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RESEARCH ARTICLE OPEN ACCESS

USE OF SIX-PHASE SYSTEMS TO REDUCE TECHNICAL LOSSES IN SUBTRANSMISSION NETWORKS OF POWER DISTRIBUTION UTILITIES

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ABSTRACT

The objective of this work is to find solutions to reduce energy losses in distribution systems, focusing on the application of six-phase systems. In the transmission segment, there are many surveys with six-phase systems. However, in the distribution segment, the situation is different and there is little research on this alternative. The main objective of this work is to demonstrate the reduction of technical losses through the conversion of a three-phase double-circuit line into a six-phase line, considering only the exchange of transformers. The work presents the reduction in loss that is generated by the application of the technology at 34.5kV distribution voltage levels; case studies considering a base network considering several topological changes and; application in a real network with fault simulation.

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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, depending on the region, part of the transport might be by alternating current, but with only one phase. 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. These new lines have brought old discussions about the optimal number of phases for power transmission and distribution. Some experts [Pierre Brian, 2005; Singh, 2006; Bin Mohd Mustafa Wazir, 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, José, 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. 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.

State of the art systems six-phase

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 [6]. Originally, HPO systemswere built from special three-phase power convertersand considered multiples of three, reaching a new system of six, nine, or twelve phases. The main advantage of this conversion is reflectedin 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 HPOsystems are shown in Fig 1.The line voltage can be converted to a phase-to-ground voltage by Equation (1).

$$V_{ff} = 2 * V_{ft} * \sin\frac{\theta}{2} \quad (1)$$

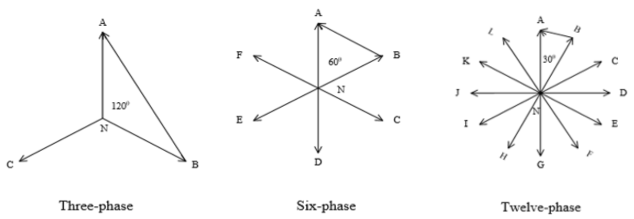

Fig. 1. Three-phase and HPO systems phasors

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).

$$V_{ft\,3\emptyset} = V_{ft\,6\emptyset} = V_{ft\,12\emptyset} \quad (2)$$

$$V_{ff\,3\emptyset} = \sqrt{3}V_{ff\,6\emptyset} = 3\,V_{ff\,12\emptyset} \quad (3)$$

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 [7]. This property is demonstrated through Equation (4).

$$V_{ft\,6\emptyset} = V_{ft\,3\emptyset} = \frac{V_{ff\,3\emptyset}}{\sqrt{3}} = \frac{\sqrt{3}\,V_{ff\,6\emptyset}}{\sqrt{3}} = V_{ff\,6\emptyset} \quad (6)$$

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

$$P_{3\emptyset} = 3 * V_{ft\,3\emptyset} * I_{fase} \quad (5)$$

$$P_{6\emptyset} = 6 * V_{ft\,6\emptyset} * I_{fase} \quad (6)$$

$$P_{12\emptyset} = 12 * V_{ft\,12\emptyset} * I_{fase} \quad (7)$$

When measuring 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).

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

Thus, for the same value of current and phase-to-ground voltage, the transmitted power would be equal. Although, 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 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.

Three-phase Conversion and HPO-6: Transmission lines of HPOcan be considered to increase the power transmitted by typical three-phase lines [8]. 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 [9]. The typical interconnection between the HPO-6 and the conventional three-phase transmission linesshown in Fig 2.

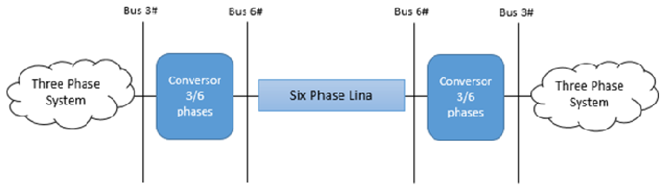

Fig. 2. Conversion of circuits for six-phase [10]

Network simulation in OPENDSS [11]: OpenDSS is an electric power distribution system (DSS) simulator designed to support the integration of distributed energy resource (RED) networks and grid modernization. It allows engineers to perform complex analyzes using a flexible, customizable, and easy-to-use platform specifically designed to meet current and future distribution system challenges, and provides a foundation for understanding and integrating new technologies and capabilities. Developed in 1997, the DSS was originally designed to take into account the impacts on time and the local grid of RED, introducing the concept of quasi-static time series analysis in the electricity industry. To coordinate and advance smart grid applications, DSS was open sourced ten years after its inception. Currently, it is ANEEL's official tool for calculating Losses in Electric Energy Distribution. For the simulations, the most important elements to be simulated are the three-winding transformers and the hexaphasic line. The coding of these elements is described below:

```
New "Transformer.Trafo1" phases=3 windings=3 %loadloss=0.4
%noloadloss=0.1 x12=5 x23=5 x13=5

wdg=1 bus=BUS2.1.2.3 conn=delta kV=69 kVA=12500 tap=1
wdg=2 bus=BUS3.1.5.3.7 conn=delta kV=34.5 kVA=12500
wdg=3 bus=BUS3.4.2.6.7 conn=delta kV=-34.5 kVA=12500
New "Reactor.Trafo1" phases=1 bus1=BUS3.7 R=15 X=0
basefreq=60

New "Line.Linha" bus1="BUS3.1.2.3.4.5.6"
bus2="BUS4.1.2.3.4.5.6"
Geometry=Arranjo1Length=30 units=km
EarthModel=Carson
New "Wiredata.Phase" GMR=0.0244
DIAM=0.721 RAC=0.306NormAmps=340
Runits=mi radunits=in gmrunits=ft
New "Linegeometry.Arranjo1" nconds=6 nphases=6
cond=1 Wire=Phase x=-4  h=29  units=ft
cond=2 Wire=Phase x=-1.5  h=29  units=ft
cond=3 Wire=Phase x=3  h=29  units=ft
cond=4 Wire=Phase x=-1.5  h=25  units=ft
```

cond=5 Wire=Phase x=-4 h=25 units=ft
cond=6 Wire=Phase x=3 h=25 units=ft

Calculation of Loss Reduction in the base case: The basic components of a line are conductors, insulators, support structure, and surge arresters [12]. There are different types of cables and arrangements for each of the structures. To perform the simulations, OpenDSSwas 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.

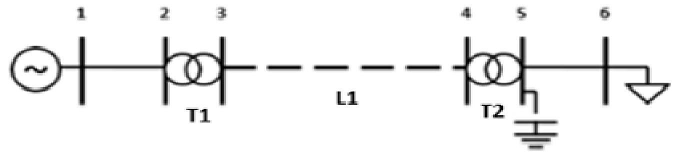

Fig. 3. Six-bus distribution line model

For the energy loss simulation, a 6-bus system wasbuilt, as shown in Fig 3.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 asix-phaseline and the otherconsidered a double three-phase line.The study considered a three-winding transformer for the 6-phase case, and rotational transposition (shifts the phase to the next downstream) in the lines. Thefollowing 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 at3MVAr, 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 II. The values of voltage drop ($Vmin$) in the network and the percentage loss values in relation to the injected energy were analyzed.$Loss$ 6represents 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 4 to 8 and the Table III illustrated the results applying only the variation of one of the circuit parameters for the six-phase and double three-phase cases.

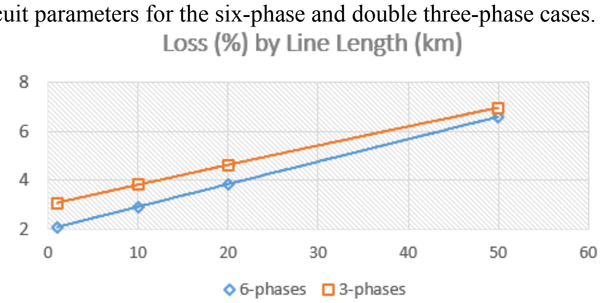

Fig. 4. Simulation changing the line length– Loss

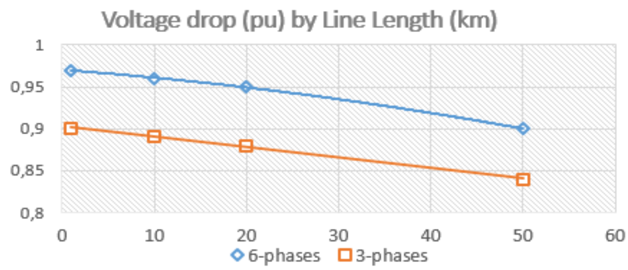

Fig. 5. Simulation changing the line length–Vmin

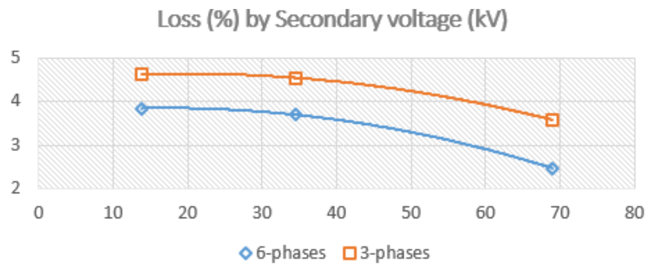

Fig. 6. Simulation changing the secondary voltage

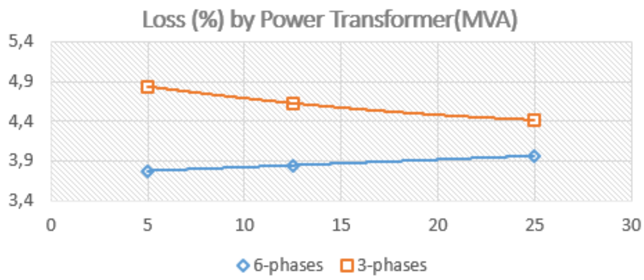

Fig. 7. Simulation changing the power transformer

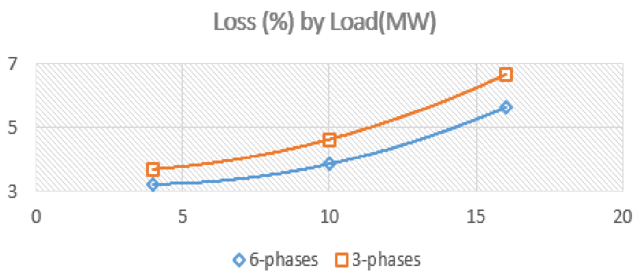

Fig. 8. Simulation changing the load

Analyzing the obtained values,it is possible to note that the six-phase linecomparing 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 linesfor 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-phaseline approach.

Calculation of Loss Reduction in the real case: The analyzed study aims to apply the concepts explained in the work in a real case, being possible to validate and deepen the characteristics in the Base Cases. In this study added as an analysis of the projects.

The network belongs to COPEL-DIS, in the western region of Paraná. The selected feeders are called: Expresso Capanema and Expresso Capanema. More details will be eliminated in the network characterization section. The Capanema and Planalto Express originate from the substation (SE) 138kV/34.5kV-13.8kV entitled Realeza. SE Realezais connected to the basic network, being the main source of supply in western Paraná. The Realeza Substation has three transformers, two of them 138/34.5kV – 15MVA and one 138/13.8kV – 10MVA, having a total power of 40 MVA. It serves ninefeeders, thePlanalto and Capanema express being derived from the same busbar (only the two being on the busbar) of one of the 15MVA transformers.

The Capanema Express has about 32 km and connects SE Realeza with SE Capanema (34.5kV/13.8kV – 10 MVA), this substation has 3 feeders derived. The Planalto Express connects SE Realeza with SE Planalto (34.5kV/13.8kV – 12.5 MVA), 28 km apart, having 4 feeders after the transformation. Originally the networks were not express, feeding some large consumers on the way, with the expansion of the Realeza system, these clients were migrated to other feeders, improving the voltage delivered at the 34.5/13.8kV substations. The two feeders share the structure for about 7 km of their lengths. Finally, a comparative study is implementedbetween the distribution and transmission segment, in order to carry out a new investment with the characteristics of thePlanalto and Capanema Express. The actual topology of the feeders, as well as the simplified topology and their hourly aggregate consumption shown in figures 9, 10 and 11, respectively. Three scenarios were built, considering different demand scenarios, some topology changes and the effect of faults (steady state only) and how these affect the level of losses and voltage in the systems. Details of each scenario will be described in their respective topics.

Current Scenario vs Transformer Exchange: Scenario 1 presents a study considering the topology described in the topic of network characterization, in which the entire load is concentrated at the output of SE Capanema. This scenario considered the 24 hourly levels of active and reactive demand of the feeders added together, with a tap at the feeder output at 1.03. The simulation result is shown in Figure 12. With the maximum demand (load factor of 88%), the loss results already take off a lot, with the hexaphasic being, on average, 7% smaller. It is also possible to observe a voltage dip at times of higher demand (between 12-20hs), with the voltage drop being slightly lower in the six-phase, figure 13.

Scenario 1 considering single-phase fault in phase C: Scenario 2 maintains the characteristics of the previous scenario, however, the opening of phase C (after some single-phase fault) is considered in both cases. The results are shown in figure 14. There was a significant increase in losses, about 20%, and an increase in the voltage drop, but the six-phase circuit showed better results at all levels.

Topological change: The last simulation presents a complete topological change being modeled the hexaphase network. From an implementation point of view, it is an unfeasible solution, but the loss reduction is quite considerable (around 25%). The result is shown in Figure 15.

CONCLUSIONS

From a technical point of view, it was possible to verify that the six-phase network can be used at a voltage of 34.5kV without prejudice to the benefits. It was observed that the voltage drop is smaller in the six-phase circuit than in the double three-phase circuit and that in situations where the circuit has the highest loads. The loss reduction benefit is greater than in the double three-phase circuit (at all levels the reduction of losses are smaller in the six-phase, during peak consumption times the relative reduction in losses is even greater). Finally, the study presented leaves us with the real possibility of converting three-phase double circuits into six-phase circuits in 34.5 kV distribution lines. The radial characteristic of the lines facilitates the operation, which will not differ from the current configuration. The reduction in losses is a significant benefit for the distributor and its consumers, who will have a reduction in the energy tariff in the medium term.

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