POWER TRANSMISSION EFFICIENCY INCREASE USING CONTROLLABLE COMPACT OVERHEAD LINES

AUTHORS:

Y.G. SHAKARIAN,
DR.SCI.,
JSC "R & D FGC UES"

L.V. TIMASHOVA,
PH.D.,
JSC "R & D FGC UES"

S.N. KAREVA,
JSC "R & D FGC UES"

V.M. POSTOLATI,
DR.SCI.,
CORRESPONDING
MEMBER OF THE
ACADEMY OF SCIENCES
OF MOLDOVA

Significant transmission line capacity increase appears to be the main advantage of compact controllable OHL. Being equipped with control devices, compact controllable OHL also provide power flux regulation according to power system regime requirements, and environmental effect mitigation due to right-of-way reduction and field strength decrease in external space of the line.

Keywords: power transmission lines, phase-to-phase approach, regime parameters regulation, OHL capacity, controllable compact overhead lines.

Growing electricity consumption requires an increased transmission capacity and controllability of modern power lines

INTRODUCTION

At the present days an intense search for new technologies aiming to provide further power transmission efficiency and reliability together with environmental impact mitigation is widely carried out. Nowadays some characteristics of operating conventional power transmission overhead lines do not fully meet up-to-date requirements, chiefly because of low capacity, control systems imperfection and appreciable negative environmental performance. Implementation of compact overhead lines, including equipped with control devices ones (compact controllable OHL) seems to be one of the most effective ways to solve above mentioned problem [1-10].

Compact controllable OHL could be designed in single-circuit, double-circuit and multiple-circuit mode. Implementation of single-circuit compact OHL allows to reach higher capacity using the same voltage level and conductor type, while double-circuit and multiple-circuit lines provide also OHL equivalent parameters regulation.

Compact OHL design involves phase configurations with minimal allowable phase-to-phase distances, optimized bundle configuration, modern tower structures with reduced phase-to-phase distances, various insulation phase-to-phase elements (insulation spacers) within the span (to provide mechanical stability of phase conductor operation under various severe weather conditions). Phase-to-phase approach results in OHL electrical and technical specs improvement and thus transmission capacity increase.

While designing double-circuit OHL phases of *different* circuits could be approached. In this case distances between approached phases of different circuits must exceed the minimal required insulation distances at maximum operating voltage and also under lightning and commutation overvoltages according to Russian State Rules for Electrical Installation (PUE-7).

Compact OHL provide electric and magnetic field parameters regulation and thereby OHL equivalent parameters and capacity adjustment.

Phase-to-phase distance reduction amplifies circuits mutual electromagnetic influence depending on phase shift (θ) between voltage systems of different circuits. Above mentioned effect is used to change and regulate equivalent parameters of each single circuit and of the line in a whole.

Phase shift between voltage systems of separate circuits can be fixed (0°, 120°, 180°) or adjustable. In the former case discreet regulation could be executed by application of appropriate connection schemes between circuits and substation buses (θ=0° and θ=120°) and implementation of transformers with different connection groups (θ=180°). In the latter case smooth regulation (0°÷180°) requires application of phase angle rotation devices (PAR), which can combine also transformer or autotransformer functions. Phase regulating devices together with controllable compensation devices application allows to execute deep regulation of equivalent transmission parameters during normal and emergency operation regimes.

Realization of compact controllable OHL technical advantages allows (being compared to conventional OHL) to obtain significant technical and economical effect, expressed in unit costs of power grid building and power transmission reduction and power system parameters improve-

INFORMATION

HISTORY OF TRANSMISSION TOWERS. FIRST DESIGNS

First transmission towers that appeared at the end of the XIX century were made out of wood. Wooden transmission towers are still used when it is economically viable. Between 1904 and 1906, a number of power lines with metal transmission towers were built in the US. The towers themselves were provided by the Aermotor Windmill Company, a US windmill producer.

The design of these US-made transmission towers featured a wide base made out of fairly thin rods. ("wide-based towers").

In the 1920–1930s, German-made transmission towers became widely popular. They featured thin, rectangular in plan, legs with a base plate placed on a solid compact foundation. This approach allowed to substantially reduce costs related to the amount of land used. In the mid XX century mass production of transmission towers made out of reinforced concrete began.

INFORMATION

COMPACT OVERHEAD LINES

The increase in transmission capacity through the use of compact transmission lines is one of the most effective ways of developing power grids as it allows to minimize transmission costs by decreasing per-unit overhead line construction costs. A more efficient use of conductor materials in power lines leads to reduction in the required land, and that creates additional economic benefits. The benefits are most noticeable in areas with high cost of land.

OHL capacity could be significantly increased by phase-to-phase distance reduction with insulating interphase spacers installation. Compact OHL operating provides higher power transmission without uprating OHL. In this case total costs decrease due to allocated land and substational equipment costs reduction.

In other countries compact overhead lines, featuring short distance between 110–500 kW phases, became widely popular. In terms of design, these can be either single-circuit or multicircuit lines, or one tower can host multiple circuits of different rated voltage.

ment. Compared to conventional overhead lines, compact controllable OHLs implementation to power grid provide the following:

- capacity increase;
- providing of wide range main regime parameters regulation;
- reduction of total costs by 10–20% per transmission capacity unit;
- OHL construction compacting and less land allocated for OHL;
- environmental impact mitigation.

Above described advantages especially increased (up to next higher rated voltage level) capacity define differences between application fields of compact controllable and conventional overhead lines and should be taken into account while OHL designing. In case of control devices application their type and power are also subjected to system functions of concrete transmission line.

Implementation of compact controllable OHL are especially reasonable in following cases:

- as intersystem transmission lines aiming to provide power fluxes between power systems (due to increased capacity and wide range regulation ability);
- as system transmission lines providing above mentioned advantages
- to provide power supply to distant major consumers;
- to provide increased power flow when voltage uprating seems to be non-efficient and another OHL building is not feasible;
- in cities or other densely populated areas (due to allocated land reduction up to 36% for 220 kV OHL and 42% for 500 kV ones).

OVERHEAD LINES' MAIN TECHNICAL PARAMETERS

Overhead lines' main technical parameters are the following:

- ohmic and inductive resistance;
- capacitive susceptance;
- conductance;
- impedance and wavelength constants;
- reactive power and natural loading;
- power vector flux;
- electric- and magnetic-field strength at the conductor surface and around the line;
- acoustic noise and radio interference levels.

Above mentioned parameters are dependent on the factors listed below:

- phase-to-phase configuration;
- single conductor cross-section;
- number of conductors per bundle;
- phase voltage values and mutual vector orientation.

OHL main technical parameter is its capacity (P), i.e. maximum active power OHL is able to transmit. Its value could be defined by following expression [12-13]:

$$P = \frac{|\dot{U}_1||\dot{U}_2|}{Z_{\text{в}} \sin \alpha_0 l} \sin \delta \quad (1)$$

where:

$\dot{U}_1, \dot{U}_2$ – voltage vectors at the beginning and at the end of the transmission line, respectively;
δ – phase-shift between voltage vectors at the beginning and at the end of the transmission line;
$Z_{\text{в}}$ – impedance (Ohm):

$$Z_{\text{в}} = \sqrt{\frac{r_0 + jx_0}{g_0 + jb_0}} \quad (2)$$

where:
$x_0 = \omega L_0$, — specific inductive resistance of OHL conductor (phase) (Ohm/km);
$b_0 = \omega C_0$ – specific capacitive susceptance of OHL conductor (phase) (mho/km);
r_0 – specific resistance of OHL conductor (phase) (Ohm/km);
g_0 – active transversal conductance of OHL conductor (phase) (mho/km), defined by following expression:

$$g_0 = \frac{\Delta P_{\text{кор.сг}}}{U^2_{\text{ном}}},$$

where $\Delta P_{\text{кор.сг}}$ – average annual corona losses, U – rated voltage;
L_0 — conductor inductivity;
C_0 — capacity of OHL conductor;
$\alpha_0 l$ – wavelength (electrical degree), where l – line length (km),
α_0 – phase shift factor (el.deg./km):

$$\alpha_0 = \omega \sqrt{L_0 C_0} \left(1 + \frac{r_0^2}{8x_0^2}\right) \quad (3)$$

When voltage values, line length and impedance are fixed, maximum possible power flux through the line is reached when $\sin \delta = 1$, i.e. when phase shift between voltages $\dot{U}_1$ and $\dot{U}_2$ is equal to 90°.

In this case expression (1) takes on following form:

$$P_M = \frac{|\dot{U}_1||\dot{U}_2|}{Z_{\text{в}} \sin \alpha_0 l} \quad (4)$$

When wave distance is equal, to 90 el. deg., $\sin \alpha_0 l = 1$ and voltage magnitudes $|\dot{U}_1| = |\dot{U}_2|$ are equal expression (4) simplifies as follows:

$$P_M = \frac{U^2}{Z_{\text{в}}} = P_{\text{нат}} \quad (5)$$

Expression (5) defines natural loading of the transmission line. This notion is rather convenient for analysis and comparison of various technical solutions during overhead transmission lines design as

COMPACT CONTROLLABLE OHL TOWERS SAMPLES

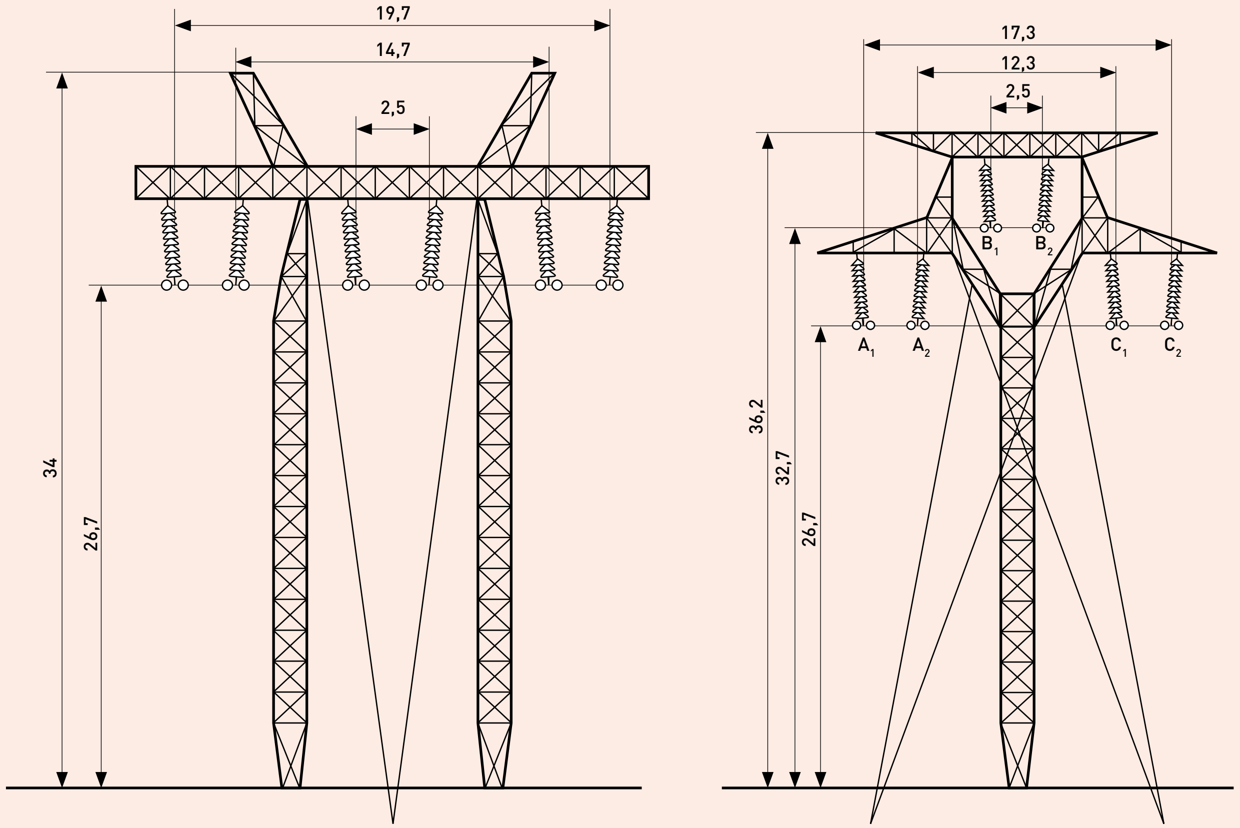

Fig. 1

it could be considered as a capacity index.

As follows from expression (5), capacity increase could be achieved by impedance reduction that on its turn could be decreased by specific inductive resistance reduction and/or specific capacitive susceptance increase, according to (2).

MAIN CONSTRUCTIVE FEACHURES OF COMPACT OHL

Main differences between **single-circuit compact and conventional OHL** of the same voltage level consist in reduced phase-to-phase distances (up to 30–50% of values typical for conventional OHL), improved design, changed bundle configuration and number of conductors per bundle increased. This causes change of electromagnetic field parameters in both interphase and surrounding space. Electromagnetic field amplification in the inner space of the line allows OHL transmission capacity increasing thus improving electrical and technical specs of the OHL. Lower electromagnetic field in the surrounding space results in environmental impact mitigation. Electrical schemes of single-circuit compact OHL do not practically differ from conventional modes. When various control devices are applied regime parameters regulation could be provided, at the same time lines' characteristic remain constant.

Double-circuit compact OHL also considerably differ from conventional ones. Each double-circuit compact OHL circuit in fact appears to be a three-phase line, like above described single-circuit compact OHL. Regime parameters regulation for double-circuit compact OHL like for single-circuit ones could be provided by control devices, implemented in grid nods. Double-circuit compact OHL circuit inherent parameters remain constant during operation.

PHASE-SHIFT DISCRETE REGULATION

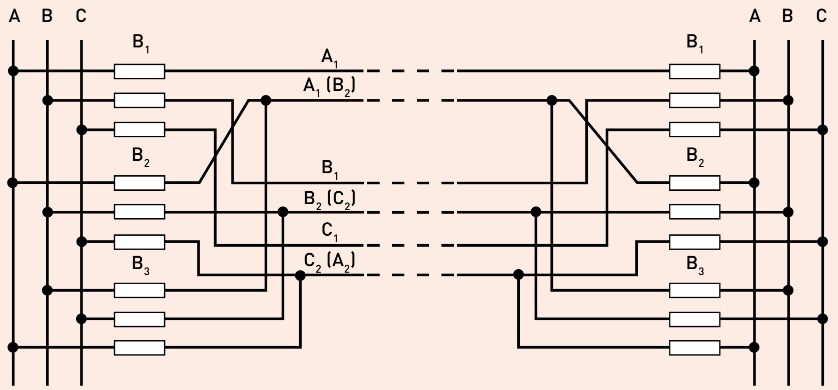

Fig. 2

PHASE-SHIFT SMOOTH REGULATION

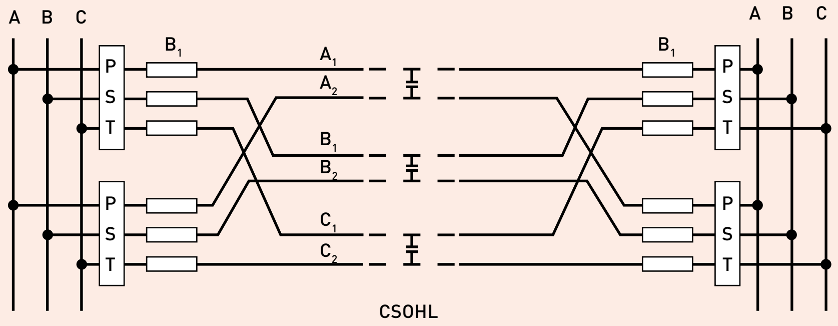

Fig. 3

Double-circuit compact controllable OHL differ from conventional ones in constructive, schematic and regime ways. Main differences consist in phase approaching in twos so in fact double-circuit compact controllable OHL consists of two pairs of approached phases of different circuits (see fig. 1).

The following technical solutions are used in **compact phase suspension** design: towers with no grounded elements in the interphase space (particularly wraparound types), special wire suspension technologies including V-shaped insulator chains or insulating cross-arms. Various insulating phase-to-phase elements (i.e. insulating spacers) can be installed in the span aiming to improve mechanical stability of closely-adjacent phase design.

Distances between approached phases of different circuits must exceed the minimal required insulation distances at maximum operating voltage and also under lightning and commutation overvoltages according to Russian State Rules for Electrical Installation (PUE-7).

Phase-to-phase distance reduction causes increased mutual electromagnetic influence between circuits, which value depends on voltage system phase shifting, i.e. relative phase displacement (θ) between three-phase voltage vector systems. This effect is used to change and regulate equivalent parameters and characteristics of each circuit and of the line in a whole. Purposeful θ regulation provides required capacity and regime parameters of transmission line. Schematically double-circuit compact controllable OHL differences from other types are in circuits connection to three-phase substational bus systems, made in a way to provide appointed phase shift (θ). Phase shift value (θ) could vary during operation within the range of 0–180°, or be fixed (0; 120°), depending on required load. Phase shifting could be achieved by appropriate phasing in OHL connection schemes (fig. 2), or by application of special phase angle rotation devices (PAR), which can combine also transformers or autotransformers functions. (fig. 3). Compact controllable OHL just like the other OHL types could be additionally equipped with regulation devices, connected either to phase-to-ground or to phase-to-phase voltage.

Double-circuit and multiple-circuit compact OHL due to circuits' mutual electromagnetic influence give an opportunity to provide line parameters self-compensation, so they are called controllable self-compensating OHL.

NATURAL LOAD OF DIFFERENT 220 KV OHL TYPES

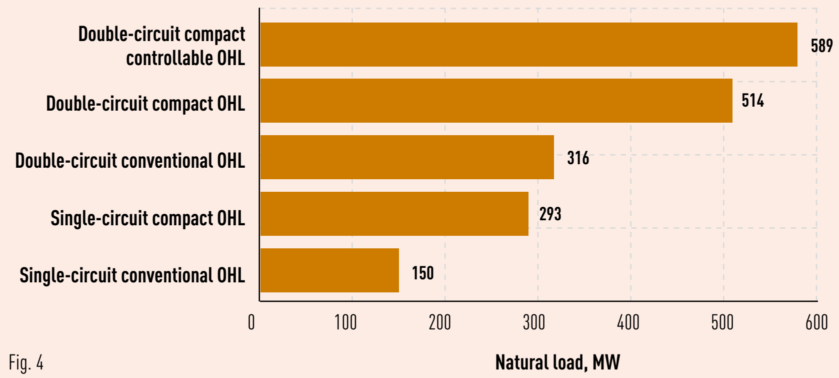

Fig. 4

TECHNICAL CHARACTERISTICS OF COMPACT CONTROLLABLE 220 KV OHL

The results of natural load comparison between conventional and compact (including compact controllable) 220 kV OHL are given on fig. 4. Fig. 4 shows that compact 220 OHL being compared with conventional ones show 1.5-1.8 times increase capacity.

The computations, carried out showed the following:

- natural load of double-circuit compact controllable 220 kV OHL is close to natural load of conventional single-circuit 500 kV OHL;
- double-circuit 220 kV compact controllable OHL unit costs do not exceed ones of single-sircuit conventional 500 kV OHL.
- significant cost saving due to difference between 220 and 500 kV control and substational equipment cost could be achieved by application of compact 220 kV OHL equipped with control devices instead of 500 kV conventional ones.

Computations of compact controllable 220 and 500 kV OHL parameters were carried out. More than 20 design cases with various number of conductors per bundle, bundle space, phase-to-phase distanses, phase-to-phase and phase-to-earth positions were studied in regimes with following phase shift values: θ=0°, θ=120° and θ=180°.

As an example, comparison between double-circuit 220 kV OHL main characterictics of compact controllable and conventional design is given below. The following technical characteristics were compared:

$P_{нат} = \frac{U^2}{Z_в}, MBm$ – natural load value;

$Q_c = U^2 b_0,\ MBAp$ – specific reactive power value;

COMPACT CONTROLLABLE 220 KV OHL TOWER “SEAGULL” (A) AND 5 CONVENTIONAL 220 KV OHL TOWER (B)

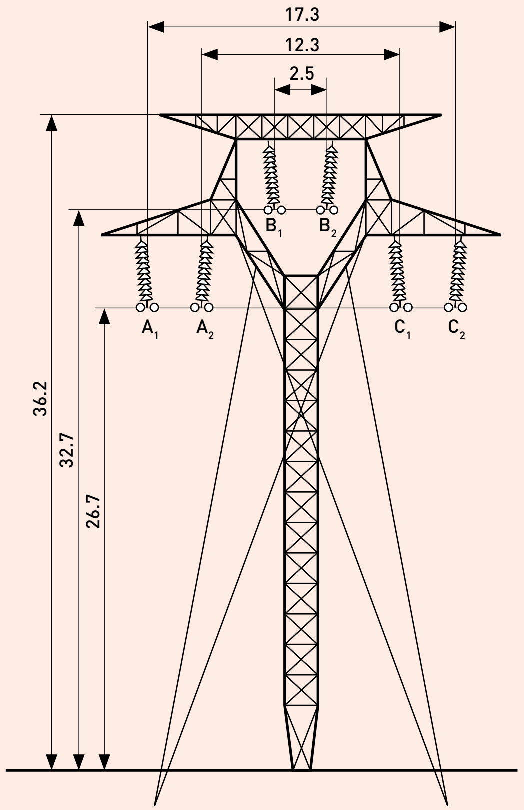

Fig. 5A

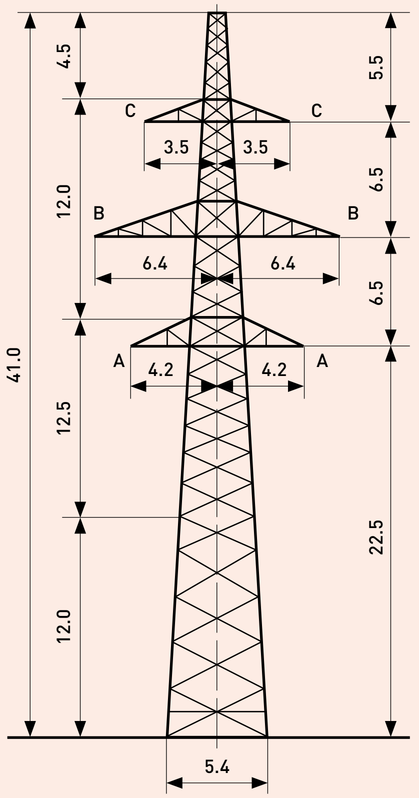

Fig. 5B

$P_{\text{нат}}/L_{\text{к}}, MBm/м$ – ratio of natural load value to right-of-way width;

$P_{\text{нат}}/S_{Al}, MBm/мм^2$ – ratio of natural load value to total conductor cross section;

- basic cost indexes of 220 kV OHL with lattice tower structures;
- cost of 1 km length 220 kV OHL and 1 MW of transmitted power (table 1).

Proposed compact controllable 220 kV OHL design is given on fig. 5A, conventional– on fig. 5B

Comparison results (fig. 6-8) show compact controllable OHL advantages and could be used for 220 kV OHL type choosing for given power facility.

Compact controllable OHL operation efficiency was studied for existing double-circuit 220 kV OHL.

For studied line following technical solutions were examined:

- double-circuit conventional 220 kV OHL (fig. 5b) with natural load equal to 305 MW, equipped with compensation devices;
- double-circuit 220 kV compact controllable OHL with delta phase configuration (fig. 5a) under phase angle equal to 120° with two ACSR conductor bundle (cross-section of single conductor is 300 mm²), with natural load equal to 524 MW

COMPARISON RESULTS BETWEEN DOUBLE-CIRCUIT 220 KV OHL MAIN CHARACTERICTICS OF COMPACT CONTROLLABLE AND CONVENTIONAL DESIGN

OHL type	Conventional 220 kV OHL (fig. 5B)	Compact controllable 220 kV OHL (fig. 5A)			
Phase shift, θ°	0°	120°		180°	
Conductor type	AC 300/66				
Number of conductors per bundle	1	2			
Impedance, Ohm	206.3	118.9	0.58*	107.8	0.52*
Natural load value $P_{\text{нат}}$, MW	304.6	529.0	1.74*	583.0	1.91*
Natural load value per one circuit P, MW	152.3	264.5	1.74*	291.5	1.91*
P/L_{row}, MW/m	5.77	9.23	1.6*	10.17	1.76*
P/S_{Al}, MW/mm^2	0.176	0.153	0.87*	0.168	0.95*
Basic cost indexes of 220 kV OHL with lattice tower structures, 103 RUR./km;	2,195	2,578.8	1.17*	2,578.8	1.17*
Cost of 1 km length 220 kV OHL and 1 MW of transmitted power, 103 RUR /MW	7.2	4.87	0.68*	4.42	0.61*

Note: * – ratio of compact controllable 220 kV OHL parameter to the respective parameter of conventional OHL.

Table 1

The researches carried out showed that according to total discounted value criterion implementation of double-circuit compact controllable OHL for 220 kV transmission line is more effective than conventional lines when transmission capacity exceeds 300 MW. When transmission capacity level reduces lower than 300 MW, conventional lines show better efficiency. Losses compensation expenses level (at 5,000 hours of maximum load utilization per year) for the whole region power system is considerably (approximately twice) higher for conventional lines (with single conductor) than for compact controllable OHL.

PHASE CONTROL DEVICES IMPLEMENTATION

Modern control devices, including phase regulators and longitude and transversal compensation devices can be used successfully to adjust compact OHL parameters.

One of the most effective methods of OHL parameters adjustment is phase control that provides the following:

- control of power flows (non-dependent on OHL design) in complex power grid in order to maintain required node voltages and minimize losses;
- redistribution of active power flows between parallel transmission lines with either same or different voltage ratings with opportunity to load one of them to the optimum system operating conditions;
- power grid mode optimization;

NATURAL LOAD OF DIFFERENT DOUBLE-CIRCUIT 220 KV OHL TYPES

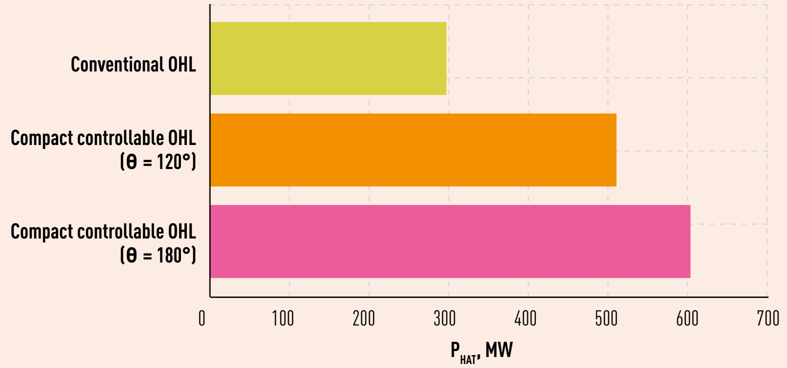

Fig. 6

RATIO OF NATURAL LOAD VALUE TO RIGHT-OF-WAY WIDTH OF DIFFERENT DOUBLE-CIRCUIT 220 KV OHL TYPES

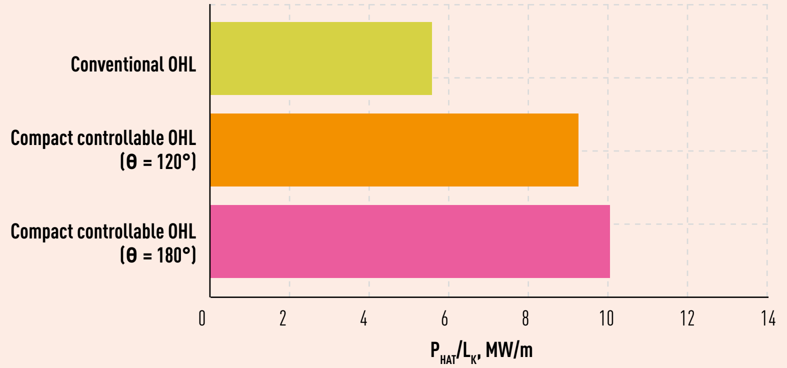

Fig. 7

RATIO OF NATURAL LOAD VALUE TO TOTAL CONDUCTOR CROSS SECTION OF DIFFERENT DOUBLE-CIRCUIT 220 KV OHL TYPES

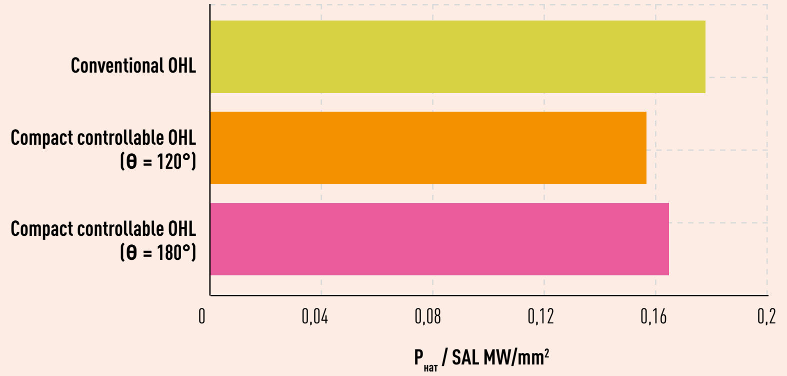

Fig. 8

- static and dynamic stability improvement;
- limit or increase of power flows according to technical or commercial requirements.

In order to provide phase adjustment in power grids, installation of special regulating transformer-type (PAR) or combined power electronic devices is required.

PARs are not aimed to increase capacity of certain overhead lines. Nevertheless, due to load optimization for every OHL in studied cross-section, its use will result in power grid capacity increase and occurs to be an effective way to increase allowable power flux through given power grid cross-section.

A phase control efficiency study for existing power grid is given below.

As a studied region a 500 kV power grid section where power flows are exchanged between interconnected power grids (OÉS) of Siberia and Ural was chosen.

Computations of different modes of the united power grid of Russia were done with a glance to the 500 kV grid development scenario in studied region, and the currently being designed 500 kV OHL (next "design transit") put into operation in particular.

Both conventional and compact single-circuit 500 kV OHL were studied. Calculation results for maximum power flow from OÉS of Siberia to OÉS of Ural are shown on fig.10. Both fixed-phase and phase-controlled (with PAR installed at the beginning of the design transit).

In the phase adjustment case different phase angles (δ_{PST}) within the range of ±60° were studied. Regime when δ_{PST} = 0° corresponds to regime without PST installation.

RESULTS OF ECONOMIC FEASIBILITY COMPARISON OF DIFFERENT DOUBLE-CIRCUIT 220 KV OHL TYPES

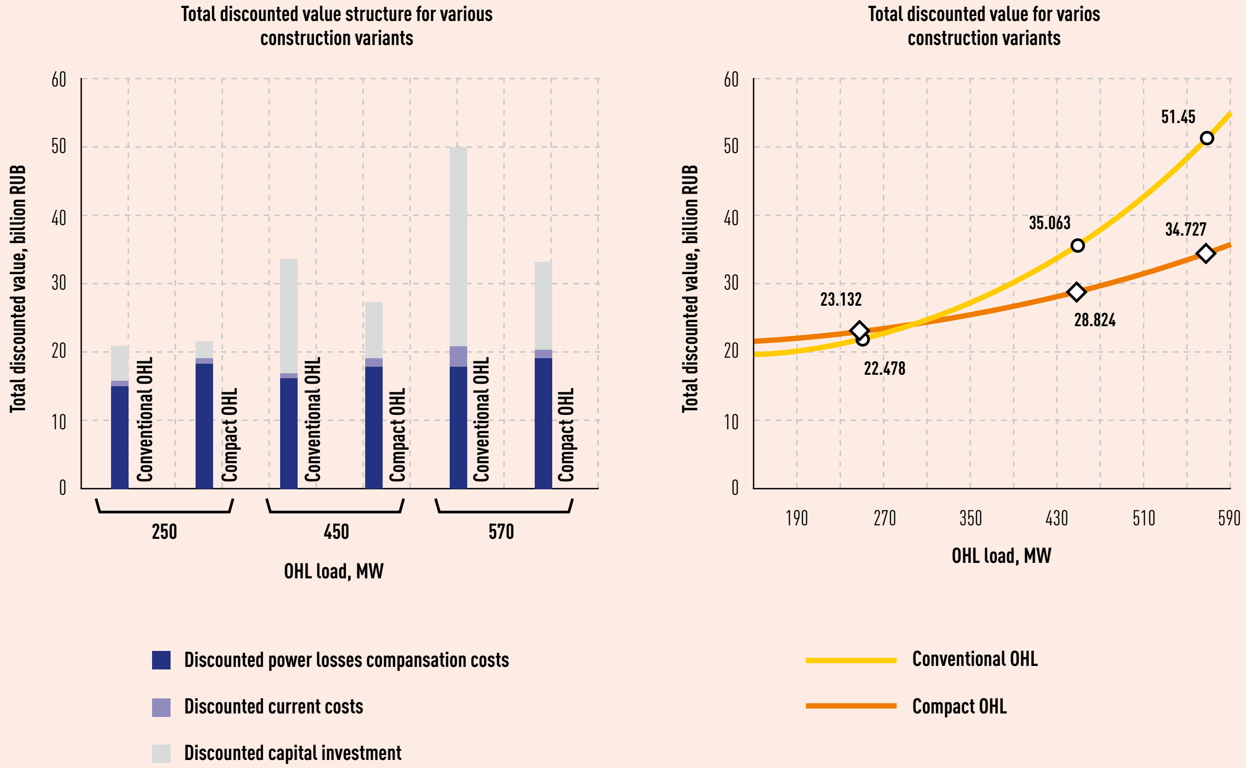

Fig. 9

As fig. 10 shows, natural power flow distribution from OÉS of Siberia to OÉS of Ural is 997 MW (when δ_{PST} = 0°) that consists of 352 MW power flow through design transit 500 kV and 645 MW power flow through 500 kV lines in Siberian and Kazakhstan power grids.

When phase was shifted due to PAR installation (δ_{PST} = ±60°), power flows through studied branches changed significantly.

When δ_{PST} is near −30°, a power flow through 500 kV OHL located on Kazakh territory is almost equal to zero, that could be considered as a regime when that OHL are switched off, and the entire power is flowing through overhead lines situated in Russia.

In this case (when δ_{PST} = −30°) power flow through design transit 500 kV OHL is 974 MW that is close to conventional 500 kV OHL under natural load.

In case of further power flows increase (over 974 MW), capacity lack will occur, if conventional OHL are chosen for design transit. In this case it seems feasible to implement compact controllable 500 kV OHL on studied transit, that will provide natural load up to 1480 MW, or to equip conventional line with with

INFORMATION

IMPLEMENTATION IN RUSSIA

A l number of design projects on constructing compact power lines have been already completed in Russia.

A 146.7 km long 330kW compact power line connecting Pskov HPP with Novosokolniki is in operation from 1993 year.

POWER FLOWS THROUGH 500 KV OHL VS. PHASE SHIFT

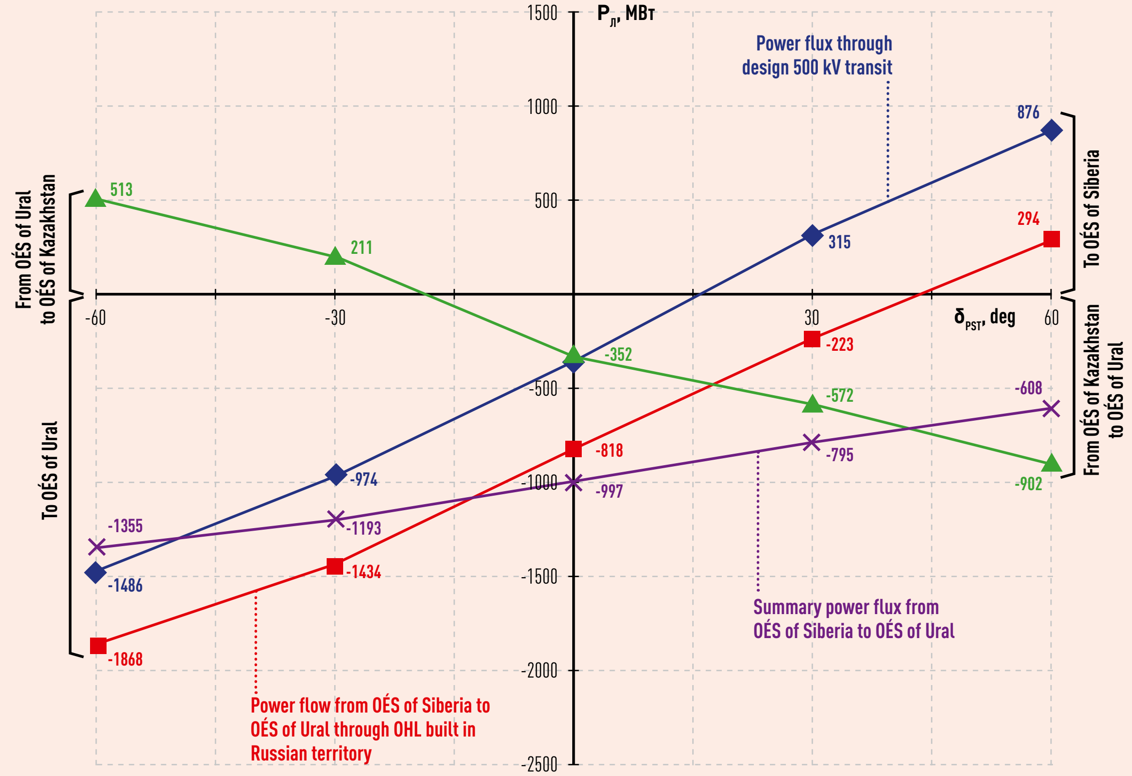

Fig. 10

longitude compensation devices of appropriate power. If necessary, the active power flows through 500 OHL could be increased up to 1,486 MW (at $\delta_{PST} = -60^{\circ}$) by phase regulator installation. Phase control efficiency during δ_{PST} changing within the range of ±60º is determined by power grid conditions.

It should be mentioned, that when $\delta_{PST} = -60^{\circ}$, a total power flow from OÉS of Siberia to OÉS of Ural though OHL located on Russian territory could reach 1,868 MW vs. 997 MW without PAR ($\delta_{PST} = 0^{\circ}$). When δ_{PST} is positive, a power flow to OÉS of Ural will drop. So at $\delta_{PST} = +15^{\circ}$, the power flow becomes equal to zero (fig. 10) and at $\delta_{PST} = +60^{\circ}$, a power flow of about 876 MW will be transmitted backwards, i.e. from OÉS of Ural to OÉS of Siberia.

It is worth mentioning that the technical and design works carried out to date together with obtained experience leads to the conclusion that it is economically feasible to use compact controllable OHL (including equipped with phase control devices ones) that provide higher capacity and power flow management according to power grid regime requirements.

CONCLUSION

Nowadays the researches, carried out, allow to draw a conclusion about economic feasibility of compact controllable OHL implementation into Russian United Power System due to provided capacity increase, environmental impact mitigaton together with right-of-way and total costs per 1 transmitted megawatt reduction.

OHL capacity could be significantly increased by phase-to-phase distance reduction with insulating interphase spacers installation.

The most effective way to improve double-circuit OHL characteristic is to develop a double-circuit compact controllable OHL, providing increased capacity and regulation ability due to amplified mutual circuit electromagnetic influence. Compact OHL operating allows to provide higher power transmission without uprating OHL. In this case total costs decrease due to allocated land and substational equipment costs reduction.

Power grid capacity increase due to implementation of compact overhead lines including, equipped with control devices ones, appears to be one of the most cost-effective ways to improve existing power grids as it helps to reduce the cost of transportation of electric energy per 1 MW of transmitted power through an increase in flow capacity, right-of-way reduction and more effective control devices application.

Compared to the conventional overhead lines, compact controllable ones provide the following:

- 1.2-1.8 times increase in capacity;
- 1.5-2 times less land allocated for OHLs at the same transmission capacity;
- ability to control power flows and their directions
- reduction of total costs by 10–20% per transmission capacity unit;
- increase in reactive power control devices' efficiency;
- use of less-capacitive and cheaper reactive power and voltage regulating devices;
- increase of OHL's mechanical strength under severe weather conditions.

REFERENCES

1. AC transmission / Postolati V.M., Brooms V.A., Astakhov Y.N., Chaly G.V., Kalinin L.P. AS 566288 (USSR). / Appl. 21/03/74. № 2006496. Publ. In BI, 1977, #27.
2. AC transmission / Postolati V.M., Venikov V.A., Astakhov Y.N., Chaly G.V., Kalinin L.P. U.S. Patent number 4001672, 1977; GDR patent number 116990, 1976; French patent number 7508749, 1977; Patent number 1488442 England, 1978; Swedish patent number 75032268, 1978; Canadian patent number 10380229, 1978; DE number 2511928, 1979; Japanese Patent number 1096176, 1982.
3. Managed power line / Astakhov Y.N., Postolati V., IT Commandant, Chaly G.V. Ed. Venikov V.A. — Kishinev Shtiintsa, 1984 – 296 p.
4. Aleksandrov GN, Evdokunin GA, GV Podporkin Parameters of overhead power lines compact design. — Electricity, 1982, #4, p. 10–17.
5. Ryzhov Y.P. Long-distance transmission of EHV: a textbook for high schools. – M .: MEI Publishing House, 2007 – 488 p., Il.
6. Postolati V.M., Bykov E.V. Efficacy of controlled self-compensated high voltage transmission lines and phase-shifting transformer type devices. Electricity, 2010, #2, p. 7-14.
7. Managed power. Issue number 8 (23), Proceedings of the Energy Institute, Academy of Sciences of Moldova for 2001-2007. Compiled d.h.t.n., academician Postolati V.M., Ph.D. Bykov E.V. – Chisinau, 2007. 234 p.
8. Postolati V.M. Scientific school in the field of controlled power. Stages of research and bibliography. Acad. Sciences of Moldova, Institute of Energy. – K .: BI 2012 (Tipogr. AȘM). – 200 c. (A series of controlled power, the book number 1, ISBN 978-9975-62-317-9).
9. Kochkin V.I., Shaqaryan Y.G. The use of flexible (controllable) AC transmission systems in power systems. — M .: Torus Press, 2011 — 312 p.
10. Dolgopolov A.G., Kondratenko D.V., Ukolov S.V., Postolati V.M. Controlled shunt reactors for electrical networks. Problemele Energeticii Regionale. Acad. Sciences of Moldova, Institute energetiki. Tipogr. AȘM, 2011, #3 (17), p. 3–23.
11. Dorofeev V. Development of the power system of Russia using the principles of active – adaptive network. Reports of the 6th International Conference TRAVEK, Moscow, 2010.
12. Venikov V.A. Long-range power. Gosenergoizdat, 1960, 311.
13. Botvinnik M.M., Strong regulation of excitation and asynchronous machines. Preface to Bronstein E.L., Shaqaryan Y. M .: Torus Press, 2011. – 160 p. ■

INFORMATION

THE MECHANISM OF PHASE SHIFTER ACTION

These are devices consisting of two transformers, placed right at the energy source: the first transformer is a controlled one and is connected in parallel to the line, while the second one is a series-wound transformer and its secondary winding is connected in series. And due to winding circuit design, voltage vector on the series winding is at a 90-electric-degree angle to the phase voltage of the grid.

By changing voltage on the series winding using the controlled transformer, one can perform turning of the total voltage vector at the beginning of the grid and thus control the angle between voltages at the beginning and at the end of the line, thus controlling the power flow.

Another possible way of implementing phase shifters is to use so called unified power flow controllers, through a chain connection of two voltage switch converters, one of which is connected in parallel to the power line, while the other one – in series.