors of a high inductance into the short-circuit system does not make the short-circuit break-off more difficult since the short-circuit current, limited by the limiter, is small so the energy cumulated in the reactors and in the remaining inductance of the short-circuit loop is also small. The energy value in the instant when the current reaches its peak value is equal to:

$$W = 0{,}5\, L I_m^2 = 0{,}5\, L U_m^2 / \omega^2 L^2 = U^2 / \omega^2 L \qquad (3)$$

where L is a sum of the reactor's and other short-circuit loop inductances. Thanks to the large value of the limiter's inductance the energy is much smaller than in case of application of a transformer having higher than normal short-circuit voltage or application of a short-circuit reactor. It is also possible, and advantageous from an overvoltage point of view, to apply slow circuit breakers causing relatively small overvoltages and usually much cheaper than these used presently.

3. OPERATION WITH THYRISTRORS' INGNITION

Thyristors during their normal operation remain permanently in the conduction mode and do not require ignition pulses. Such an operation mode is the most reliable one but then each increase of the load current above the current I_r flowing through reactor causes that the reactors are switched into the circuit permanently. In order to obtain switching on the reactors into the circuit only during the emergency over-current and at the beginning of a short-circuit in particular, voltages U2 and U3 from the transformers maintaining the constant current flowing through the reactors should be adjusted in such a way that the value of these currents should be higher than the maximal overcurrents permitted at a normal exploitation. This leads to a substantial over-dimensioning of all the elements of the limiter in comparison to those assumed at the nominal load. This is a disadvantage particularly when the limiter protects big electric motors of a great starting current or a line supplying these motors. The second consequence is that at the high value of a constant current flowing in reactors the losses in reactors' windings, diodes and thyristors can be high.

A method of the constant gate pulses sequence supply has been worked out. The pulses do not have any influence on the system behavior during it normal operation and they allow to avoid self-switching of the reactors into the circuit during the non-emergency overcurrents and during short-circuits do not prevent the reactors from their switching on into the short-circuit loop as described over. The pulses are synchronized with the supply voltage without the necessity of a high precision of the synchronization (the allowed error of several ms, without another control or measurement systems, especially without the necessity the short-circuit detection. The constant operation of the thyristors starting systems is a very positive factor since usually the devices operating permanently and controlled during their normal operation are more reliable than the devices operating occasionally only in emergency. Application of this solution allows for the selection of the constant current flowing in reactors, during the normal operation, of a significantly smaller value than the amplitude of the overcurrent allowed in the circuit. This current can be equal for example to amplitude of the nominal current of the protected by the limiter line or the protected device. Thanks to that substantial losses in the limiter during its normal operation can be avoided as well as the smaller and therefore cheaper rectors can be applied. Only the nominal currents of diodes and SCR thyristors—because of their small thermal capacitance, should be selected as the value bigger than the maximal overcurrent allowed, however, these elements are relatively cheap and their price does not influence significantly the final price of the limiter. Simulation results of the limiter operation during an overcurrent and a short-circuit in which the above described thyristor control method has been applied is presented in the next chapter.

When the short-circuit current contain large aperiodic component then switching on into the short-circuit loop of the second reactor can be shifted in time by several periods of the alternating voltage. This can make the short-circuit turn off more difficult and result in the necessity of application diodes and thyristors of a higher nominal value of the parameter I^2t hence the higher value of the nominal current. A method of a constant sequence gate pulses feeding has been worked out. The method does not require short-circuit detection and allows for the reduction of an aperiodic component of the short-circuit current within less than 20 ms from the instant of a short-circuit beginning. Simulation results of the operation of such a limiter with the described above thyristors' control method is presented in the next chapter.

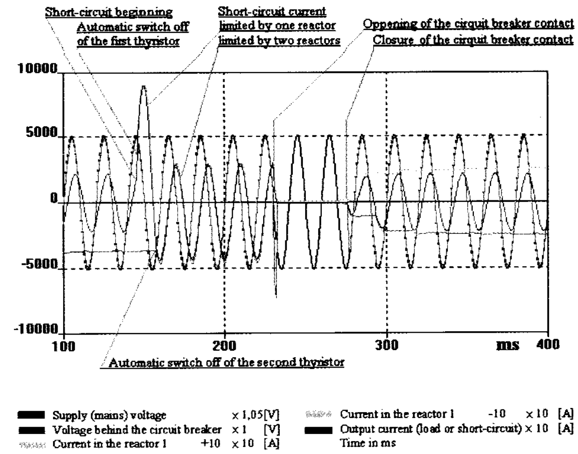

Fig. 3. Characteristics of voltages and current in a circuit with the limiter during the time of a short-circuit, after its switch off by a circuit breaker and after the circuit breaker re-closure (simulation results obtained in TCad)

4. RESULTS OF SIMULATION INVESTIGATIONS

4.1. Operation of the limiter without thyristors' ingnition

The simulation program Tcad [1] has been applied for the computer based simulation investigations of the limiter operation. Fig.3 presents simulation results of a limiter operation cooperating with a normal circuit-breaker during switching off a short -circuit and self-acting re-closure (SAR). The figure presents voltage and current characteristics before the short-circuit, during the time period from the short-circuit beginning to the instant of the short-circuit switch off by a circuit breaker (B_1 in fig.1.) and after the circuit breaker re-closure. In order to fit the figure to the page time period from the short-circuit switch off to the circuit beaker re-closure has been assumed shorter than those found in practice. The reactors' inductances assumed in the simulation diagram were so high that the amplitude of the steady short-circuit current is approximately equal to the constant current flowing through the reactors before the short-circuit. This mens that the limited short-circuit current is not bigger than the overcurrent allowed during the normal exploitation. Practical realization of such a radical short-circuit current limitation is not only possible but also very easy from the technical point of view. The only problem can be a high cost of reactors.

After the short-circuit has been switched off the current does not flow hence after the circuit breaker re-closure the current starts from and its value increases within several periods in the way shown on the simulation illustration (after the circuit breaker closure).

4.2. Operation of the limiter with thyristors' ingnition

Fig. 4 shows simulation results which confirm accuracy of the worked out method of thyristors' ignition. The method allows the limiter's reactors selection appropriately to the value of the nominal current and not to the over-load. The

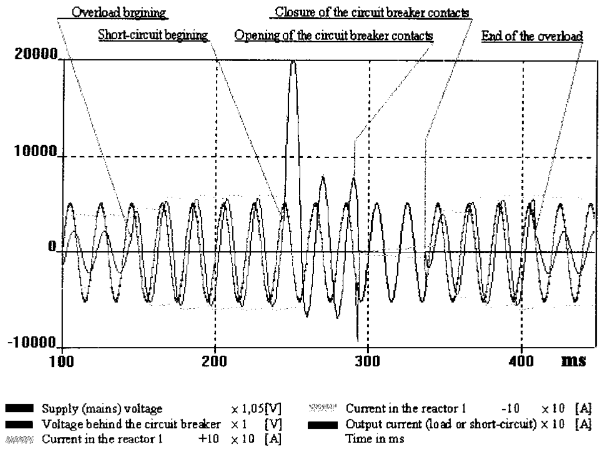

Fig. 4. Simulation of the limiter operation during an overcurrent and the short-circuit during an overcurrent.

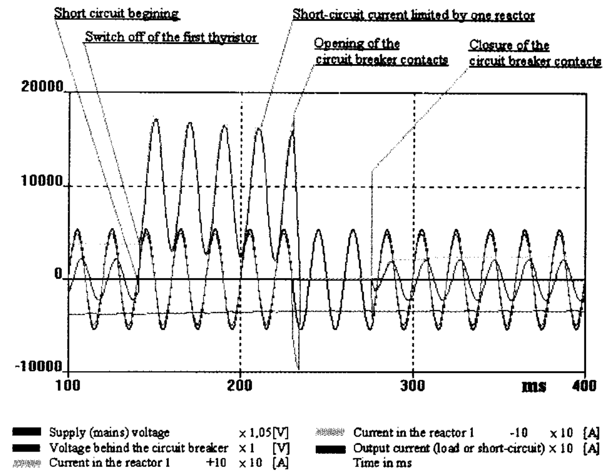

Fig. 5. Simulation results of the operation of a limiter without thyristors' ignition pulses

limiter limits the speed of the overcurrent increase only during 2–3 periods from the over-load beginning. Starting from the instant when during the over-load a short-circuit occurs, the limiter operation with the thyristors' ignition during the short-circuit becomes similar to that when the thyristors are not supplied with the ignition pulses which has been shown in fig. 3.

When the voltage phase at the short-circuit beginning is close to $\omega t = 0$ or $\omega t = \pi$ then the short-circuit current contains a substantial aperiodic component. The short-circuit current varies then in a way shown in fig.5. At the instant of the short-circuit beginning one of the limiter's reactors was switched on into the short-circuit loop but the second of the reactors can be switched on into the circuit when the actual value of the short-circuit current exceeds the value of the constant current flowing through the reactor. This can be obtained only then when the aperiodic component of the short-circuit current decreases significantly hence after a long time period. When the periodic component of the short-circuit current is high then the switching off of short-circuit, realized by a circuit breaker, takes place in an inconvenient condition and till the instant of the trip out the rms value of the short-circuit current can be approximately 2–3 times as big as that in case of a short-circuit with a low aperiodic component of the short-circuit current. The aperiodic component of the short-circuit current can be reduced by means of appropriate thyristors' ignition.

Fig. 5 and fig. 6 show simulation results of a limiter operation during the short-circuit in the two cases: without thyristor ignition pulses and with the thyristor ignition pulses applied in order to limit the aperiodic component of a short-circuit current.

5. EXPECTED RESULTS OF THE INDUCTIVE CURRENT LIMITER APPLICATION

During the normal operation the voltage drop at the current limiter is negligible. During the normal operation the limiter "is not seen" by the network, so the limiter reactors' inductances can be very large. Only at the beginning of the short-circuit a substantial voltage drop (on them) arises.

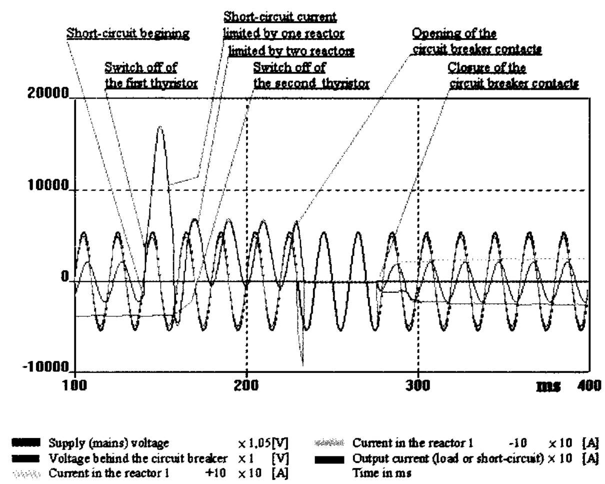

Fig. 6. Simulation results of the current limiter operation during the short-circuit. The current limiter having thyristos' ignition pulses causing limitation of the aperiodic component of the short-circuit current.

The „rigidity" of the network within the protected by the inductive current limiter part of the power system is expressed as a relation of a short-circuit power to the nominal power of the transfer system (ESCR—Effective Short Circuit Ratio) becomes a self-variable quantity. During the normal network operation the value can be large depending on the network configuration and during the short-circuit it becomes automatically a small value close to 1 depending on the limiter parameters. The change takes place without the presence of any measurement and system, instantly, at the beginning of a short-circuit. This is the new feature of the proposed and presented solution, not seen in the presently utilized devices.

The following results of the practical application of the new method of short-circuit currents limiting can be forecast:

1. Automatically, instantaneously and radically limits the short-circuit current in a much more efficient way than that realized by fuses and fast circuit breakers (effect of

the limiter operation is instantaneous whereas the result of the fuse or circuit breaker operation can be observed only after the short-circuit loop has been interrupted). There are no technical barriers in obtaining of any level of the short-circuit current limitation. This is only the matter of the core reactors' cost, remaining elements of the limiter are cheap.

2. Correction of the electrical energy quality, due to:

2.1. Significant improvement of the power network reliability, since:

a) reliability of the devices not endangered to the operation of large short-circuit currents is bigger. A possible failure can prove not danger since thanks to the limiter the short-circuit current can be even smaller than the overcurrent allowed.

b) the limiter itself as a simple device, without any mobile elements and mechanisms, automatic control is almost of the same reliability as the short-circuit reactor. The low price, apart from reactors, allows for a significant overdimensioning a multistage redundancy. The limiter's failure is not synonymous with the power system failure, since all the limiter's phase elements are galvanically connected with the voltage of one phase only, into which they are switched on. The limiter's failure decreases only, or eliminates the results of its protective action.

2.2. Decreasing or a decrease possibility of the power system voltage variations (changes, falls, distortions of the sinusoidal voltage shape) due to:

a) limiting the influence range of the failure conditions on the power quality in the network thanks to the radical separation of the short-circuit due to the large impedance of the limiter's reactors. When the impedance is sufficiently high then the obtained separation can be so efficient that within the period of a short-circuit in the network before the limiter neither even the shortest voltage drop can be observed or, defining it more precisely, even the shortest drop of an actual value of a not distorted sinusoidal voltage, higher than 10% of the nominal voltage

b) possibility of the decrease of the voltage variations caused by a variable or a nonlinear load. The presently applied methods of short-circuit current limiting by means of the permanent increase of the circuit impedance (such as, for example: special network configuration, sectionalization of buss-bars, high values of transformers' short-circuit voltage) are no longer required since the same effect can be obtained with a help of the presented above short-circuit current limiter.

2.3. Creation of the better conditions the application of a very fast self-acting re-closure of a circuit breaker contacts. This can be obtained thanks to that after the rapid voltage recovery the current limiter limits the value of a self-staring current of different devices, for example asynchronous motors with an unsuppressed magnetic filed.

3. Possibility of the replacement of the currently applied devices protecting from the results of large short-circuit currents with the new ones, much cheaper devices.

4. There is a possibility of the choice of one out of the three ways of switching into operation of the protected by the limiter device, for example energetic line:

— switching on of the network voltage after the limiter start-up, then the limiter has no influence on the line switch on process. The start-up consists in the earlier voltage supply of the small auxiliary transformers which force the constant current flow through reactors

— simultaneous switching on of the network voltage and the auxiliary transformers' supply. Then the load current increases gradually within the first several periods of the voltage, the limiter limits starting current surges of some devices.

— simultaneous switching on of the network voltage and the auxiliary transformers' supply, without thyristors' ignition pulses. The pulses are switched on with a large time delay. During the delay the reactance of the both in series connected reactors is switched on into the circuit and thus limits the current, for example starting current of electric motors.

It seems that the necessity a short-circuit limiter application can occur, particularly within the near future. The solution can have a significant utilitarian meaning particularly after the prospective regulations' changes and an unavoidable change of the market demand for the electrical energy meeting special requirements [2].

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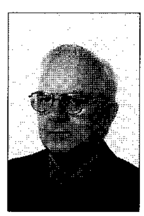

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