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Cite as: AIP Conference Proceedings **2686**, 020005 (2022); https://doi.org/10.1063/5.0113363
Published Online: 05 December 2022

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# Electric Power Supply of Steel Producing Companies: Schematic Design Solutions to Improve Reliability of Power Grids

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**Abstract.** This research is aimed at improving electric power supply reliability at major industrial plants by applying schematic design solutions. The authors analyzed the features of branch electric power distribution systems at a metallurgical plant; considered options of their revamping to improve reliability of electric power supply; carried out experimental research on splitting 110 kV meshed system at the integrated iron and steel works. When performing the research, mathematical simulation methods and full-scale experiment methods were used. Following the research, we proposed three options to revamp the power grid at the industrial plant applying schematic design solutions: Scheme A - separating substations, causing problems, in an individual block; Scheme B - separating independent 110 kV closed electric power grids; Scheme C – splitting the meshed system into two independent circuits. It is proved that the most efficient solution is Scheme C, which is characterized by a lower number of unscheduled downtimes of the facilities by mitigating the effects of faults in one of meshed systems on a continuous operation of shops powered from the neighboring grid; eliminated risks of simultaneous stops of all or the majority of metallurgical shops of the works during short circuits in 110 kV grids; and a considerable reduction in short circuit currents and active losses in 110 kV industrial grids. An aggregate benefit from the proposed measures aimed at revamping of the electrical grid of metallurgical units by applying schematic design solutions is over USD750,000/year.

## INTRODUCTION

Ferrous metallurgy is one of energy-consuming industries in the Russian Federation. A main share of the production potential is attributed to the largest companies, such as PJSC Magnitogorsk Iron and Steel Works, PJSC Novolipetsk Steel, PJSC Severstal and others. Since 1994, there is a positive trend in a growth of output and extension of a range of finished products with higher consumer properties. Sustainable leading positions in the metal market result from a large-scale introduction of new technologies and revamping of metallurgical units [1, 2]. As reported by [3], total steel production in CIS in 2017 reached 100,933 thousand tonnes, with 70% of steel produced

*2nd International Conference on Energetics, Civil and Agricultural Engineering 2021 (ICECAE 2021)*
AIP Conf. Proc. 2686, 020005-1–020005-13; https://doi.org/10.1063/5.0113363
Published by AIP Publishing. 978-0-7354-4278-8/$30.00

in Russia. Large-scale production determines a need for an integrated approach to resources, including expenses for electricity and reorganization of the electric power supply systems of metallurgical plants.

Multi-stage production at large metallurgical plants includes steel melting in basic oxygen and electric arc furnaces; steel treatment in ladle furnaces; and casting using billet and slab continuous casting machines. Section mills, two-stand reversing mill, galvanizing and color coating lines, hot and cold rolling mills are introduced into operation and revamped [4, 5]. As a result of the technical upgrading program, annual steel output reaches 12 m t for a company. Measures aimed at the upgrading of metallurgical plants entailed a growth of electric load and electricity consumption. At present, half-hour maximum load is over 1 m kW. Changes in a structure and quantity of electric energy receivers ("receivers") resulted in a share of electricity consumption at steelmaking and rolling shops increased from 25% to 40%. Such shops are equipped with energy-consuming process and power electrical facilities with abruptly variable and impact loads, and many receivers, highly sensitive to voltage dips in the grid.

The most considerable failures in terms of a scope and gravity of consequences of voltage dips for Russian industrial plants are short circuits and atmospheric electrical discharge in 110-220 kV grids. Short circuits in a plant distribution system entail voltage dips, whose depth is determined by a distance to a point of short circuit and structural features of the electric power supply. Voltage dips can give rise to a stop of production shops and, in some cases, break down a sustainable parallel operation of electrical stations and the energy system. An industrial plant experiences over 100 cases of deep voltage reduction per year, about 40% of them are due to short circuits on the plant power system lines [6]. In more than half of the cases voltage dips are reasons for a simultaneous stop of three shops and over and load drop of the plant reaches 100-250 MW. An average duration of the post-accident downtime, for example, for a rolling shop is 45 minutes. When repairing equipment by replacing damaged rolls or removing a rolled strip from the strand due to voltage dips, a pause in the production process increases up to 1 hour and over. In case of unscheduled shutdowns, losses of finished products are estimated at 100-150 t of rolled sheets in first 15 minutes of a hot rolling mill and 50 t of highly profitable rolled sheets for a cold rolling mill. There are recorded cases when underproduction of the plant exceeded 3000 t of rolled products due to two failures only [2].

At present, there are some areas of theoretical and experimental studies in the Russian Federation and leading foreign countries dealing with the following challenges:

– introduction of low current electronic and microprocessor equipment in motor control centers, power semiconductor converters and other receivers with power units of electronic devices and microprocessor terminals highly sensitive to a voltage value [7-10],

– influence of voltage dips on equipment damage and faults in processes of industrial plants [11-14],

– preparation of criteria and algorithms to evaluate costs for recovery of a steady operation of continuous production facilities after emergency situations attributed to voltage dips in power systems [15-18].

The research is aimed at increasing reliability of electric power supply at major iron and steel plants applying schematic design solutions for branch distribution systems.

To achieve the goal, the authors analyzed the features of branch electric power distribution systems at a large metallurgical plant; considered options of revamping of a grid structure to increase reliability; and carried out experimental research on splitting 110 kV meshed system.

## DESCRIPTION AND FEATURES OF BRANCH ELECTRIC POWER DISTRIBUTION SYSTEMS AT THE METALLURGICAL PLANT

The electric power supply system of the industrial plant has 35-220 kV branch distribution circuits and 110 kV meshed system (Fig. 1). The meshed system combines shop electric power plants and mains of the Russian power systems operating in parallel. Junction points of the meshed system are connected with grid areas consisting of radial and backbone transmission lines. 35-220 kV power grids are structured as overhead lines and inserted cables, 170 m-2.5 km long. Total length of overhead lines per circuit reaches 400 km, and cable transmission lines, up to 8,000 km. High voltage grids have connected step-down and distribution substations, over 30 of them have a primary voltage of 35-220 kV. Total installed capacity of the transformers reaches 6,000 MVA.

Legend for Fig. 1: SS *N* is an N numbered substation; SHPP is a superheater power plant; SBPP is a steam blower power plant; GEPP is a gas engine power plant; CHP is a combined heat and power plant; CEP is a central electric plant.

Energy security of large plants is ensured by in-house electricity generation. For example, electricity needs of one of the largest metallurgical plants are satisfied by the combined heat and power plant (CHP), the central electric plant (CEP), steam blower power plant (SBPP), gas engine power plant (GEPP), the mini-CHP plant and the superheater power plant (SHPP) (Table 1). Intra-company sources cover electrical energy consumption of the plant by 80-85%.

Electric power stations are equipped with 27 turbo generators with a nominal capacity of 4 to 60 MW and a voltage of 3 to 10 kV. Their aggregate operating capacity is up to 650-670 MW. A share of required fuel is replaced with secondary energy resources, namely blast furnace and coke oven gases, waste steam from basic oxygen furnaces.

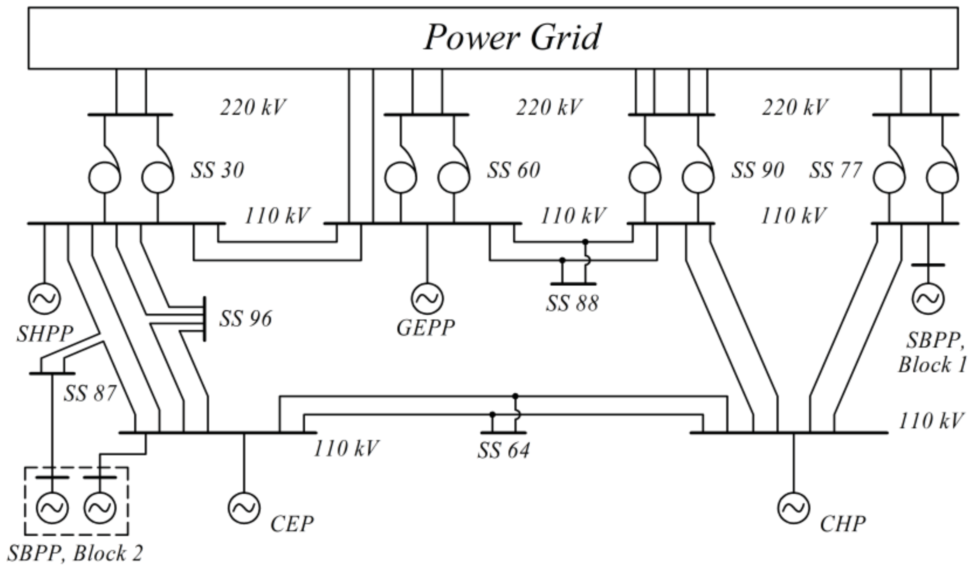


**FIGURE 1.** Scheme of the meshed system at the industrial plant

**TABLE 1.** Parameters of the electric power stations at the industrial plant

| **Description** | **Main data** | |
|---|---|---|
| | **Installed capacity, MW** | **Year of commissioning** |
| CEP | 193 | 1931 |
| SBPP | 102 | 1931 |
| CHP plant | 330 | 1954 |
| Mini-CHP plant | 4 | 2000 |
| SHPP | 15 | 2003 |
| GEPP | 18 | 2005 |

With a gradual commissioning of modern facilities and highly-automated complexes, we face challenges of ensuring reliability of electric power supply. An external and intra-plant power supply system does not correspond to large-scale tasks on the revamping of metallurgical facilities. Undercapacity of power equipment at some substations and overhead lines make it possible to connect new consumers. Power flow control modes have high losses in capacity and electricity. Voltage dips as a result of short circuits in 110 kV grids are accompanied by large-scale shutdowns of receivers and, as a consequence, emergency shutdowns of processes at metallurgical shops.

To increase reliability and economic efficiency of power supply, high voltage grids were scheduled to be revamped in two areas: upgrading of power equipment, control and safety systems of substations; and extension and changes in the configuration of 110-220 kV grids.

The reported number of faults in 110 kV grids of the works under consideration is within 67-84 incidents per year. A special group is formed by faults annually resulted from short circuits in 110 kV grids with a constant frequency of 7 to 9 events. Deep voltage reduction on clamps of receivers of the consumer is a main reason for stop of drives and interruption of a continuous production process at metallurgical shops.

A sudden shutdown of technological complexes in all or the majority of the shops as a result of short circuits in grids is characterized by a sharp and deep load drop, which is accompanied by long downtime of equipment. Uncontrolled load drop is determined by switching off the receivers in reaction of microprocessor control systems to reduced voltage and de-energized relays and contactors in drive control circuits.

Table 2 contains data on load reduction *ΔP* and time *T* spent for recovery of a process to a steady state for one calendar year.

Reasons for short circuits are lightning strokes, explosions of cable joints, breakage of an overhead earth wire, false switching of earthing switches on busbars and sparkover of a high voltage bushing of 40 MW transformer.

Table 2 shows that a load drop is within a broad range of 48 to 280 MW, maximum value is 35-40 % of the average daily load of the plant, and a downtime period varies from 10 to 90 minutes. A determining factor in increasing a downtime period is attributed to consumers of electric arc furnace and rolling shops. Revamped process lines are equipped with modern automated machines, whose receivers have high unit capacity, and are more sensitive to voltage dips in the grid.

**TABLE 2.** Parameters of major emergency events at the industrial plant

| Description of events | | |
|---|---|---|
| **Location** | **ΔP, MW** | **T, min** |
| 110 kV overhead lines SS 30 - SS 29*, No.1 | 280 | 75 |
| 110 kV overhead lines SS 87 - CEP | 181 | 65 |
| 110 kV overhead lines SS 30 - SS 60, No.1 | 229 | 90 |
| 40 MVA transformer, CHP | 204 | 80 |
| 110 kV busbars, CEP | 117 | 20 |
| 80 MVA transformer, CHP | 230 | 90 |
| 110 kV overhead lines SS 90 - SS 63*, No.2 | 130 | 70 |
| 110 kV cable transmission lines SS 30 - SS 60, No.2 | 48 | 10 |

*SS 29 and SS 63 are the shop substations, not shown in Fig.1.

An intense load drop at the plant as a result of short circuit on overhead lines is due to some factors:

- synchronized forced stops of main drives of rolling mills in four rolling shops, and
- undue shutdown of electric arc furnaces and ladle furnaces in the electric arc furnace and basic oxygen furnace shops, while decreasing load from 170 MW to 34 MW.

**TABLE 3.** Short circuit currents in junction points of 110 kV grid for an original power system diagram

| Junction points of the system | Short circuit current, kA | |
|---|---|---|
| | **Single-phase** | **Three-phase** |
| CHP | 41.6 | 43.4 |
| CEP | 46.5 | 44.5 |
| SS 30 | 47.1 | 44.5 |
| SS 60 | 43.0 | 42.2 |
| SS 77 | 33.9 | 36.8 |
| SS 90 | 33.3 | 34.1 |

Features of building the power grid for a metallurgical plant are as follows:

1) the power grid is 110 kV meshed system concentrated to the utmost extent on a limited area,
2) it is allowed to have a symbolic representation of the power grid of the metallurgical plant as a busbar with connected step-down substations of consumers, electric power plants and coupling autotransformers with 220 kV system-forming grids (Fig. 1),
3) the power grid structure includes receivers located as close as possible to a powerful system source, major generating facilities of own electric power plants, short transmission lines as a heavy gauge wire.

The above features of the power grid result in a state when short circuit in any point is accompanied by a flow of dangerous high currents and a deep reduction of voltage [19, 20, 21].

It should be noted that development of 110 kV grids and growth of generating facilities at electric power plants of the industrial company entailed a growth of single- and three-phase short circuit currents, significantly exceeding set points of circuit breakers (Table 3). Operating circuit breakers with a breaking capacity of 25, 31.5 and 40 kA considerably decreases reliability of the grid at the plant. To increase reliability of the power supply system by replacing the existing devices with circuit breakers with higher breaking capacity is not feasible due to high expenses.

A negative effect of emergency events such as short circuit on process and switching equipment of the substations is mitigated by changing a configuration of the grid of the plant. At present, it is of interest to analyze the schematic design solutions that increase reliability of the power supply system of the plant considering the structural features for a long operation period and requiring low capital expenses.

## A MODERNIZED STRUCTURE OF BRANCH ELECTRIC POWER DISTRIBUTION SYSTEMS AT THE METALLURGICAL PLANT APPLYING THE SCHEMATIC DESIGN SOLUTIONS TO IMPROVE RELIABILITY

Switching equipment in 110 kV lines offers several options of modernization of the meshed electric power supply system at the plant.

### *REVAMPING BY SEPARATING PROBLEM SUBSTATIONS IN AN INDIVIDUAL BLOCK (SCHEME A)*

Regarding Scheme A, two substations SS 60 and SS 90 are separated by breaking 110 kV transmission lines into SS 30 - SS 60 and SS 90 - CHP. As a result, an original meshed grid is transferred into two independent circuits with a two-way feed (Fig. 2): SS 60 - SS 90 (*Circuit I*); SS 30 - CEP - CHP - SS 77 (*Circuit II*).

These circuits are closed on two 500/220 kV system substations.

When grids are revamped according to Scheme A, short circuit currents decrease by 20-35% on busbars of SS 60 and SS 90 only (Table 4).

**TABLE 4.** Short circuit currents in junction points of 110 kV grid for the system with a two-way feed according to Scheme A

| Circuit | Junction points of the system | Short circuit current, kA | |
|---|---|---|---|
| | | Single-phase | Three-phase |
| I | SS 60 | 28.6 | 27.6 |
| | SS 90 | 26.0 | 25.6 |
| II | SS 30 | 34.8 | 33.9 |
| | CEP | 36.8 | 36.5 |
| | CHP | 32.8 | 36.6 |
| | SS 77 | 30.1 | 33.3 |

The strength of Scheme A is building a barrier to protect a group of core process shops against voltage dips, whose occurrence is attributed to faults on long 110 kV overhead lines for agricultural purposes (FC). These lines bordering with SS 60 and SS 90 (Fig. 2) become closed off from an industrial part of the grid of the city energy hub.

Weaknesses of the grid revamping according to Scheme A are as follows:

1) short circuit currents in junction points of SS 30, SS 77, *CHP* and *CEP* are 83-90% of breaking capacity of circuit breakers installed in 110 kV *SG (SG- switchgear),*

2) failure to provide transfer capability of *110 kV lines* in post-fault modes of one-way communication between two electric power plants (*CHP, CEP*) and the energy system, when switching off SS 30 and SS 77 from 220 kV grid, and some areas of the grid SS 30 - *CHP* - *CEP* - SS 77 require strengthening, and

3) potential loads on transmission lines exceeding acceptable continuous heating capacity.

The revamping according to Scheme A does not contribute to reaching a goal of reducing risks of a simultaneous shutdown of all or the majority of shops, as residual voltage in junction points of the grid *SS 30 - CHP - CEP - SS 77* is low.

### *REVAMPING BY SEPARATING INDEPENDENT 110 KV CLOSED ELECTRIC POWER GRIDS (SCHEME B)*

The mode with separated independent closed electric power grids is provided by switching off bus coupler circuit breakers at 110 kV SG of substations SS 30, SS 60, SS 77, SS 90, as well as CHP and CEP (Fig. 3).

Legend for Fig. 3: *BSB* N is a bus section breaker.

When transferring from a parallel operation to a separate operation of autotransformers and transmission lines, two absolutely similar meshed grids are formed maintaining an original configuration. In case of short circuit in a separate circuit, capacity of in-feed sources will be lower and equivalent resistance with regard to a system source will be higher. Thus, short circuit currents decrease to the level when circuit breakers reliably localize a point of failure (Table 5).

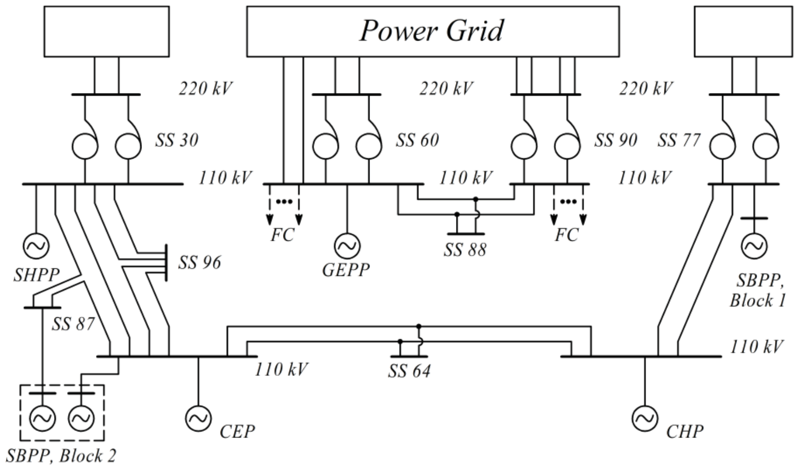


**FIGURE 2.** Revamping by separating the 110kV meshed system at the industrial plant into two circuits (Scheme A)

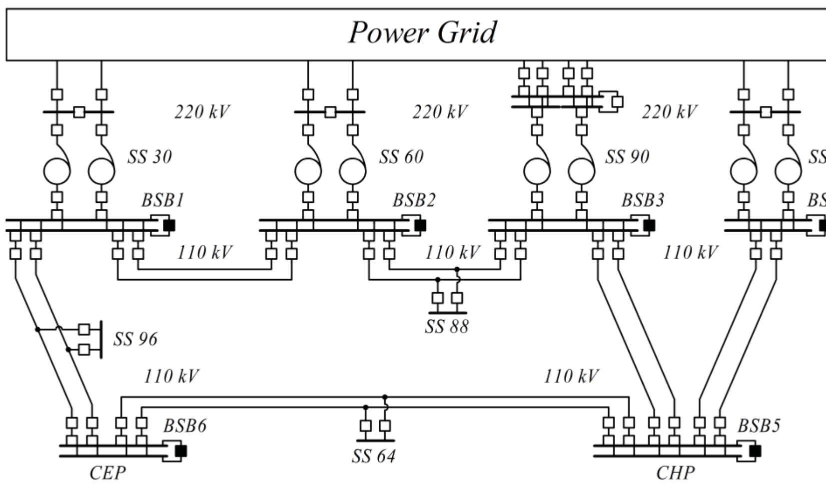


**FIGURE 3.** Separating with two independent 110 kV meshed electric power grids (Scheme B)

**TABLE 5.** Three-phase short circuit currents in meshed grids according to Scheme B

| Grid No. | Current in a point of short circuit, kA | | | | | |
|---|---|---|---|---|---|---|
| | **CHP** | **CEP** | ***SS 30*** | ***SS 60*** | ***SS 77*** | ***SS 90*** |
| 1 | 32.7 | 30.0 | 33.0 | 27.9 | 23.4 | 20.2 |
| 2 | 33.1 | 30.4 | 33.2 | 28.0 | 23.6 | 20.3 |

It should be noted that schematic design solutions according to Scheme B do not minimize risks of a sudden stop of a group of metallurgical shops. The reason is maintaining mutual weak influence of two 110 kV grids through connections formed by 220/110 kV autotransformers and actuated bus coupler circuit breakers in 220 kV SG of SS 30, 60, 77, 90. Therefore, voltage decreases in both grids, if short circuit occurs in one of them. Residual voltage in the running system is higher than in the system experiencing short circuit, but not enough for a normal operation of receivers.

Let us assume that bus coupler circuit breakers are disabled not only in 110 kV SG, but also in 220 kV SG of SS 30, 60, 77, 90, and transmission lines and autotransformers operate separately both in 110 kV and 220 kV grid. Short circuit in one of 110 kV grids entails deep voltage dips in junction points of the second grid. However, this fact does not interfere with the development of the fault, having a high probability of stopping many or all metallurgical shops at the same time.

A distribution system of any of the shops is designed and built so that its operating power supply sources are both meshed 110 kV grids. Consequently, sudden shutdowns of receivers and following stops of the production process occur irrespectively of a grid experiencing short circuit.

Scheme B has a more complicated operation of grids, when adjusting safety and system automation, and control of grid equipment and power supply modes. Electric power losses will increases by 25% or higher at the same volumes of transferred electric power, because current load of the grid elements will show an existing unequal distribution of loads of receivers between 110 kV busbar systems of substations and electric power plants.

*REVAMPING BY SPLITTING THE MESHED SYSTEM INTO TWO INDEPENDENT CIRCUITS (SCHEME C)*

Figure 4 shows a diagram of the meshed system with independent circuits. Practical operability of the proposed solution is confirmed by analyzing grid parameters in normal, repair and emergency modes. To evaluate an option of splitting the meshed system into two independent circuits, we used information about actual modes collected in seven years in the automated power equipment control system.

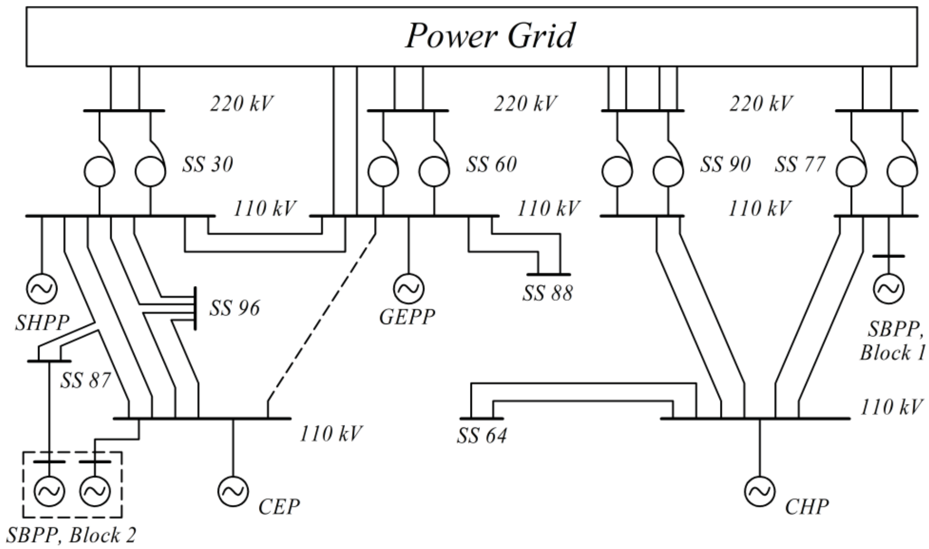


**FIGURE 4.** The two-circuit configuration of 110 kV meshed systems (Scheme C)

Strengths of Scheme C are a mutual location of substations SS 30, 60, 77, 90 and CHP and CEP on site, steady values and directions of flows of capacity by lines of the meshed system, a low load ratio of 220/110 kV autotransformers.

We revealed points of a prudent splitting of the meshed system under consideration:

- the first breaking is to be between SS 60 and SS 90, while keeping to feed SS 88 from S 60, and
- the second breaking is to be on 110 kV transmission line between CEP and SS 64 (Fig. 4).

As a result, the electric connection between two grid areas CEP - SS 30 - SS 60, on the one part, and CHP - SS 77 - SS 90, on the other part, at 110 kV is fully eliminated. However, these two circuits remain interconnected, but only through 220 kV grids of the external power system.

The simulation proved the expected positive results of the suggested modernization of the electric power supply system:

1) Scheme C will not entail a considerable redistribution of capacity in normal modes or result in overloads of lines and autotransformers (Table 6 and Table 7),

**TABLE 6.** Load of 110kV line in a normal mode for Scheme B and Scheme C

| No. | Continuous current carrying capacity, % | | |
|---|---|---|---|
| | Grid elements | Scheme B | Scheme C |
| 1 | CEP - SS 96 | 17 | 18 |
| 2 | SS 30 - SS 60 | 15 | 17 |
| 3 | CHP- SS77 | 18 | 18 |
| 4 | CHP - SS 90 | 16 | 18 |
| 5 | CHP - SS 64 | 3 | - |
| 6 | SS 90 - SS 88 | 4 | - |

**TABLE 7.** Load of 220/110 kV autotransformers in a normal mode for Scheme B and Scheme C

| No. | Autotransformer load, % | | |
|---|---|---|---|
| | Grid elements | Scheme B | Scheme C |
| 1 | SS 30 | 39 | 39 |
| 2 | SS 90 | 45 | 45 |
| 3 | SS 77 | 26 | 27 |
| 4 | SS 90 | 42 | 41 |

2) current loads of the transmission lines and other transmission equipment do not exceed continuous current carrying capacity in post-emergency modes: load of main 110 kV transmission lines in post-emergency modes is within a range of 13-52% of maximum continuous current carrying capacity of wire heating; regarding post-emergency modes initiated by switching off 500 kV and/or 220 kV transmission lines, and/or 500/220 kV and 220/110 kV autotransformers in system-forming grids of the city load center, load of 110 kV grids of the plant is also within an acceptable range of 17 to 72%,

3) voltage in elements of the double-circuit modified grid in normal, repair and post-emergency modes is under GOST 32144-13 (EN 50160:2010),

4) dierct relations between industrial power plants and 220 kV regional power system are kept in two directions, with CHP operating parallely with a system source through substations SS 77 and SS 90, and CEP, through SS 30 and SS 60,

5) no possibility of an autonomous operation of CHP and CEP at the same time in case of short circuit in 110 kV grid, as residual voltage on 110 kV busbars of the electrc power plant in the undamaged grid exceeds the setpoint (50 kV), which determines threshold conditions to activate the dividing emergency automation system,

6) no factors to create circuits from 110 kV transmission line and equipment for equalizing currents between two new meshed grids,

7) it becomes easier to adjust relay protection at SS 64 and 88, which were junction points of the meshed system, and after breaking receive power fron one direction.

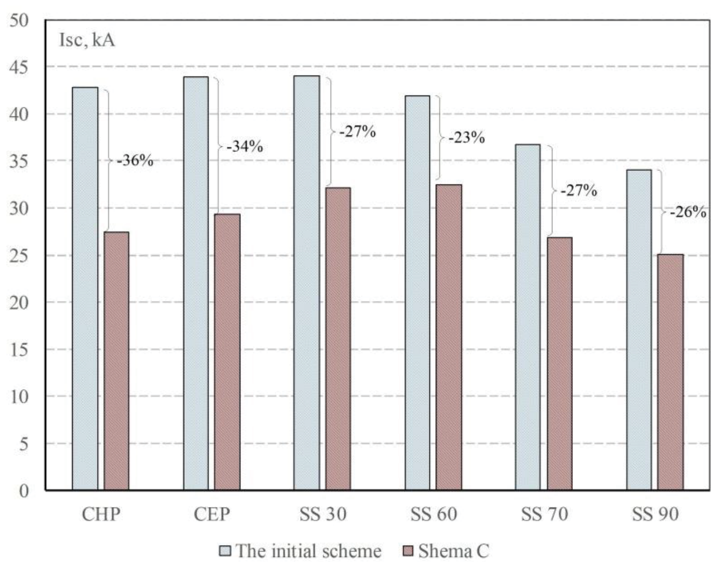


**FIGURE 5.** Chart of three-phase short circuit currents in junction points of 110 kV grid

Thus, the conversion of 110 kV meshed system into two independent circuits according to Scheme C with a simple configuration does not have insoluble negative consequences, but to increase the transmitting capacity of the line CEP - SS60 from 445A to 690A, a steel reinforced aluminum cable section is to be increased from 150 $mm^2$ to 300 $mm^2$ at a section 4.5 km long. Positive effects from the conversion of the scheme are as follows:

- by dividing 110 kV grid in the stated breaking points, we create maximum effect in settling problems of power supply of industrial consumers, which is revealed in a deep reduction of short circuit currents in all junction points of the grid by dividing and eliminating local generating sources (CHP or CEP+SBPP) with a capacity of 270-330 MW from the direct feeding of any point of short circuit (Table 8).

- maximum short circuit currents (Isc) are lower than breaking currents of installed circuit breakers (Fig. 5) and existing circuit breakers can be replaced with circuit breakers with a breaking capacity of 50 kA according to the schedule and in less tight time,

- in case of a failure, voltage dips in the grid with short circuits remain deep (Table 9), but voltage reduction in a neighboring closed circuit will not be fatal or entail deactivation of the receivers. A production process is not terminated at shops with power supply from the running system.

An option of revamping the power grid according to Scheme C is a schematic design solution increasing stability of receivers and reducing short circuit current to allowed values.

**TABLE 8.** Short circuit currents in junction points of 110 kV grid for Scheme C

| **Junction points of the system** | **Short circuit current, kA** | |
|---|---|---|
| | **Single-phase** | **Three-phase** |
| CHP | 26.2 | 27.7 |
| CEP | 32.2 | 29.5 |
| SS 30 | 35.7 | 32.3 |
| SS 60 | 34.7 | 32.4 |
| SS 77 | 25.0 | 26.9 |
| SS 90 | 25.4 | 25.1 |

**TABLE 9.** Residual voltage in 110 kV double-circuit grid at three-phase short circuit

| **Short circuit point** | **Residual voltage, kV** | | | | | |
|---|---|---|---|---|---|---|
| | **CHP - SS 77 - SS 90** | | | **CEP - SS 30 - SS 60** | | |
| | **CHP** | **SS 77** | **CHP** | **SS 77** | **CHP** | **SS 60** |
| CHP | 0 | 16.1 | 48.7 | 94.8 | 91.0 | 90.2 |
| SS 77 | 9.3 | 0 | 51.3 | 93.5 | 89.5 | 88.7 |
| SS 90 | 38.2 | 46.1 | 0 | 87.7 | 83.0 | 82.0 |
| CEP | 95.7 | 96.1 | 93.6 | 0 | 6.2 | 18.7 |
| SS 30 | 95.1 | 95.6 | 93.0 | 19.1 | 0 | 17.3 |
| SS 60 | 93.7 | 94.2 | 91.5 | 27.3 | 14.0 | 0 |

## A COMPARISON OF RESIDUAL VOLTAGE IN THE ORIGINAL AND DOUBLE-CIRCUIT SCHEMES OF 110 KV MESHED SYSTEMS ACCORDING TO SCHEME C

**TABLE 10.** Correlation coefficients between residual voltages for two options of schemes (the original scheme and Scheme C)

| Pair correlation coefficients | | |
|---|---|---|
| Pairs of the facilities under study | Original mesh circuit | Double-circuit scheme (Scheme C) |
| CHP - CEP | 0.752 | -0.920 |
| CHP - SS 30 | 0.633 | -0.919 |
| CHP - SS 60 | 0.289 | -0.907 |
| CHP - SS 77 | 0.730 | 0.980 |
| CHP - SS 90 | -0.508 | 0.676 |
| CEP - SS 30 | 0.870 | 0.982 |
| CEP - SS 60 | 0.590 | 0.941 |
| CEP - SS 77 | 0.330 | -0.910 |
| CEP - SS 90 | -0.441 | -0.880 |
| SS 30 - SS 60 | 0.765 | 0.970 |
| SS 30 - SS 77 | 0.194 | -0.666 |
| SS 30 - SS 90 | -0.350 | -0.864 |
| SS 60 - SS 77 | 0.140 | -0.500 |
| SS 60 - SS 90 | -0.163 | -0.853 |
| SS 77- SS 90 | -0.820 | 0.690 |

To evaluate reliability of two options of the grids subject to voltage dip, we analyze results given in Table 3 and Table 8. To determine how remote short circuit influences the voltage dip value at main stations and 110 kV substations, we applied the Pearson correlation coefficient. The results are given in Table 10. The analysis showed that facilities located in different semi-rings had a strong negative correlation. This means that in over 85% of cases short circuit in one semi-ring will not produce a significant influence on facilities in another semi-ring.

Residual voltages for critical facilities are calculated using TKZ-3000 software:

1) cold rolling mill 2000 (SS 31, SS 31A),
2) cold rolling mill 2500 (SS 94, SS 41),
3) the electric arc furnace shop (SS 77, SS 04), and
4) the basic oxygen furnace shop (SS 29, SS 29P, SS 96, SS 96K).

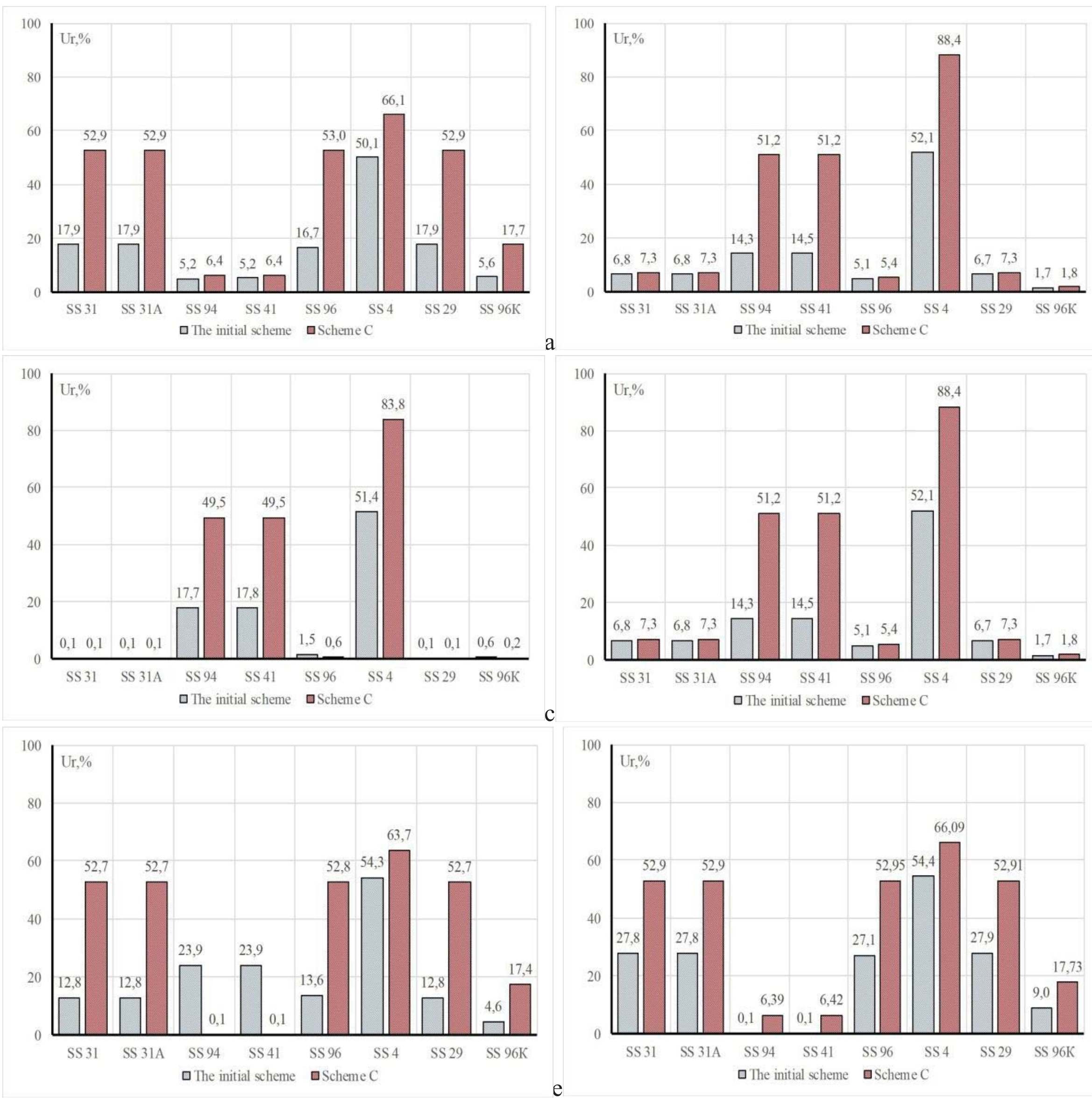


**FIGURE 6.** Shares of residual voltage in junction points of 110 kV grid: a – CHP; b – CEP; c – SS 30; d – SS 60; e – SS 77; f – SS 90

Residual voltages for the original mesh circuit and the transformed double-circuit scheme (Scheme C) of 110 kV grid are given in Table 11.

**TABLE 11.** Residual voltage at the most critical facilities

| Short circuit point | Residual voltage at the substation of the shop, kV | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **SS 31** | **SS 31A** | **SS 94** | **SS 41** | **SS 96** | **SS 04** | **SS 29** | **SS 96K** |
| CHP | 19.7/58.2 | 19.7/58.2 | 5.69/7.03 | 5.73/7.06 | 18.4/58.3 | 55.1/72.7 | 19.7/58.2 | 6.2/19.5 |
| CEP | 7.43/7.99 | 7.43/7.99 | 15.7/56.3 | 15.9/56.3 | 5.55/5.98 | 57.3/97.2 | 7.4/7.99 | 1.9/2.0 |
| SS 30 | 0.13/0.12 | 0.13/0.12 | 19.5/54.5 | 19.6/54.5 | 1.65/0.6 | 56.5/92.2 | 0.1/0.12 | 0.6/0.2 |
| SS 60 | 14.1/10.6 | 14.1/10.6 | 26.3/53.9 | 26.3/53.9 | 15.0/11.0 | 59.7/905 | 14.1/10.6 | 5.0/3.68 |
| SS 77 | 34.4/57.1 | 34.4/57.1 | 34.5/34.2 | 34.5/34.2 | 34.5/57.1 | 67.6/77.7 | 34.4/57.1 | 11.5/19.1 |
| SS 90 | 30.6/58.0 | 30.6/58.0 | 0.09/0.12 | 0.12/0.15 | 29.8/58.1 | 59.8/70.1 | 30.7/58.0 | 9.9/19.1 |

The numerator shows residual voltages for the initial scheme, and the denominator, for the grid according to Scheme C.

The difference in residual voltages (Ur) of two schemes is shown in diagrams in Fig. 6.

The residual voltage visualization shows that in scheme C residual voltages remain considerably higher for the receivers, operating in "the running zone".

## EXPERIMENTAL STUDIES ON DIVIDING 110 KV MESHED SYSTEM AT THE METALLURGICAL PLANT

To evaluate whether it is practical and feasible to modify the power grid of the continuously operating metallurgical plant, we planned and carried out the full-scale experiment on dividing 110 kV meshed system into two closed circuits with a simple configuration according to Scheme C.

For the purposes of the experimental research, we set the tasks:

1) prove that there are no negative consequences in distribution of currents and voltage levels in every circuit of 110 kV scheme,

2) establish a correlation between actual mode parameters of electric power supply and simulation values,

3) evaluate a threshold limit power flow from one circuit to another one, when building an electrical connection between them through 6-10 kV distribution systems by switching operations.

Upon development and modification of the existing power supply system of the plant, and adjustment of instrumentation and control equipment to register parameters in the network, the experiment was performed.

As a result of a stage-by-stage deactivation of 110kV transmission line CEP – CHP, on the part of CEP, and SS 60 - SS 90, on the part of SS 90, the meshed system was transformed into two independent single-circuit grids CEP - SS 30 - SS 60 and CHP - SS 77 - SS 90. To test for overload of 6-10 kV cable lines by power flows between 110 kV ring systems, CEP and SS 77, we also made an interconnection by several cable lines.

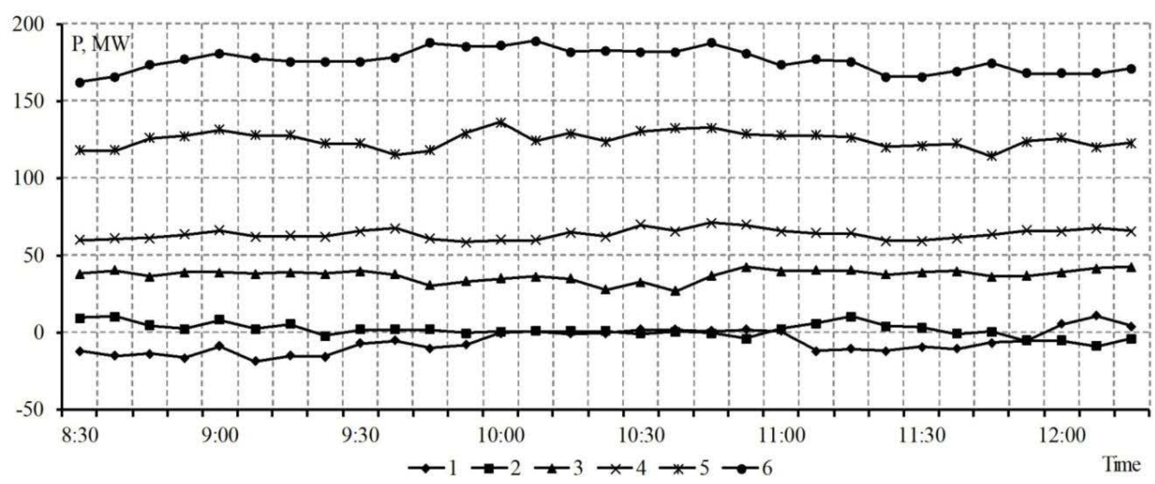


**FIGURE 7.** Tme diagram of flows of active power in 110 kV transmission lines: 1 – CHP - CEP; 2 – SS90 - SS60; 3 – CHP - SS77; 4 – CHP - SS90; 5 – SS 30 - SS 60; 6 – CEP - SS 30

The test duration was 55 minutes. In 55 minutes an original state of 110 kV meshed system was fully restored.

The results of the experiment are as follows:

1) currents in 110 kV transmission lines, connecting CHP and CEP with substations SS 30, SS 60, SS 77, and SS 90, did not exceed threshold limit values for wire heating,

2) an actual distribution of flows in 110 kV grid and simulation results at the existing ration between capacity of industrial power plants and joint loads deviated by 10 % or less,

3) diagrams showing active power P during the experiment held from 10:30 a.m. to 11:05 a.m. showed almost no differences from power fixed for six 110 kV substations before and after the experiment (Fig. 7).

The experiment showed that the proposed configuration of 110 kV grid according to Scheme C did not eliminate a risk of equalizing currents. It presents implicitly and occurs in case of an electric connection between circuits through (6) 10kV distribution system. Active power at one of sections of "the bridge", 10 kV cable line, increased from 900 kW to 7.8 MW, at the other section, from 3.1 to 10.1 MW (a higher increase is attributed to a turbogenerator of block 1 at the steam blower power plants in this area). Backward flows of power received from SS 77 through 110 kV transmission line and transmitted to 110 kV system through 110/10 kV transformer of CEP decreased to a value of such growth. No changes in flows in other branches are stated.

When current load on 10 kV cable liens increases, new maximum values of such currents do not exceed 50-65% of values allowed for a long time. Consequently, power flows from one 110 kV ring system to another one through 6(10) kV distribution system do not constitute a threat to 10 kV cable transmission lines.

Based on the experimental studies, it is fair to state that:

1) it is acceptable to divide the meshed system of the metallurgical plant into two independent circuits according to Scheme C,

2) modes of power distribution and voltage levels in the grid after the revamping satisfy technical requirements for operation of substations and transmission lines.

## CONCLUSIONS

Theoretical and practical studies in the field of the analysis and structure of power grids at industrial plants showed that every year 110 kV grids of a large metallurgical plant experience 7-9 short circuits resulting in a sharp and deep load dump accompanied by stops of the majority or all continuous production shops.

A maximum decease in aggregate electricity consumption of the large metallurgical works totals 280 MW or 40% of average daily load, and time required to restore it amounts to 1.5 h. A volume and rate of load dump at the works in case of short circuit depend on the depth and duration of voltage dips, which are determined by the configuration of meshed systems. A dangerous, high level of short circuit currents (up to 47 kA) and unduly low residual voltages in junction points of 110 kV line (35-55 kV or lower) are attributed to a close location to a high-capacity system source with a considerable generation (650 MW) of industrial power plants, and a system with a meshed topology and limit concentration on a limited area.

Reliability of power supply of the receivers of metallurgical facilities is increased by simplifying a configuration of 110 kV industrial grids with respect to a short-time break in power supply and a deep voltage reduction. The most efficient, common and low-cost way to reduce short circuit currents and risks of a sudden group stop of metallurgical shops is to transform 110 kV meshed system into independent closed circuits with a simple configuration.

The full-scale experiment in the power supply system of the operating metallurgical works showed that the division of 110 kV meshed system into two grids contributes to the following:

- a lower number of unscheduled downtimes of the facilities by mitigating the effects of faults in one of meshed systems on a continuous operation of shops powered from the neighboring grid,
- eliminated risks of simultaneous stops of all or the majority of metallurgical shops of the works during short circuits in 110 kV grids,
- a deep reduction of short circuit currents in 110 kV industrial grids, and
- reduction of active losses in110 kV industrial grids by 280 kW.

The aggregate annual effect from the proposed measures to revamp the power grid of metallurgical facilities applying the schematic design solutions is determined by reducing electric power losses and emergency shutdowns of the receivers in case of voltage dips attributed to short circuits in 110 kV grids. A total economic benefit exceeds USD 750,000 per year.

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