# FAULT-CURRENT LIMITATION IN SLOVENIAN ELECTRIC-POWER TRANSMISSION SYSTEM

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## POVZETEK

*Graditev novih vodov in povezav v elektroenergetskih sistemih (EES), rast proizvodnih enot in prehodi na višje napetostne nivoje (npr. iz 220 kV na 400 kV) so naravna in logična smer razvoja EES za izboljšanje stabilnosti obratovanja in zanesljivosti napajanja. Po drugi strani pa se lahko pojavi težava previsokih kratkostičnih tokov. Povečanje kratkostičnih tokov je tako pričakovati v omrežjih, ki napajajo gosto naseljena območja. Povečevanje kratkostičnih moči je problematično, ko preseže vrednost, za katero so projektirana obstoječa stikališča in stikalne naprave v stikališčih. V članku so opisane metode znižanja kratkostičnih tokov v 110 kV omrežjih. Te metode so lahko pasivne (t.j. stalno povečanje impedanc omrežja tako v normalnem obratovanju kot med motnjami) ali aktivne (t.j., zelo hitro povečanje impedance ob motnjah). Ker je tipična struktura razdelilne transformatorske postaje na 110 kV nivoju dvozbiralčna z dvema transformatorjema, je posebna pozornost posvečena vstavljanju omejevalnikov kratkostičnih tokov v medzbiralčne povezave. Rezultati omejevanja kratkostičnih tokov so prikazani za prenosno omrežje EES Slovenije za stanje v letu 2030.*

## ABSTRACT

*Reinforcement of electric-power systems (EPS) with construction of new power lines, additional interconnections between networks, a growth in generating capacity and upgrade to a higher voltage levels (e.g., from 220 kV to 400 kV) is a natural and logical way of development of EPS in order to improve the stability and reliability. However, on the other side, these reinforced networks can reach or even exceed their limits with respect to the short-circuit current withstand capability. The problem of too high fault currents can be firstly expected in reinforced networks that supply big cities. This paper presents and discusses various methods for limiting these fault currents in 110 kV electric-power network. These methods can be either passive (i.e., increase of impedance at nominal and fault conditions) or active (i.e., small impedance at nominal load and fast increase of impedance at fault occurrence). As typical structure of substation at 110 kV level is in the form of double busbar with two transformers, special attention is paid on inserting fault-current limiters at the position of bus coupler. The results of application of various fault current limiters are presented on the case of Slovenian EPS for the year 2030.*

# 1. INTRODUCTION

In weak electric-power systems (EPS) there are problems with overloaded lines and consequently with the stability and reliability of electric-power supply. Construction of new lines and transition to higher voltages may reduce these problems, however, on the other side a problem of too high fault currents appears. An increase of fault currents may be expected in networks that supply large cities. An increase of fault currents becomes problematic when they exceed the value that was applied for projecting existing switching substations and switchgears. Reconstruction of switching substations and replacement of switchgears would lead to very high costs, so practically everywhere solutions for fault current limitation are searched.

In the paper various approaches for fault-current limitation are presented, from topological approaches that establish such a structure of the network that disables too-high fault currents to fault current limiters that add impedance to the network or interrupt selected network connection. Results of application of various fault current limiters are presented on the case of Slovenian EPS in the state of development as it is planned for year 2030.

Considering double-busbar substation applying two parallel transformers, an ideal position for fault-current limiter is at the location of a bus coupler. In the paper the effect of various fault-current limiters at this location is described. For the time being, the most common solution for fault current limitation are current limiting reactors, so special attention is given to application of these devices that are permanently in operation, but their character come into effect during high short-circuit currents.

Other types of fault current limiters are also presented in the paper. Some of them are still in research stage and some are available only for medium-voltage level up to 35 kV. The devices that are presented—besides current limiting reactors—are: a) devices that apply semiconductor elements like GTOs or IGBTs; b) Super-Conducting Fault Current Limiters (SCFCL); c) Pyrotechnic fault current limiter with commercial name Is-Limiter, where a small explosive charge is used as the energy store for opening of the switch (main conductor); d) Magnetic fault current limiters (MFCL) that have low impedance during normal operation and high impedance during fault conditions and e)Resistance with positive temperature coefficient (PTC resistance).

# 2. FAULT CURRENT LIMITERS

Fault current limiters increase impedances or interrupt connections. They can be passive (i.e., an impedance is permanently included in EPS) or active (i.e., activated when the fault occurs). Fault current limiters and measures for limiting fault currents are presented in fig. 1. Fault current limiters affect also on protection devices, so special attention is needed when parameters of those protection devices are determined. From the protection devices’ point of view it is good if fault-current limiting devices do not interrupt current totally in order to detect and disconnect faulted part of the EPS.

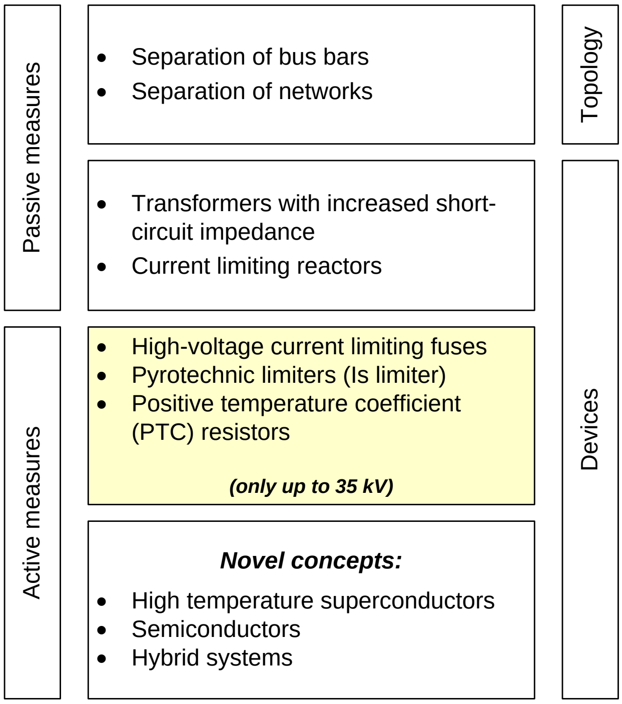


Fig. 1: Fault current limiters and measures for limiting fault currents

Currently commercial available active devices (excluding semiconductor technology that is very expensive) are only for up to 35 kV level. For 110 kV level there are various active devices in research or test phase because the need for these devices on 110 kV level is more and more frequent [1]. Currently for 110 kV only passive measures are available, usually operating with separated bus bars or current limiting reactors are applied. In 110 kV networks that include many generating capacities in the vicinity of large cities the problem of too-high fault currents can be solved with the application of fault current limiters at generator-side of the network at medium-voltage, for which commercial available active devices exists.

## 3. FAULT CURRENT LIMITERS IN BUS COUPLER

In the case of substation with double busbars fed by two transformers an efficient location for fault current limiter (FCL) is at the position of a bus coupler, as it is presented in fig. 2. In fig. 2a fault currents are presented for the case without FCL and in fig. 2b for the case with FCL that reduces fault currents, but not interrupt it (e.g. in the case of current limiting reactor). Without FCL both transformers feed fault current. If FCL is inserted between busbars, in normal operation only a small portion of current flows through it. However, when the fault occurs, contribution of one transformer is reduced irrespective of the location of the fault. In the case of separated busbars fault current would be halved, but redundancy of the network is reduced and in some cases n-1 criterion is not fulfilled.

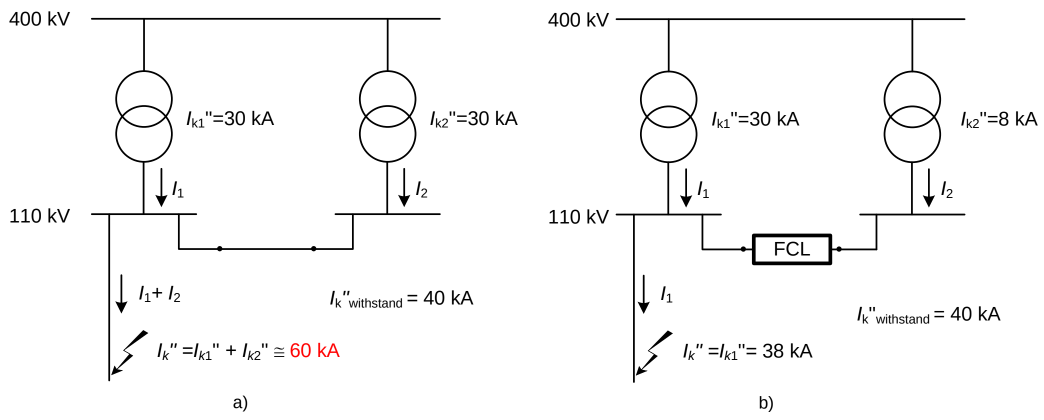


Fig. 2: Fault currents in double-busbar substation: a) without FCL b) with FCL

# 4. TYPES OF FAULT CURRENT LIMITERS

## 4.1 Current limiting reactors

Current limiting reactors are series air core reactors, usually build for outdoor installation. Besides for limitation of fault currents they can be used for:

- power flow control in parallel lines,
- voltage control with thyristor-controlled reactor,
- damping of inrush and outrush currents of capacitor banks,
- limiting unstable arc-furnace current and voltage,
- filter circuits to reduce harmonic content in the network,
- HVDC systems.

Voltage drop $\Delta U$ on reactor depends on power factor and it can be calculated as:

$$\left|\frac{\Delta U}{U_{\mathrm{N}}}\right| = 1 - \frac{1}{\sqrt{1 + 2 \cdot u_k \sqrt{1 - \cos^2(\varphi)} + u_k^2}} \tag{1}$$

where $U_{\mathrm{N}}$ is nominal network voltage, $cos(\varphi)$ is power factor and $u_{\mathrm{k}}$ is short-circuit impedance of reactor. According to (1) voltage drop on reactor is presented in fig. 3 for various cos($\varphi$).

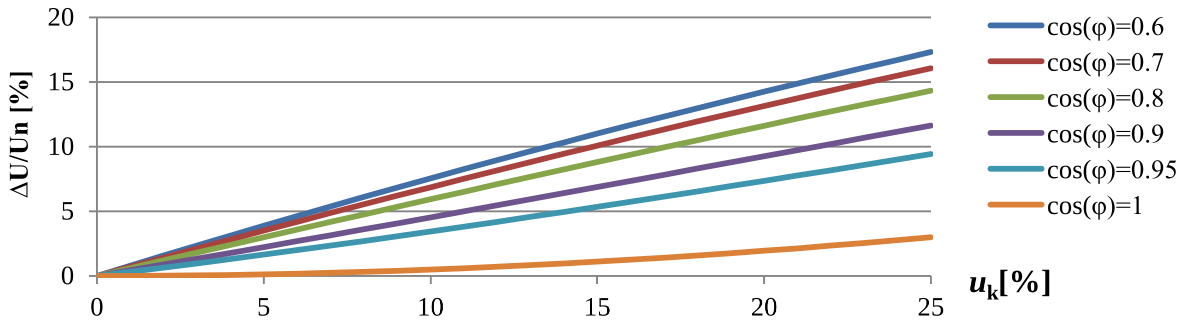

Fig. 3: Voltage drop on reactor for various power factors *cos(φ)*

If only one transformer supply double-busbar substation, the so called "duplex" reactor can be applied [2]. In this case the two coils are combined to form a joint reactor with the center terminal connected to the supply transformer. If the busbar sections are loaded symmetrically, the magnetic coupling in the two half coils will reduce the effective reactance and therefore the voltage drop. In the event of a short circuit the full reactance of the half coil is effective.

## 4.2 Solid-state devices

In solid-state devices GTOs or IGBTs are used to switch-off fault currents. Beside semiconductors (i.e. GTOs and IGBTs) some auxiliary elements are also used. Solid-state devices can either limit fault currents (Solid-State Current Limiter - SSCL) or totally interrupt fault currents (Solid-State Breaker – SSB). Main advantages of solid-state devices are especially very fast switching and absence of arc, while disadvantages are losses in normal operation and high costs of devices [3]. Another possibility is application of hybrid device that combine solid-state elements and fast mechanical switch.

## 4.3 FACTS devices

### 4.3.1 Series compensation

FACTS devices can be connected in parallel or in series with the network. Parallel devices are usually used for voltage control and reactive power compensation, while series devices are usually used for power-flow control. For limiting of fault currents series devices that control their reactance are suitable. Those devices are called SCCL (*Short-Circuit Current Limiter*) and are composed of series-connected reactance and condenser that is controlled by parallel thyristor [4]. Primarily those devices are used for power-flow control, but due to their fast control they can be used also for fault current limiting or for damping of power-flow oscillations or improving of transient stability [5].

### 4.3.2 Interphase Power Controller – IPC

IPC is basically a concept of power-flow control. It is a passive device composed of conventional devices (i.e., transformer, condenser, and reactor). For networks at both sides of the device an IPC behaves like a current source with following characteristics [6]:

- Active power flow in normal operation is almost constant,
- Short-circuit power of connected networks is practically not increased.
- Faults at one side of an IPC do not affect network at the other side
- No harmonic distortion is added to the network.

The concept of IPC is theoretically very well described. Regardless to interesting specifications it was not realized in practice.

## 4.4 Devices that apply superconductors

Devices that apply superconductors are called Super-conducting Fault Current limiters (SCFCL). They are in test-stage in many networks in the world. Commercially are not available yet. However, after the technology will be matured, the expected price would be about 10-times higher than that of mechanical breaker [7]. Various concepts are possible, as resistance, as reactance or as a combination of resistance and reactance. These devices are in test stage in both medium-voltage and high-voltage (110 kV and higher) networks. In normal operation the impedance of SCFCL is negligible. A disadvantage of an SCFCL is the energy needed for cooling of superconductor to temperatures below 77 K.

### 4.4.1 Resistive SCFCL

In the first stage of development an SCFCL were built as resistance. During the fault critical current of the superconductor is surpassed and its resistance increases rapidly, leading to the current limiter being quenched before the first peak value of the short-circuit current is reached. To prevent hot spots in superconductor additional resistance is used that is parallelly joined to the superconductor. This additional resistance also limits overvoltages that might occur due to rapid change of resistance of superconductor. To prevent further heating of superconductor, faulted current should be switched-off after a few periods [8]. After the fault a superconductor must be cooled to reach superconductivity again and it can last few seconds for thin superconductors and up to a minute for thick superconductors [8].

### 4.4.2 Resistive SCFCL with an auxiliary magnetic field

Instead of a resistance, a normal conducting coil in parallel to the superconductor can be applied to suppress hot spots during the quench. In this setup the normal conducting coil is arranged coaxially outside a superconducting tube. This type makes use of the magnetic field dependence of the superconductor’s critical current. The quench starts at the weakest point of the superconductor and the growing resistance forces the current to flow in the parallel coil. The resulting magnetic field of the coil lowers the critical current in the still superconducting portions where the quench is therefore accelerated, which in turn mitigates the hot-spot problem.

### 4.4.3 Inductive SCFCL

The device consists of an iron core, a primary (normal conducting) winding and a superconducting cylinder. The device can be viewed as a transformer with a shorted (superconducting) secondary winding. An option with normal secondary winding that is short-circuited with a superconductor is also possible. With proper construction of a device various combinations of resistance and reactance can be achieved. Important advantage of such a device is that cooling system is electrically isolated from the network. The disadvantage is that it needs iron core that has large volume and high weight. Resistive SCFCL can be up to 4-times smaller than inductive SCFCL [8].

### 4.4.4 Saturated iron core SCFCL

Two copper coils with two iron cores are inserted in the circuit. The iron core is kept in saturation during normal operation through the magnetic field of an additional superconducting winding, as it is presented in fig. 4. The impedance of the device is low in normal operation. In case of an overcurrent the increased AC current through the normal conducting coil causes that the core departs from saturation. Therefore, the impedance of the device increases during a fault. One iron core reduces current in the first half of the period and the other iron core reduces current in the second half of the period, as it is presented in fig. 4. The superconducting winding is exposed only to DC currents in this concept and always stays in the superconducting state so that it needs no recovery time after a fault [8].

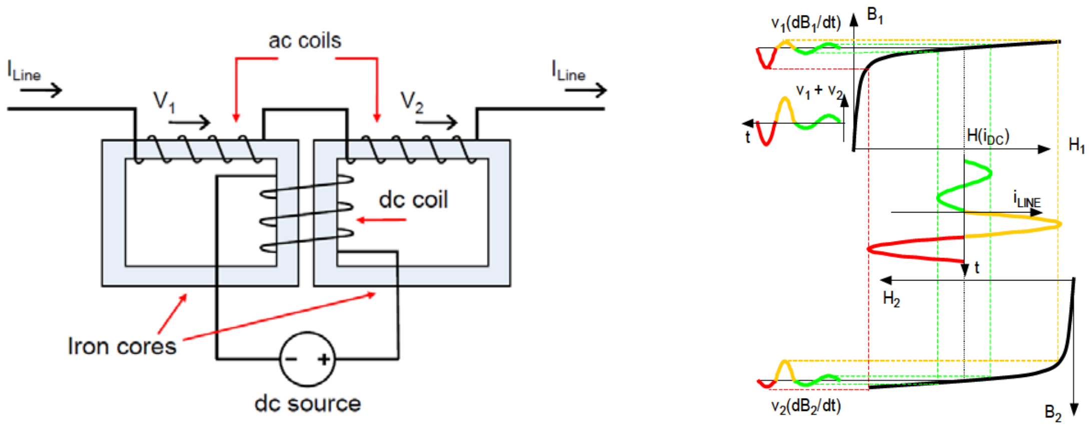


Fig. 4: Structure of saturated iron core SCFCL and voltages on AC windings when high currents occur

### 4.4.5 Superconducting Fault Current Limiting Transformer

The technology of transformers with superconducting windings starts two decades ago in order to decrease losses [9]. A decade ago ideas appear about the fault current limitation with the application of transition of superconductor out of the superconducting state [10]. 5) Superconducting Fault Current Limiting Transformer can be modeled as a conventional transformer plus resistance. The size of the resistance can be set according to the level of fault-current limitation, but on the other side too-large resistance could decrease transient stability [11].

### 4.4.6 Hybrid SCFCL

Hybrid SCFCL combines superconductor with parallel reactor and with fast mechanical switch [12]. Scheme of hybrid SCFCL presents fig. 5. When the fault occurs, resistive SCFCL re-direct the current on parallel reactor, then fast mechanical switch disconnects superconductor. In this way heating of superconductor is reduced, so after the fault it can be faster re-connected to the network. Similar hybrid systems without superconductor are also described in literature. Instead of superconductor thyristors or positive-temperature coefficient (PTC) resistors can be applied [7].

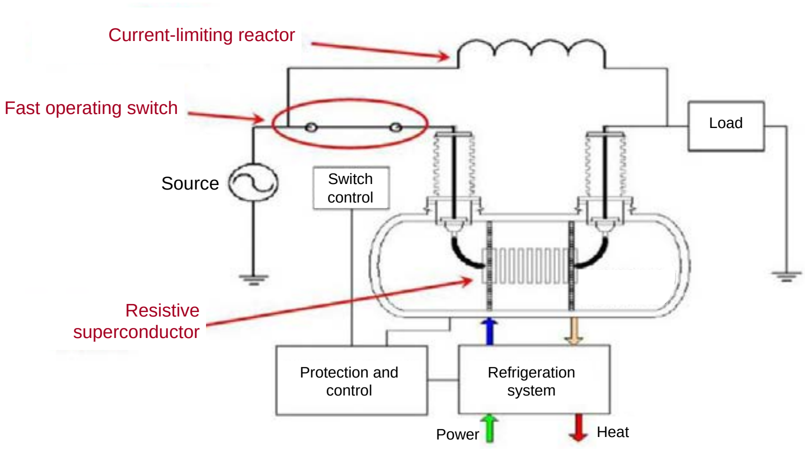


Fig. 5: Hybrid SCFCL

## 4.5 Devices with explosive charge – $I_S$-limiter

Commercial name for these devices is “$I_S$-limiter« (produced by ABB), so this name is usually used in literature. $I_S$-limiter consists of two parallel parts. The first part is main conductor that consists of stripes (bursting bridge) and explosive charge inside while the second part is a fuse. In order to achieve the desired short opening time, an explosive charge is used as the energy store for opening of the main conductor. When the main conductor is opened, the current continues to flow through the parallel fuse, where it is limited within 0.5 ms and then finally interrupted at the next voltage zero passage. The current flowing through the $I_S$-limiter is monitored by an electronic measuring and tripping device. At the very first rise of a short-circuit current, this device decides whether tripping of the $I_S$-limiter is necessary. In order to reach this decision, the instantaneous current and rate of current rise at the $I_S$-limiter are constantly measured and evaluated. When the setpoints are simultaneously reached or exceeded, the $I_S$-limiter trips. The structure of $I_S$-limiter is presented in fig. 6. After each interruption of a fault current $I_S$-limiter must be refurbished in manufacturer’s works. The main conductor, the parallel fuse and the charge must be replaced [13]. $I_S$-limiter can be applied for voltages up to 40 kV and currents up to 2000 A. Current state of technology is not available for 110 kV or higher.

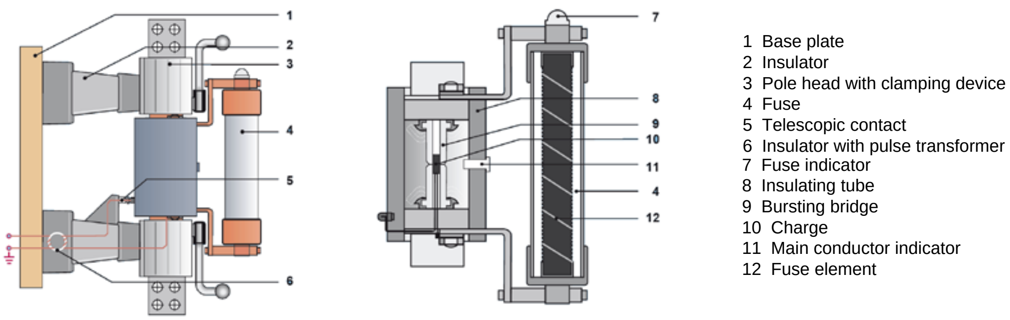


Fig. 6: Structure of $I_S$-limiter

### 4.6 Magnetic fault current limiter - MFCL

MFCL is based on a laminated iron C-core with a demagnetized magnet in its air gap. The winding on magnetic core is series-connected to the network. MFCL will automatically increase its reactance during a fault in a power system to which it is connected. During normal operation the magnet is in a demagnetized state. Its permeability is close to the air value and the MFCL behaves like an air-cored reactor with a low inductance. When the fault occurs, the fault current drives the magnetic field beyond the magnet's coercive value. The magnet becomes magnetized and closes the flux path through the magnetic circuit. Thus the inductance of the device is increased, which reduces the fault current level. MFCL is described in detail in [14].

### 4.7 Devices with PTC resistors

Resistors with positive temperature coefficient (PTC) have low resistance in cold state. In case of a fault, the PTC-resistor is heated up by the fault current from the conducting cold state to the insulating hot state. When fault current is suppressed, simple mechanical switch in series with the PTC resistor can disconnect the fault. In order to be able to use PTC-resistors as fault current limiters in medium-voltage networks an appropriate number of PTC-elements have to be connected in series. To control the voltage across these elements varistors are connected in parallel to the PTC-elements. Prototypes were developed for 12 kV voltage level. For higher voltages this type of fault current limiters were not researched yet.

## 5. RESULTS OF CALCULATIONS

Short-circuit currents with application of various fault current limiters are presented on the case of Slovenian electric-power system in the state of development as it is planned to be in the year 2030. This state includes a transition from 220 kV to 400 kV, new 400 kV interconnections to Italy and Hungary, new generating capacities and reinforced 110 kV network according to plans of national transmission system operator. Results are presented for two most loaded substations near Ljubljana, the capital of Slovenia, i.e. Bericevo and Klece. Results in Table I presents 3-phase short-circuit currents in kA for the case without fault current limiters, for fault current limiters inserted in bus coupler in substations Bericevo and Klece with various impedances and for separated buses in substations Bericevo and Klece [15]. Withstand short-circuit capacity of substation's equipment is 40 kA. From results we can obtain that the impedance of 10 Ω is large enough to limit short-circuit currents under permissible value. Additional increase of impedance does not have any significant effect.

Table I: Short-circuit currents in kA for various measures for fault-current limitation

| measure | without | 5 Ω | 10 Ω | 15 Ω | 20 Ω | separated |
|---|---|---|---|---|---|---|
| Beričevo | 57,4 | 41,0 | 38,1 | 36,9 | 36,1 | 33,4 |
| Kleče | 57,3 | 41,6 | 38,0 | 36,3 | 35,3 | 31,8 |

## 6. CONCLUSIONS

Various methods for fault-current limiting in transmission power systems at 110 kV level (and some for medium-voltage level) are presented in this paper. Most of these methods are still in test or research stage, only current-limiting reactors are currently used (besides operating with separated bus coupler). In Slovenian EPS in the year 2030 current limiting reactor in two substations near Ljubljana (the capital of Slovenia) on the 110 kV level would be enough to keep short-circuit currents within permissible range.

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