DOI: 10.48011/sbse.v1i1.2460

Utilization of Six-Phase Systems to Reduce Technical Losses in Subtransmission Networks of Power Distribution Companies

Felipe Ribeiro Miranda*.
Carlos Frederico Meschini Almeida.*
Carlos Marcio Vieira Tahan*

**Department of Electrical Energy and Automation from Escola Politécnica of Universidade de São Paulo, São Paulo, Brazil (Tel: 55-11-99224-8936; e-mail: felipe.rm30@gmail.com / cfmalmeida@usp.br / cmv.tahan@usp.br).*

Abstract - The objective of this work is to find solutions for the reduction of energy losses in the distribution systems, focusing on the number of phase conductors. In the transmission segment, there are many surveys with six-phase systems. Due to the current regulatory framework in Brazil, the economic viability of this solution is highly restricted. In the distribution segment, the situation is different and there is little research on this alternative. The segment's valuation model (PRICE-CAP) enables greater technical and economic viability. The main objective of this work is to demonstrate the reduction in technical losses by transforming a three-phase double circuit line into a six-phase line. The work presents: the regulatory framework that shows the advantage of investing in the distribution segment; and performs simulations considering OpenDSS to illustrate the reduction of technical energy losses.

Keywords - Electric sector evaluation; Power distribution networks; Six-phase lines; Technical and Economic Evaluation; Reduction of Technical Losses.

1. INTRODUCTION

In Brazil, the transmission and distribution of electricity are predominantly by alternating current (AC) transported by three-phase lines. In transmission, for specific cases, the transport is by direct current (DC) lines. In distribution, part of the energy transport occurs by alternating current, but with only one phase, depending on the length of the network and the load supplied. The different techniques coexist in the Brazilian electric system, each option is chosen according to the technical and economic feasibility that the situation requires.

The growing utilization of electricity and the agglomeration of consumers in urban areas make the construction of new lines increasingly difficult (ISSICABA, 1988), due to costs or physical issues. Thus, power distribution companies resort to the construction of new subtransmission systems with double three-phase lines or to expand the current subtransmission from one to two lines. The lines are electrically independent, but share the same civil structure, which is enhanced for accommodating the new arrangement (PIERRE, 2005).

These new lines have brought old discussions about the optimal number of phases for power transmission and distribution. Some experts (SINGH, 2006) state that changing the topology to single six-phase lines aggregates technical gains over the current double three-phase lines. Despite the technical feasibility, current works (JARDINI, 2011) attempt to make economic comparisons between new power transmission line projects following the current regulatory framework for transmission projects. For these studies, economic viability occurs for very specific topology and distance cases.

One of the reasons for this, is the lack of six-phase transformers available on the market. There are no large manufacturers, and no recurring consumers to buy them, which increases the cost of acquisition over traditional equipment for three-phase systems. Another point is the lack of projects and qualified professionals for dealing with this type of system. Therefore, while there are technical benefits from six-phase systems, there is no economic viability for deployment in distribution systems with the current regulatory framework.

In this work, one illustrates the adoption of six-phase lines for replacing typical double three-phase lines in high and medium voltage (69 and 34.5 kV) systems. As the regulatory model of the Brazilian distribution system has a more stable methodology for capital recovery and advanced metrics to measure technical gains, greater economic viability is expected for implementing six-phase lines in the distribution networks, without losing the technical benefits already studied for power transmission systems.

The main objective of this study is to demonstrate the reduction in technical losses and to transform a double three-phase line into a single six-phase line. Also, the benefits and feasibility of six-phase lines arrangement are presented for distributors to replace the current double three-phase lines in some situations.

The proposed methodology considered the current regulatory framework in Brazil and grid simulations in OpenDSS. Technical analysis and the result of new investments were calculated considering the current regulatory approach, as defined in (ANEEL, 2015) and (ANEEL, 2018).

2. STATE OF THE ART SYSTEMS SIX-PHASE

2.1 Transmission Systems at High Phase Order (HPO)

The six-phase system is a particular case of the HPO. The idea of transmitting at HPO was firstly introduced in 1972, (BARTHOLD, 1972). Originally, HPO systems were built from special three-phase power converters and considered multiples of three, reaching a new system of six, nine, or twelve phases.

The main advantage of this conversion is reflected in the phase-to-phase (line) voltage magnitude, i.e., that for one specific phase-to-ground voltage magnitude, the HPO system reduces the line voltage magnitude, if compared with a traditional three-phase system. The phasors for typical three-phase systems and HPO systems are shown in Fig 1. The line voltage can be converted to a phase-to-ground voltage by Equation (1).

$$V_{ff} = 2 * V_{ft} * \sin\frac{\theta}{2} \tag{1}$$

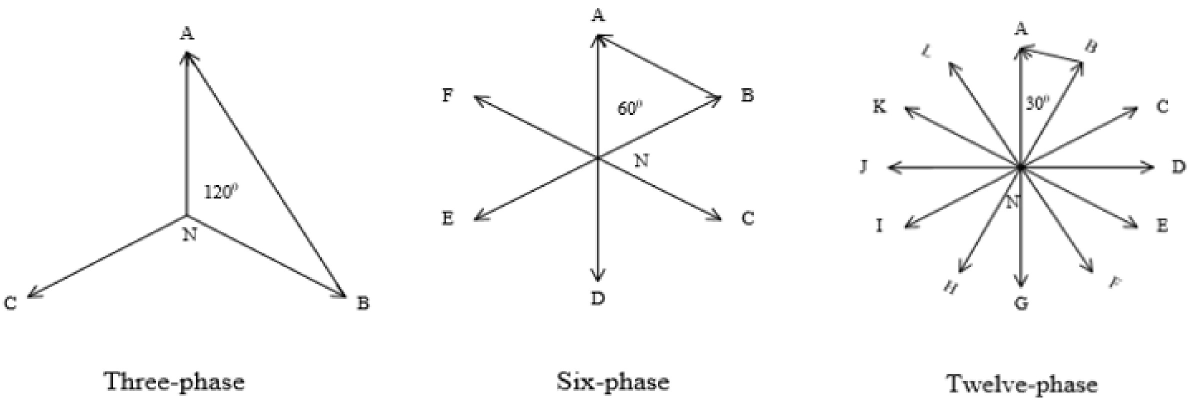

Fig. 1: Three-phase and HPO systems phasors

2.2 Electrical Property of the HPO System

As shown in Fig. 1, electric angles between the phases decrease as the phase order increases. The line and phase-ground voltages can be represented by Equations (2) and (3).

$$V_{ft\,3\emptyset} = V_{ft\,6\emptyset} = V_{ft\,12\emptyset} \tag{2}$$

$$V_{ff\,3\emptyset} = \sqrt{3}\,V_{ff\,6\emptyset} = 3\,V_{ff\,12\emptyset} \tag{3}$$

Where:

- $V_{ft\,3\emptyset}: phase - ground\ voltage\ -\ 3\ phases$
- $V_{ft\,6\emptyset}: phase - ground\ voltage - 6\ phases$
- $V_{ft\,12\emptyset}: phase - ground\ voltage - 12\ phases$
- $V_{ff\,3\emptyset}: line\ voltage - 3\ phases$
- $V_{ff\,6\emptyset}: line\ voltage - 6\ phases$
- $V_{ff\,12\emptyset}: line\ voltage - 12\ phases$

One special property is that the line voltage in six-phase systems is equal to the phase-to-ground voltage (SHARMA, 2017). This property is demonstrated through Equation (4).

$$V_{ft\,6\emptyset} = V_{ft\,3\emptyset} = \frac{V_{ff\,3\emptyset}}{\sqrt{3}} = \frac{\sqrt{3}\,V_{ff\,6\emptyset}}{\sqrt{3}} = V_{ff\,6\emptyset} \tag{4}$$

The energy provided by a three-phase line and an (HPO) line can be expressed as illustrated in Equations (5), (6), and (7).

$$P_{3\emptyset} = 3 * V_{ft\,3\emptyset} * I_{fase} \tag{5}$$

$$P_{6\emptyset} = 6 * V_{ft\,6\emptyset} * I_{fase} \tag{6}$$

$$P_{12\emptyset} = 12 * V_{ft\,12\emptyset} * I_{fase} \tag{7}$$

When comparing the lines, it is necessary to equalize the number of conducting wires, so that the comparison can be correct. The result of comparing the six-phase line with a double three-phase line is described in Equation (8)

$$P_{2-3\emptyset} = 6 * V_{ft\,3\emptyset} * I_{phase} \tag{8}$$

Thus, for the same value of current and phase-to-ground voltage, the transmitted power would be equal. However, the line voltage of the three-phase line is greater by a root of three factor, is compared with the line voltage of the six-phase system. Given that, there are a few aspects that should be highlighted in order to continue with the proposed methodology in the present paper.

To transport a specific amount of electric power, a double three-phase line requires a higher line voltage or a larger current. On the other hand, for the same voltage and current values, a six-phase line can carry three times more electric power than a double three-phase line.

2.3 Three-phase Conversion and HPO-6

Transmission lines of HPO can be considered to increase the power transmitted by typical three-phase lines (CRUZ, 2009). The conversion can be made through special transformers in a similar manner it is already performed for current transmission system cases, just adapting the technology involved for adequate rated voltage and power levels. There are several studies on the insertion of a six-phase line in the grid (DENG, 2012). The typical interconnection between the HPO-6 and the conventional three-phase transmission lines shown in Fig 2.

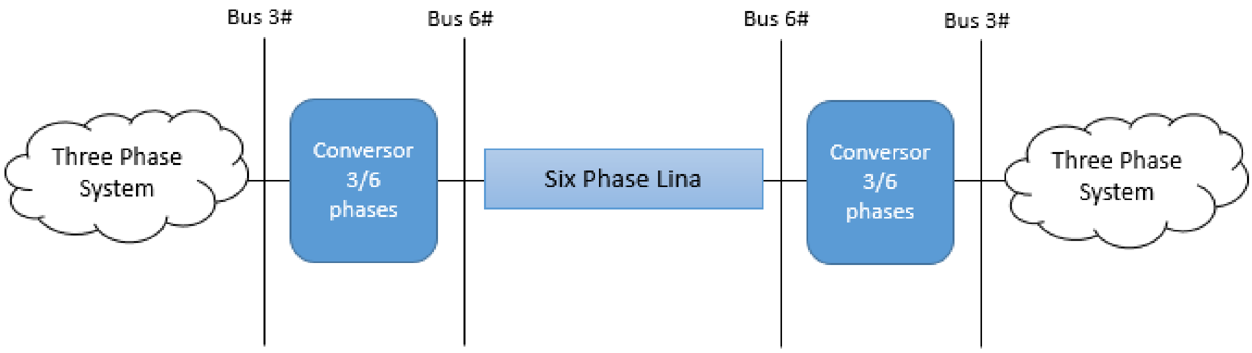

Fig. 2: Conversion of circuits for six-phase (ARANDA, 2016).

3. ECONOMIC EVALUATION MODEL

To clarify the benefits from six-phase lines in subtransmission systems from power distribution companies, the evaluation models were presented in this paper. For any segment of the electricity sector, it is necessary to evaluate the return on invested capital, and the technical and operational benefits involved. In this study, the focus was on the CAPEX and technical revenue model. For each of the segments involved, one explored the characteristics of the current regulations.

3.1 CAPEX in Electricity Distribution Utility

The assets in the distribution sector need to have comparative indicators associated with prudence for recognition of their costs. However, the most important aspect of for this kind of analysis is to understand the pricing window, the useful life of the asset, and its time of use before exchanging it or stating its obsolescence.

The assets have a number of years as regulatory useful life (which is about 35 years for lines' technology, and around 13 years for other items). At every tariff revision period (r_n), following the entry into operation of an asset, its current value is recalculated, as illustrated in Fig 3. This process is repeated for each revision, during the years between the entry into operation and the end of useful life from the asset (ul).

The base value is equal to the gross investment (I). The liquid revenue of a line begins with I on the asset's date of entry into operation (initial year) and it ends in the ul instant (example: 13 years) with a null value. The effective value that is entered in the base depends on when each revision is carried out.

The RRQ (regulatory remuneration quota) value is proportional to the investment (I) and the rate of depreciation ($1/ul$). The NCR (net capital remuneration) is already equal to the value of the depreciated basis (d) multiplied by the WACC - weighted average cost of capital - (currently at 8.09 % after taxes).

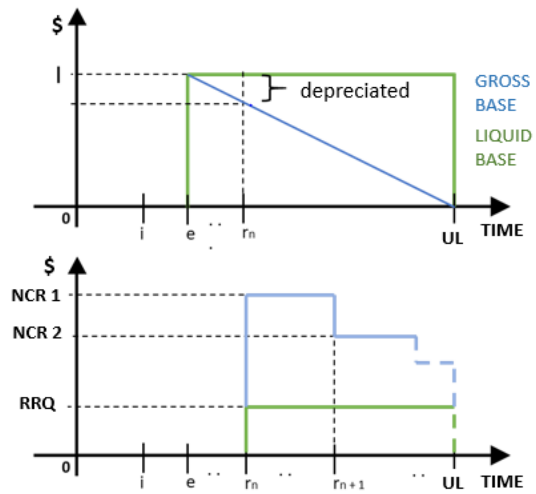

Fig. 3: Regulatory Revenue of an Investment

3.2 Technical Revenue in Electricity Distribution Utility

In addition to determining the corresponding income value for an asset, an assessment model is necessary to evaluate the impact of its technical revenue on the distribution utility cash flow. The technical income has its accumulated value since the beginning of operation (e), after powering the asset up, until the first revision (r_n).

The regulator manages to capture fully or partially the technical revenue after tariff revision, transferring the gains to consumers, as illustrated in Fig 4. For the proposed methodology one considered a 100% technical revenue capture after the first revision.

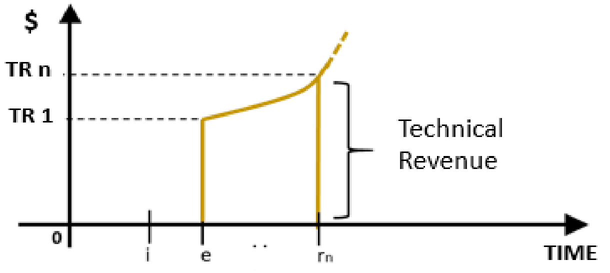

Fig. 4: Behavior of Technical Revenue

3.3 Tariff Model in the Transmission for the Coverage of the Flow of Payments

When investing in power transmission, the owner of the enterprise must worry about watching the impact on cash flow due to the realization of the investment. The tariff must cover all costs related to the service. An unforeseen investment could reduce the profit margin of the shareholders of the power company. The evaluation model for the transmission system is described in Fig 5.

To perform the economic analysis a PRICE model was considered. According to this model, each investment is broken down by groups of purchases of the equipment, considering the company's rate of return or the interest charged (in case of third-party financing). The purchases are normalized, creating a unique value for all assets in operation.

3.4 Comparison between Compensation Models

To compare the models a real transmission line study was considered (EPE, 2013). According to this study, the expansion of a subtransmission system should be performed through a new 230/69 kV substation, which would be powered by a new 230 kV double three-phase line, which would replace the previous one with a 40 km length.

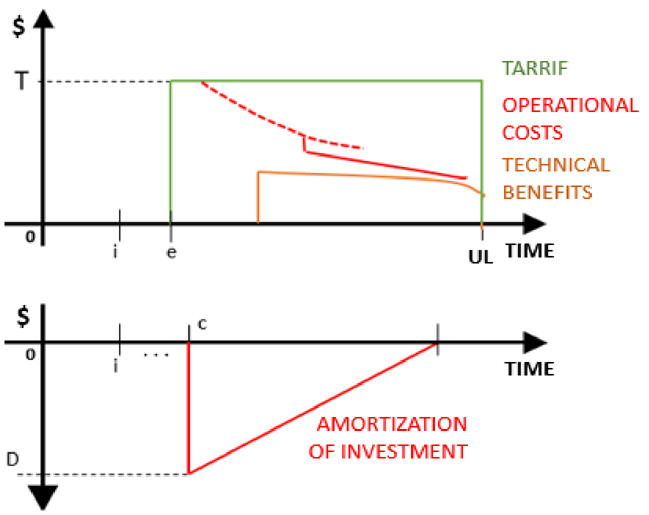

Fig. 5: Evaluation model in the Transmission

Based on this study, simulated cases of building a new double three-phase line and a six-phase line were carried out. The investment was evaluated by the transmission and distribution of remuneration models. The results, including the project net present value (NPV) were presented in Table 1. To facilitate the comparison, the values were normalized according to the original case.

Table 1: Relative Comparison of Investments

Comparative Investments	Transmission		Distribution
	3-phases	6-phases	6-phases
Cost Line	1.00	1.20	1.20
Cost Transformer	1.00	1.50	1.50
Capital Recovery	1.00	1.00	2.80
Energy Losses	1.00	0.83	0.83
NPV	1.00	0.64	3.10

It is possible to note that the six-phase line project is more attractive if carried out by a distribution utility, due to the difference in the economic models, even with the cost being relatively higher.

4. CALCULATION OF LOSS REDUCTION

The basic components of a line are conductors, insulators, support structure, and surge arresters (GONEN, 2014). There are different types of cables and arrangements for each of the structures. To perform the simulations, OpenDSS (DUGAN, 2011) was considered due to its ease of use and the possibility of suitably inserting the line parameters. The system is not based on any specific real network, allowing freedom for changes in the simulations.

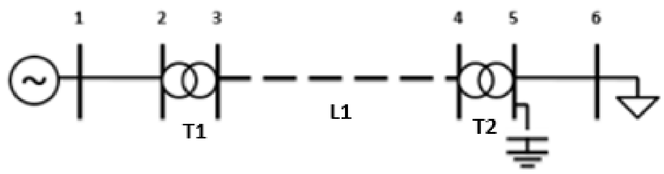

Fig. 6: Six-bus distribution line model

For the energy loss simulation, a 6-bus system was built, as shown in Fig 6. The model consists of two three-phase lines with 1 meter between buses 1-2 and 3-4, two transformers between buses 2-3 and buses 4-5, a capacitor on bus-5, a load on bus-6, and a supply in bus-1.

Cases were simulated under identical conditions, varying only the configuration of line 3-4 and their respective transformers, one case considered a six-phase line and the other considered a double three-phase line. The study considered a three-winding transformer for the 6-phase case, rotational transposition (shifts the phase to the next downstream) in the lines, and a V ϴ supply. The following parameters were kept constant during both simulations: power factor at 0.92 inductive; ZIP load model at 50% for constant power and 50% constant impedance; capacitor power at 3 MVAr, zero-sequence impedance at 0.001 Ohm per kilometer and transformers tap at unity level.

The varied parameters in each study are listed below:

- T1 V1 (kV) – Primary voltage for transformer #1 (buses 2-3), i.e. voltage between buses 1 and 2.
- T1 V2 (kV) - Secondary voltage for transformer #1 (buses 2-3), i.e. voltage between buses 3 and 4.
- T2 V2 (kV) – Secondary voltage for transformer #2 (buses 4-5), i.e. voltage between buses 5 and 6.
- POT (MVA) - Transformers rated power.
- Loadloss (pu) - Load loss factor for transformers.
- Noload (pu) - No load loss factor for transformers.
- L1 r1 (pu) - Positive sequence resistance per kilometer of line 3-4.
- L1 x1 (pu) - positive sequence reactance per kilometer of line 3-4.
- L1 dist (km) – the distance in kilometers of line 3-4.
- Load (MW) - load consumption

The obtained results are presented in Table 2.

Table 2: Simulation of Lines considering Variation of Parameters

Parameters															
T1 V1 (kV)	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	69.0	34.5
T1 V2 (kV)	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5	69.0	34.5
T2 V2 (kV)	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	69.0	34.5
POT (MVA)	12.5	12.5	12.5	12.5	12.5	25.0	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Loadloss (pu)	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.92	1.42	1.42
Noload (pu)	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.72	0.32	0.32
L1 r1 (pu)	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.41	0.00	0.21	0.21	0.21	0.21	0.21
L1 x1 (pu)	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.00	0.89	0.09	0.49	0.49	0.49
L1 dist (km)	20.0	10.0	1.0	50.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Load (MW)	10.0	10.0	10.0	10.0	10.0	10.0	4.0	16.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
6-Phase															
V min	0.95	0.96	0.97	0.90	0.94	0.96	1.00	0.89	0.93	0.96	0.94	0.96	0.94	0.97	0.93
Loss 6 (%)	3.85	2.93	2.10	6.59	3.87	3.97	3.22	5.63	5.58	2.03	3.87	3.82	5.14	2.47	3.90
3-Phase															
V min	0.88	0.89	0.90	0.84	0.87	0.90	0.94	0.83	0.86	0.89	0.87	0.89	0.87	0.95	0.91
Loss 3 (%)	4.63	3.83	3.09	6.96	4.84	4.42	3.69	6.66	6.11	3.02	4.64	4.63	6.38	3.58	5.07
Ratio															
L6/L3	0.83	0.76	0.68	0.95	0.80	0.90	0.87	0.85	0.91	0.67	0.84	0.83	0.81	0.69	0.77

The values of voltage drop ($Vmin$) in the network and the percentage loss values in relation to the injected energy were analyzed. $Loss$ 6 represents the loss of the six-phase line and $Loss$ 3 represents the loss of the double three-phase line. The ratio of the losses between the six-phase and three-phase lines were represented by $L6$ / $L3$. Figures 6 to Figure 10 illustrated the results applying only the variation of one of the circuit parameters for the six-phase and double three-phase cases.

Fig. 6: Simulation changing the line length - Loss

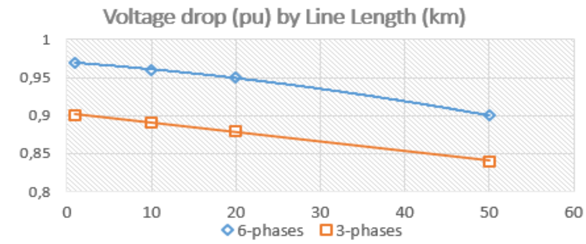

Fig. 7: Simulation changing the line length - Vmin

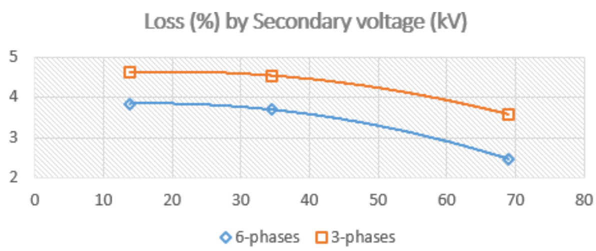

Fig. 8: Simulation changing the secondary voltage

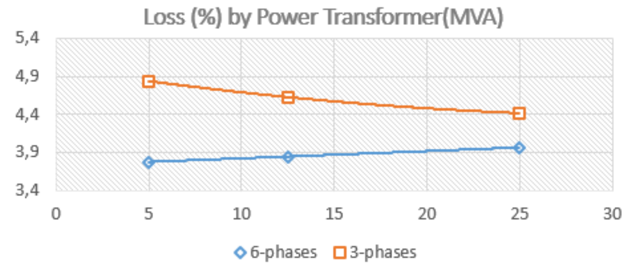

Fig. 9: Simulation changing the power transformer

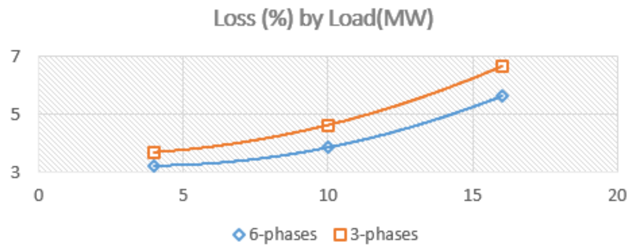

Fig. 10: Simulation changing the load

Analyzing the obtained values, it is possible to note that the six-phase line comparing to the double three-phase double line presents:

- Higher loss reduction ratio for higher all load values. This is due to a better sizing for the transformers.

- Lower loss reduction ratio for longer line lengths and higher impedance. It is important to emphasize that past studies did not consider the same network structure; usually a smaller economic conductor is used for the six-phase lines, which reduces the losses when compared to the three-phase lines for longer lengths.

- The voltage drop is always smaller. Therefore, it needs less reactive compensation. This is due to the reduction of circulating current per phase.

- The higher the voltage level, the greater the difference in loss reduction. The current reduction due to voltage increase is proportionally greater for the six-phase line approach.

5. CONCLUSIONS

This study concluded that the six-sided line is a possible solution for reducing losses and improving voltage levels in the power grid. In the economic evaluation, it was possible to prove that the auction remuneration model, considered for transmission agents, does not benefit the six-phase line, since it is currently more expensive than the traditional ones. The use of this arrangement in distribution at 69 kV or express lines for rural regions, at 34.5kV, would be a great solution to foster the market, replacing the distribution's assets with remuneration, enabling reduction in technical losses, and reducing voltage drops.

So, the six-phase (or other three-phase multiples) systems have the advantage of making future leads for single, two and three phase loads easier than direct current lines, which are not used for high voltage distribution systems. The study contributed to the state of the art, as it presents a reinterpretation of classic studies, set in another segment (distribution utility), which is more viable to spread the technology.

REFERENCES

Aranda, L., "Alternatives to electricity Conventional Transmission. Bogotá 2016.

Barthold, L.O., "High Phase Order Power Transmission", CIGRE Study Committee No. 3 1 Report. 1972 and ELECTRA In., pp. 139-24 153,

BRASIL. ANEEL - National Electric Energy Agency. Electricity Distribution Procedures in the National Electric System - PRODIST. Module 7 - Calculation of Distribution Losses – Review 5 – January/2018. URL:https://www.aneel.gov.br/documents/656827/14866914/M%C3%B3dulo7_Revisao_5+-+Retificado/669bf2b6-7fb4-07e8-f5fd-0bea4d83ad34.

BRASIL. ANEEL - National Electric Energy Agency. Tariff Regulation Procedures - PRORET. Module 2.3 - Regulatory Remuneration Basis - Review 2 – Nov/2015. URL:http://www2.aneel.gov.br/cedoc/aren2015686_Proret_Submod_2_3_V5.pdf

BRASIL. EPE – Energy research company. Bidding studies for distribution expansion, Brasilia - SP URL http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-183/Relat%C3%B3rio%20PELP%202020%201%20semestre.pdf

Cruz, C. W., "Magnetic field mitigation strategies originated by power transmission lines", Technical University of Lisbon, 2009.

Deng, X., "Exploring six-phase transmission lines for increasing power transfer with limited right of way", Arizona State University, 2012.

Dugan, R.C., T.E. An open source platform for collaborating on smart grid research. In 2011 IEEE Power and Energy Society General Meeting, 1{7. IEEE. doi:10.1109/PES.2011.6039829. URL https://ieeexplore.ieee.org/document/6039829/

Gonen, T, "Electrical Power Transmission System Engineering: Analysis and Design", CRC Pres, 2014.

Issicaba, J, "Transformation of a double circuit transmission line in three-phase transmission line hexafásica", Federal University of Santa Catarina, 1988.

Jardini, J, " Alternativas não convencionais para transmissão de energia elétrica - Volume 1"pag 254-271, Brasília – Brasil, 2011.

Pierre, B., "Increased security rating of overhead transmission circuits using compact phase design and high phase order", IEEE, 2005.

Sharma, S., "the Review on Phase Order Transmission System Over Three Phase Double Circuit Transmission System" Publish in: International Conference on Science Technology Engineering Management, Singapore, 2017.

Singh, L. P., "Advanced Power System Analysis and Dynamics", New Age International, 2006.

Wazir, B. M., "Static and dynamic impacts of three to six-phase conversion of selected transmission line in an electric energy system", University Tecnologia Malaysia, 2006.