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Line Overload Limitation Automation

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1 INTRODUCTION

The occurrence of transmission line overload is a relevant problem for the distribution network of the Moscow Power System. Overhead lines (OHLs), cable lines (CLs) and mixed cable-overhead lines (MLs) can all be exposed to danger.

The danger of the thermal line overload mainly consists in the following:

- for OHLs – wire extension with temperature rise → wire slack increase → possible flashover in the air gap and a short circuit occurrence → line tripping,
- for CLs – insulation ageing progressing → possible disruption and a short circuit occurrence → line tripping,
- for MLs – the combination of the above mentioned factors: during the summer season the overhead part is in main danger, during the winter season – the cable part (as a rule).

If the line is tripped during the overload occurrence, the consumers' load will fall on other links that may cause these links' overload occurrence and result in cascade tripping. Therefore an overloaded line tripping has to be considered as the last possible measure. Emergency control actions aimed at the line unloading should be introduced.

As a result the Moscow United Electric Grid Company (MUEGC) placed an order at the Institute «ENERGOSETPROJECT» (ESP) for the development of the line overload limitation automation (LOLA) and execution of several works for actual 110 kV transits that were associated with overloads. As a result of the projects made, the main principles of the automation operation were determined and functional and structural (so-called «architectural») LOLA schemes were developed. Based on these works, since 2009 the «Enera Engineering» OJSC has been developing the working documentation, which is aimed at the LOLA system hardware implementation. The experience gained during the common working process is analyzed and summarized in this paper to be shared.

Line overload limitation devices that were earlier used had a current-responding element and actualized emergency control actions depending on the current overload value. Heating and cooling conditions of the line were neglected. The LOLA device developed by the ESP Institute enables one to determine thermal line overload (i.e. its overheating). This solution is more accurate in principle that makes it possible to specify and minimize emergency control actions.

2 STUDY

In case of emergency occurrence in the network it is required to determine the thermal overload of the line, i.e. the current conductor temperature has to be found and compared to allowable values (continuously allowable temperatures are 70 °C for OHLs and 85 °C for CLs; emergency allowable temperatures are 90 °C for OHLs and 100 °C for CLs). These allowable values might vary in different references, so that they are given as recommended ones. The thermal balance of the conductor [1] is used as a basis of the current temperature calculation.

For the thermal line overload determination in practice the line is modeled as a first-order inertial element, which is characterized by a thermal time constant of the wire. This makes it possible to consider the temperature change in time and implement the dynamic temperature assessment. As main parameters determining the wire heating two easily available measurements are used:

- 1) the electric current of the most loaded part of the line,
- 2) the ambient air temperature.

For the overload protection a potentially dangerous part of the line is subjected. Usually this is the most loaded one.

For most cases it will be:

- a) for a line with a tap – the leading section (before the tap at the feeding end),
- b) for a line made of different conductors (wires with different sections, cables with different types) – the section with the lowest throughput capacity,
- c) for a line with the reversed power flow – both ends of the line if both of them might be overloaded with the different flow directions (which was proved by calculations or in practice),
- d) for a mixed line – the most loaded overhead and the most loaded cable part,
- e) for a double-circuit line – the most loaded parts of both circuits.

In practice there are some cases when an overload occurs on two lines connected in series in one transit which has inner power selections (the load of substation busbars and taps). In different emergency cases different parts of such transit can be overloaded. It is reasonable to consider such lines taken together because they can be protected by one LOLA device (this solution is also economically efficient). This was a presupposition for the decision that the unified LOLA algorithm should determine the overload of the two serial parts with the reversed power flow.

As a setting for the line modeling in the LOLA device the thermal time constant of the conductor is used. It is calculated according to the following.

For a wire (overhead part) the thermal time constant T , sec (which is the ratio of the wire heat capacity and its heat irradiation), can be computed from the formula [1]:

$$T = \frac{mC}{\alpha_c + \alpha_e} \text{ (sec)}, \quad [1]$$

where m is mass of one meter of the conductor, kg/m;

C – heat capacity of one meter of the conductor, (W·sec)/(kg·°C);

α_c – coefficient of heat emission by the convection, W/(m·°C);

α_e – coefficient of heat emission by the radiant emission, W/(m·°C).

For the heat capacity computation of the wire its manufacturer-given characteristics are required; for the coefficient of heat emission by the convection computation the wind speed and air temperature should be taken into account; for the coefficient of heat emission by the radiant emission computation the air temperature and wire surface condition should be considered [1].

For a cable (cable part) the thermal time constant is calculated depending on the cable line construction conditions: under the ground or in the air (in a tunnel/chute/cable channel etc.). The cable heat irradiation meets the thermal resistance of the following:

- 1) cable insulation,
- 2) protective coverings,
- 3) outer cable armour,
- 4) soil.

According to this, the thermal time constant for a cable in the air is calculated from the formula [2]:

$$T = (S_1 + S_3) \cdot [c_{th} + 0,5(c_{ins} + c_l)] (h), \quad [2]$$

where S_1 – thermal resistance of the cable insulation, $(^\circ\text{C} \cdot \text{cm})/\text{W}$;
 S_3 – thermal resistance of the protective covering, $(^\circ\text{C} \cdot \text{cm})/\text{W}$;
 c_{th} – specific heat capacity of the cable threads, $(\text{W} \cdot \text{h})/(\text{cm}^3 \cdot ^\circ\text{C})$;
 c_{ins} – specific heat capacity of the thread insulation, $(\text{W} \cdot \text{h})/(\text{cm}^3 \cdot ^\circ\text{C})$;
 c_l – specific heat capacity of lead, $(\text{W} \cdot \text{h})/(\text{cm}^3 \cdot ^\circ\text{C})$.

The thermal time constant for a cable under the ground is calculated from the formula [3]:

$$T = (S_1 + S_2 + S_4) \cdot [c_{th} + 0,5(c_{ins} + c_l + c_{cov})] (h), \quad [3]$$

where S_2 – thermal resistance of the protective coverings of the underground cable, $(^\circ\text{C} \cdot \text{cm})/\text{W}$;
 S_4 – thermal resistance of the soil around the cable, $(^\circ\text{C} \cdot \text{cm})/\text{W}$;
 c_{cov} – specific heat capacity of the protective coverings, $(\text{W} \cdot \text{h})/(\text{cm}^3 \cdot ^\circ\text{C})$.

Specific heat capacities of materials are given in technical catalogues and hand-books; thermal resistances depend on the cable line construction conditions and can also be calculated [3].

In addition to the conductor temperature, the LOLA device also determines a current value, which is continuously allowable for the line at the present weather conditions. The continuously allowable current I_a is a current value that corresponds to a condition when the conductor steady-state temperature is equal to the continuously allowable temperature. This value is calculated from the formula [4] for OHLs:

$$I_a = \sqrt{\frac{(\alpha_c + \alpha_s) \cdot (\theta_a - \theta_{air}) - P_r}{R_c}} (A), \quad [4]$$

where θ_a is allowable conductor temperature, $^\circ\text{C}$;
 θ_{air} – ambient air temperature, $^\circ\text{C}$;
 P_r – solar radiation intensity, W/m^2 ;
 R_c – resistance of one meter of the conductor at allowable temperature, Ohm/m .

This formula follows from the wire thermal balance in a steady-state.

After the thermal time constant computation, the current conductor temperature can be calculated from the formula [5]:

$$\theta_c = \theta_{in} + (\theta_{st} - \theta_{in}) \cdot (1 - e^{-t/T}) (^\circ\text{C}), \quad [5]$$

where θ_{in} is initial conductor temperature, $^\circ\text{C}$;
 θ_{st} – steady-state temperature of the wire, $^\circ\text{C}$;
 t – time passed from a transient process beginning (or from the beginning of a reference hardware time interval), sec.

Steady-state conductor temperature can be computed in accordance with the electrical current value and the weather conditions as well as the wire heating/cooling conditions taken into account. An average steady-state temperature for previous period can be used as an initial temperature.

By means of the comparison of the current conductor temperature calculated and the continuously allowable temperature θ_a used as a setting, the LOLA device determines the line overload occurrence:

$$\theta_c \geq \theta_a. \quad [6]$$

This is the condition that activates the LOLA device to operate on an alarm signal. Simultaneously the time period which is rest until the control action actualization begins (unless the line current decreases) is transmitted to the dispatcher or substation personnel.

As another setting of the LOLA device the continuously allowable current value should be used (see the formula [3]). This value is being constantly recalculated in the microprocessor computation cycle. By means of the comparison of the line current and this value an alarm signal is formed for warning the personnel:

$$I \geq I_a, \quad [7]$$

where I – the most loaded part current, A.

In that way, the line overload occurrence is determined (and output with the alarm signal) by both the line current and the temperature. However, automatic control actions cannot be chosen according to the current overload value, because the current increase over the continuously allowable value is not always followed by the line overheating.

If the conductor temperature keeps on rising, the LOLA device starts to actualize the automatic control actions (ACAs) step-by-step:

$$\theta_c \geq K_i \theta_a. \quad [8]$$

Here K is a multiplier for a certain overload fixation stage. As a rule, the LOLA device has two stages. The ACAs selection and implementation will be considered afterwards.

The LOLA device does not determine required scope of the control actions. It actualizes pre-chosen measures and operates in an iterated way. When the measures taken are enough to unload the line, it stops operating according to the following condition:

$$I \leq 0,95 I_a. \quad [9]$$

The conductor temperature is an inertial parameter, so it cannot be used as an overload liquidation criterion. It is supposed that the main danger is gone when the line current decreases to the continuously allowable value (with a small margin).

The most available measure for the line overload liquidation is load shedding. As the load shedding time should be as short as possible, automatic reverse load switching-on is provided in the LOLA device. It is implemented by means of automation after the conductor temperature decrease, but first a permission of the dispatching personnel is required. The line current is being controlled simultaneously, because a too high level of the load switching-on (for the post-emergency period) might result in another overload occurrence.

Different measures can be used as automatic control actions. In principle, all of them can be divided into three groups:

- 1) Decrease of the power generated in the feeding end of the transit:
 - one-sided disconnection of (auto)transformers, feeding the busbar section where the protected line is commutated,
 - temporary limitation of power plant generation – switching-off of hydro power plant generators, power restriction of the heat power plant generators (via turbine controlling mechanism), gas turbine switching-off in combined steam-and-gas-cycle plants.
- 2) Increase of the infeed in the loading end of the transit – reserved feeding capacities introduction:
 - power plant engaging – switching-on of stand-by hydro power plant generators or involving hydro-aggregates previously worked in synchronous compensator mode; power increase for heat power plant generators already working; gas-turbine switching-on in combined steam-and-gas-cycle plants, local mobile gas turbine power plants starting; temporary limitation of district heating steam extractions of the combine heat and power plants in order to increase electrical power,
 - busbar-connecting circuit breaker switching-on in order to feed the load from two transformers (instead of one).
- 3) Decrease of the power consumed in the loading end of the transit:
 - reactive power sources switching-on in order to compensate a part of the load and increase the voltage level,
 - load shedding,
 - one-sided disconnection of a line that goes away from the ending substation.

The “feeding end” and “loading end” terms are used conditionally, because any 110-220 kV part of the Moscow power system has the power feed at the both ends. Another feature of this system is widely used grid splitting (sectionalizing).

The LOLA device does not select ACAs automatically due to the fact that the actions selection requires too much data, including topology of the adjacent grid. This would also significantly complicate the device logic and reduce its reliability. In this connection, all the ACAs selection is being done beforehand by technical engineers during the projecting process.

It is reasonable to consider the LOLA operation using a certain example. A simplified scheme shown in the figure 1 is needed.

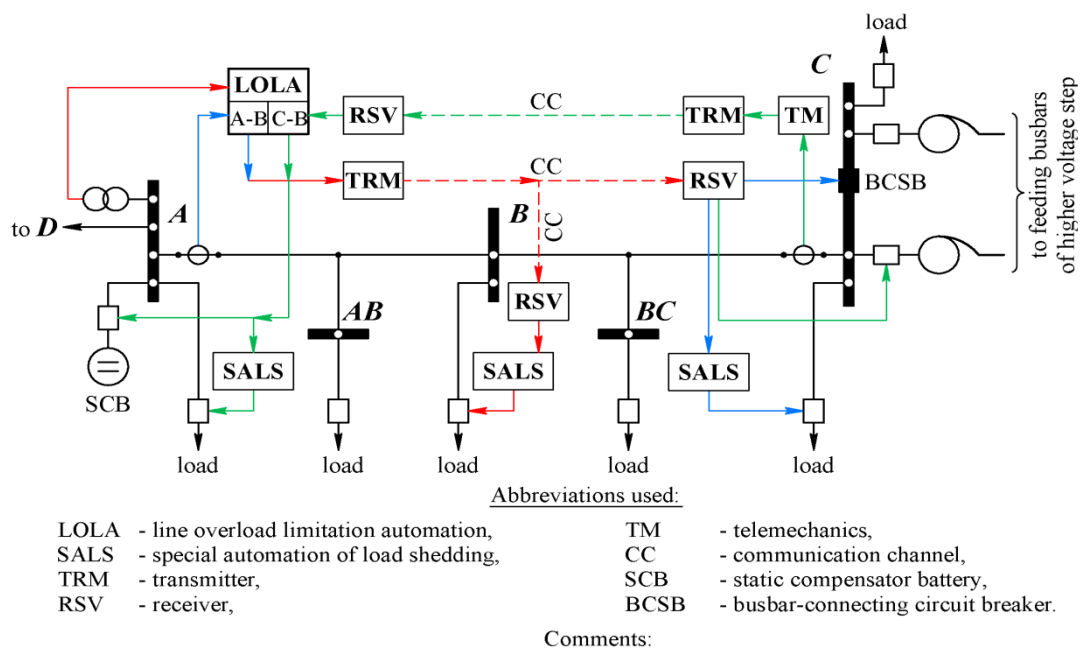


Fig. 1: An example of the LOLA system implementation for a 110 kV grid part

The protected transit consists of two lines: A-B and B-C, each has a tap and the power feed at the both ends. In different emergency cases a power flow reverse takes place.

When the power flow has a direction $A \rightarrow B \rightarrow C$ both the lines are overloaded, but the most loaded part is near the A substation busbars (loading section). Hence, the current has to be controlled in this section. The emergency control measures are:

- first stage – busbar-connecting circuit breaker switching-on in the C substation (increase of the infeed in the loading end of the transit),
- second stage – load shedding in the B and C substations (decrease of the power consumed in the loading end of the transit).

The part of the algorithm related to the A-B line overload determination is painted in blue in the figure 1.

When the power flow has a direction $C \rightarrow B \rightarrow A$ both lines are also overloaded, but the most loaded part is near the C substation busbars, so the current is controlled in this section. Emergency control measures are:

- first stage – one-side disconnection of the feeding autotransformer of the C substation (decrease of the power generated in the feeding end of the transit) and the static compensator battery of the A substation switching-on (decrease of the power consumed in the loading end of the transit),
- second stage – load shedding in the A and B substations (decrease of the power consumed in the loading end of the transit).

The part of the algorithm related to the C-B line overload determination is painted in green in the figure 1. The part painted in red relates to the both A-B and C-B lines.

Load shedding in the tap substations (AB, BC) also decreases the line overload. However, it requires new communication channel organization, which is the most expensive element of the LOLA system. The LOLA system should include as few objects as enough. In particular, this can be achieved by means of proper control actions selection – when the ACAs are the same for different emergency cases (for instance, load-shedding in the B substation). It is reasonable to install the LOLA device in the substation where the current is measured (in order to economize on telemechanics) and some ACAs are actualized (to economize on communication channels).

According to this, a simplified functional scheme of the LOLA device installed in the A substation can be shown. This configuration can be considered as a universal one, because here one device provides the protection of two lines with the reversed power flow and different ACAs for

different emergency cases. This scheme is shown in the figure 2; colours mean the same as in the figure 1.

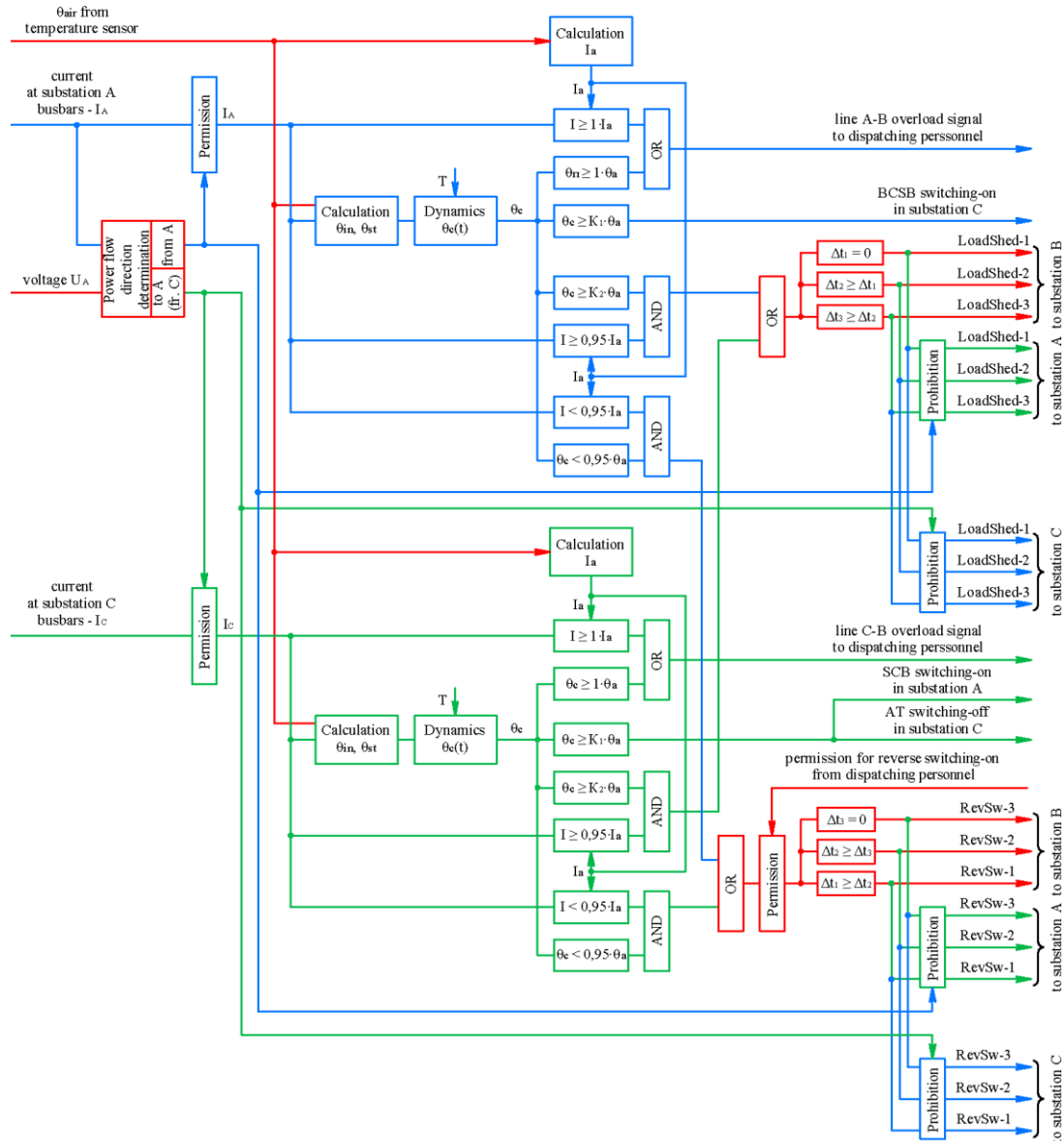


Fig. 2: The LOLA device unified configuration

The solutions used for this configuration relate completely to LOLA implementation for OHLs. For CLs and MLs protection some special features should be also taken into account.

Cable line overheating slightly depends on the ambient air temperature because cable lines are laid underground. Hence, the air temperature measurement and the sensor itself are not necessary. Fixed continuously allowable current value (not a recalculated one) is used as a setting. This value is rated by a cable manufacturer and is determined according to the cable line construction conditions; it can be often found in a catalogue or a hand-book.

For mixed lines, the cable insert can limit the line throughput capacity during the winter season (as a rule) while the overhead part has better cooling conditions due to a low ambient air temperature. And vice versa, during the summer season the cable part has better cooling conditions. The consumer's load is lower in summer but grid elements repairs (including transmission lines) take place at the same time. Due to these elements' outages, power flows are transmitted through the links rest in operation, so their current levels can be significantly higher than in winter. Therefore a line overload occurrence is possible in summer and winter both and MLs have to be protected the whole year round.

The LOLA device configuration given above considers these special features and is suitable for CLs and MLs protection too.

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In the table 1 an overview of the ESP Institute solutions provided in 2008 for the MUEGC objects is given.

Project for a SS	Devices installed	Lines protected	Emergency control measures	
			1st stage	2nd stage
500 kV SS Ochakovo	LOLA1	110 kV OHL Odintsovo – Ochakovo I	one-sided disconnection of the feeding 220/110 kV AT in the SS Ochakovo	
	LOLA2	110 kV OHL Odintsovo – Ochakovo II		
110 kV SS Vernadskaya	LOLA1	110 kV OHL Semenovskaya – Vernadskaya I	one-sided disconnection of the feeding 220/110 kV AT in the CHPP#20	LS in the SS Vernadskaya
	LOLA2	110 kV OHL Semenovskaya – Vernadskaya II		
110 kV SS Nekrasovka	LOLA1	110 kV OHL Kraskovo – Nekrasovka I with a tap	one-sided disconnection of the 110 kV OHL Mineralnaya – Nekrasovka	LS in the SS Nekrasovka, Progress, Mineralnaya, Chistaya, Kuchino
	LOLA2	110 kV OHL Kraskovo – Nekrasovka II with a tap	one-sided disconnection of the 110 kV OHL Progress – Nekrasovka	
220 kV SS Krasnogorskaya	AIR (LOLA function included)	110 kV OHL Hertsevo – Pavshino – Krasnogorskaya with a tap	110 kV BCSB switching-on in the SS Krasnogorskaya	
110 kV SS Cheremushki	LOLA1	110 kV ML CHPP#20 – Cheremushki – Youzhnaya I with a tap	one-sided disconnection of the feeding 220/110 kV AT in the CHPP#20	LS in the SS Cheremushki, Ziuzino, Nagornaya
	LOLA2	110 kV ML CHPP#20 – Cheremushki – Youzhnaya II with a tap		
110 kV SS Serpukhov	LOLA1	110 kV OHL Oka – Serpukhov I	SCB switching-on in the SS Pushchino	LS in the SS Serpukhov, Pushchino
	LOLA2	110 kV OHL Oka – Serpukhov II		
110 kV SS Klyazma	LOLA1	110 kV OHL Trubino – Klyazma I&II with a tap	SCB switching-on on the SS Pushchino, warning signal of the MGTPP start in the SS Pushchino	LS in the SS Pushkino, Topol
	LOLA2	110 kV OHL Rosa – Pushkino – Klyazma		LS in the SS Klyazma, Pushkino, Topol, Podlipki, N. Podlipki
	LOLA3	110 kV OHL N. Podlipki – Topol – Podlipki –Klyazma with taps		

Abbreviations used:

AIR – automatic introduction of reserve

AT – autotransformer

BCSB – busbar-connecting circuit breaker

LS – load shedding

SCB – static compensator battery

SS – substation

Table 1: The LOLA solutions provided for the MUEGC by the ESP Institute

3 CONCLUSION

The LOLA device developed by the ESP Institute enables one to determine the thermal line overload quite accurately but does not require any complex or expensive hardware for its implementation. The LOLA logic can be implemented for most microprocessor devices. The calculations of the LOLA settings can be done by most technically educated engineers. The line current and ambient air temperature measurements, which are needed for the LOLA device operation, are also easily available. According to this, the LOLA device application can be widely recommended for 110 kV distribution lines.

There are some real perspectives for the usage of the LOLA device in combination with direct conductor temperature measurement. For this purpose high-voltage temperature sensors are required. These sensors can be installed locally in controlled parts of the line or they can monitor the conductor temperature along the whole line. These measures lead to the significant rise in the LOLA system price, but at the same time they make it possible to use the maximum line throughput capacity. This solution can be recommended for the 220 kV lines forming the “skeleton” of the power system.

The LOLA projects made by the ESP Institute have been coordinated with MUEGC and the regional dispatch management of Moscow and the Moscow region. Based on these works, the «Energia Engineering» OJSC has been developing the working documentation. The AIR device including the LOLA function has been already installed, adjusted and put into industrial operation in the 220 kV SS Krasnogorskaya, as well as the LOLA devices of the Nekrasovka and Vernadskaya SS. The AIR device of the Krasnogorskaya SS has already operated properly.

The LOLA devices usage enables one to liquidate automatically a line thermal overload, prevent its switching-off by the relay protection and possible cascade tripping. However, in most cases the LOLA device is not the only one required to provide the reliable overload protection. Other emergency control devices, communication with the adjacent objects and LOLA–dispatcher interaction are also needed. The theory and practice prove that the reconstruction of the grid regions and the replacement of the wires and cables with new ones with greater throughput capacity is the best measure to avoid line overloads. The task of the power supply reliability increase should not be entirely placed on the emergency automation. Primary measures are development and reconstruction of the electric grid itself.

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