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# Analysis of the Voltage Profiles with Uprating Technique by Third Harmonic Voltage Injection ⋆

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**Abstract:** This paper presents a study concerning the transmission line uprating method by injection of third harmonic voltage (THV). The method has been recently employed as a more economically feasible proposal to raise the transmission voltage level without the requirement for changes in the structural elements of overhead lines. The superposition of a third harmonic voltage component with the fundamental component at the sending and receiving ends of the line increases the amplitude of the fundamental voltage component without exceeding the electrical insulation tolerance limits, which results in a rising of the power transfer capability. This work shows a study on the behavior of the voltage profile of several OHTLs, represented by Bergeron's model, which were uprated by the THV technique. The results have shown that THV technique is a feasible option for OHTLs of up to 200-km length. For OHTLs longer than 200 km, phase voltages may exceed safety levels which imposes a limitation in the uprating of the long lines by this technique.

**Resumo:** Este artigo apresenta um estudo sobre o método de recapacitação de linhas de transmissão (LTs) por injeção de tensão do terceira harmônica (TTH). Esse método foi recentemente empregado como uma proposta mais econômica e viável de aumentar o nível de tensão de uma LT sem as alterações nas estruturas das linhas ou torres. A superposição de uma componente de tensão de terceira harmônica com a componente fundamental nos terminais emissor e receptor de uma LT aumenta a amplitude da componente de tensão fundamental sem exceder a tensão elétrica limite suportada pelo isolamento da estrutura, resultando em um aumento da capacidade de transferência de energia. Este trabalho mostra um estudo sobre o comportamento do perfil de tensão de várias LTs, representadas pelo modelo de Bergeron, que foram recapacitadas pela técnica de injeção de TTH. Os resultados mostraram que a técnica de injeção de TTH é uma opção viável para LTs de até 200 km. Para LTs mais maiores do que 200 km, os níveis de tensão podem exceder o valor limite das tensões, impondo restrições à recapacitação de linhas longas por essa técnica.

*Keywords:* electromagnetic transients; transmission line; harmonic voltages; uprating technique;voltage profile
*Palavra-chaves:* transitórios eletromagnéticos, linhas de transmissão; tensões harmônicas; técnicas de recapacitação; perfil de tensão

## 1. INTRODUCTION

Socioeconomic development of the population results in an increase of energy demand, which must be followed by an increase in the power generated by the electric utilities. However, an increment in the power generation requires greater effort from the conductors that convey that energy.

In this context, an increase in power generation should occur simultaneously with the improvement of the overhead transmission lines (OHTLs), which transfer electric energy to the consumer centres. In this way, several methods to increase conveyed power in OHTLs are proposed in the literature, which can be classified into current and voltage uprating techniques. Current uprating technique involves replacing the phase conductors by newer ones with thermal and ampacity limits and/or increase the number of conductors per phase which requires less efforts from each

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conductor Reisdorff (2006); Kühnel et al. (2017); Pytlak and Musilek (2012); Albizu et al. (2005).

The voltage uprating technique increases the power transfer with minimal structural modification, which can result in a higher power transmission with reduced electrical losses when compared to the former technique for the same amount of power Bhattarai et al. (2010). Voltage uprating also requires more electrical efforts from the insulators, which in some cases, they need to be replaced in order to meet the safety levels. However, an alternative method that takes better advantage of the insulator strength and structures was presented by Alaei and Khajehoddin (2016). The method consists of injecting a 180-Hz zero-sequence, a third harmonic voltage (THV), in a given 60-Hz power system. This THV technique reduces the peak of the phase voltages and, consequently, the power conveyed can be increased by the variation in the amplitude of the THV generator. As a consequence, the existing AC lines could be uprated by this method which allows to maximize power flow by increasing phase voltage without structural modifications in the transmission towers.

This paper presents a study of the phase voltages along the extent of OHTLs with injected THV component. Results show that the uprating technique proposed in Alaei and Khajehoddin (2016) is an efficient procedure that allows increasing the phase voltage level of OHTLS of less than 200 km, without exceeding the safety levels. However, this technique is not applicable when longer lines are considered. In this case, the voltage profiles show that there are several points along the line length where the voltage limits are exceeded, and other uprating technique must be carried out/studied.

## 2. UPRATING TECHNIQUE BY THV INJECTION

The system assumed by the presented uprating method consists of a generator connected to the transmission line through a delta-star transformer; it also considers that the line is connected to the distribution or sub-transmission system by a star-delta transformer. The uprating approach studied in this work consists of injecting a third harmonic voltage (THV) in the star centre of the transformers at both ends, as shown in Fig. 1 Alaei and Khajehoddin (2016).

In Fig. 1, the third harmonic generators may be synchronous machines or frequency inverters. The third harmonic component will be present only in the line section between the two transformers shown in Fig. 1, because third harmonic components will be filtered out in line voltages due to the delta windings of both transformers. In the presented uprating approach, each of the fundamental phase voltages is added with the injected THV, thus causing a reduction in the amplitude of the resulting phase voltages. This way, it is possible to raise the amplitude of the fundamental phase voltages and, consequently, the power transmitted by OHTL. This is made in such a way that the resulting phase voltage amplitudes do not exceed the nominal value of the structure. Which means that the permitted conductor-to-ground distance for the maximum voltage level will not be violated. As an example, it is considered an OHTLs with nominal phase voltage of 1 p.u. In order to achieve the maximum peak phase voltage

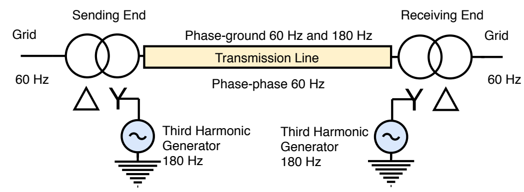


Figure 1. Schematic diagram of the uprating method by the THV injection.

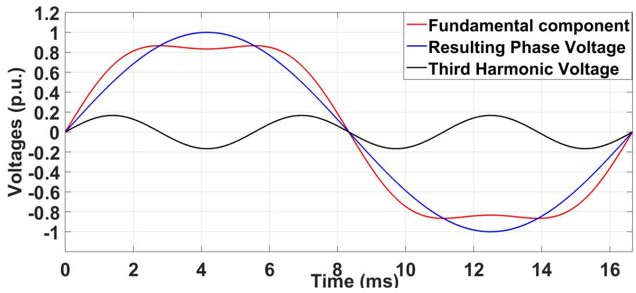


Figure 2. Waveforms of the fundamental, third harmonic and resulting phase voltages.

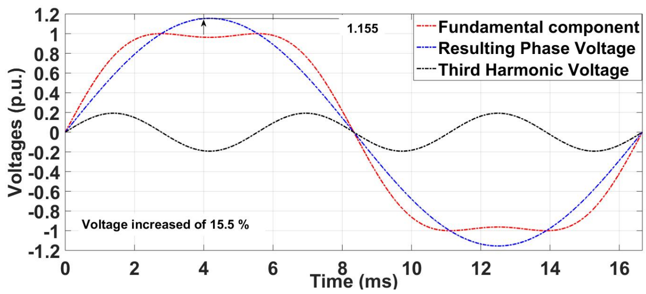


Figure 3. Waveforms of the fundamental, third harmonic and resulting phase voltages with an increase of 15.5% in the amplitude of the harmonic voltage source.

reduction with the injection of THV, the 180 Hz component amplitude must be 1/6 of the fundamental component amplitude Houldsworth and Grant (1984). Fig. 2 shows the wave-forms of one of the phase voltages in a OHTL with injection of third harmonic component, along with its fundamental component (60 Hz) and the injected third harmonic voltage (180 Hz).

As it can be seen in Fig. 2, in the presence of the THV, phase voltage amplitude decreases from 1 p.u. to 0.867 p.u. This way, fundamental phase component can be increased in up to 15.5% Houldsworth and Grant (1984) so that the resulting phase voltage is kept under the limit of 1 p.u., as shown in Fig. 3. It is important to mention that the resulting phase voltage waveform will only present the desired shape, as in Fig. 2, if the crest voltage of the fundamental component coincide with the trough voltage of the THV at the same time, this case can be considered as a reference value for phase displacement $\Delta\Phi$.

Therefore, the optimal peak phase voltage reduction occurs when $\Delta\Phi = 0°$ and the amplitude of THV is 1/6 of the fundamental component amplitude. The phase shift $\Delta\Phi$ in practice would be difficult to be zero at every point along the extent of a lossy OHTLs at the same time, since in this medium traveling wave velocity is dependent on the frequency, resulting in signal dispersion in long OHTLs Shenkman and Zarudi (1998). The THV injection at both ends of the system with a continuous phase control solves the problem of signal dispersion at these spots. However, the behaviour of phase voltages along the extent of the uprated OHTLs still needed be analysed in order to test the feasibility of the method. These analyses are shown in the next section.

## 3. NUMERICAL RESULTS

The study was carried out with the distributed parameters transmission line (DPTL) model that is commonly built in solvers for power systems. This model was designed based on Bergeron's line model (BLM) Dommel (1969). As the frequency dependence (Skin effect) on the resistance and inductance of the phase conductors are not taken into account, the OHTLs are represented by BLM which is a discrete-time line model based on the travelling waves reflections, which computes accurately the transient and steady state responses in power systems Andrade et al. (2013); MAMİŞ et al. (2010). Additionally, energization maneuvers present a low-frequency range, and DPTL can be considered constants for this phenomenon CIGRE (1990).

Since the OHTLs studied do not possess reactive compensation, it may present a voltage increase in long lines due to its distributed parameters. For the case study of this work, it was considered a 230 kV transmission line that operates with load angle of 24.2°. The OHTL in question is considered to be fully transposed and not compensated. The silhouette and parameters of the OHTLs are shown in Fig. 4. In the Simulink/Matlab, three different systems was designed in order to study a given OHTL with length $d$ under three different perspectives, as presented in Fig. 5.: a conventional OHTL (without THV injection)(Fig. 5a), a OHTL with THV injection (Fig. 5b), and a OHTL without the main generator and load in order to study the behaviour of the THV component in the system (Fig. 5c). The conventional OHTL, presented in Fig. 5a, was simulated so the phase voltage waveform of the uprated system could be compared with. Besides, phase voltages of the referred conventional OHTL can be treated as fundamental components, which is useful for analysis on the phase shift between fundamental and third harmonic components. Combining the characteristics of the OHTLs presented in Figs. 4 and 5, OHTLs were simulated with different values of length $d$ and results are shown in details as follows.

### *3.1 200-km long OHTL*

Fig. 6 shows the voltage profile of a 200-km long OHTLs with and without THV injection, and also the isolated third harmonic component.According to Fig. 6, at every point analysed in the 200-km long OHTLs, the conventional OHTLs maintains its peak phase voltage in 1 p.u. The peak phase voltage with THV injection remains under the theoretical value of 0.867 p.u., and the third harmonic component maintains its peak values around its nominal voltage value of 0.167 p.u. Fig. 7 shows the waveforms at the midpoint of the 200-km line. Fig. 7 indicates that no phase shift between fundamental and third harmonic component is present at the midpoint of the 200-km line, and the peak voltage value of the 180-Hz component is under its nominal value. Therefore, the resulting phase voltage presents peak reduction according to what is expected by the uprating method under study.

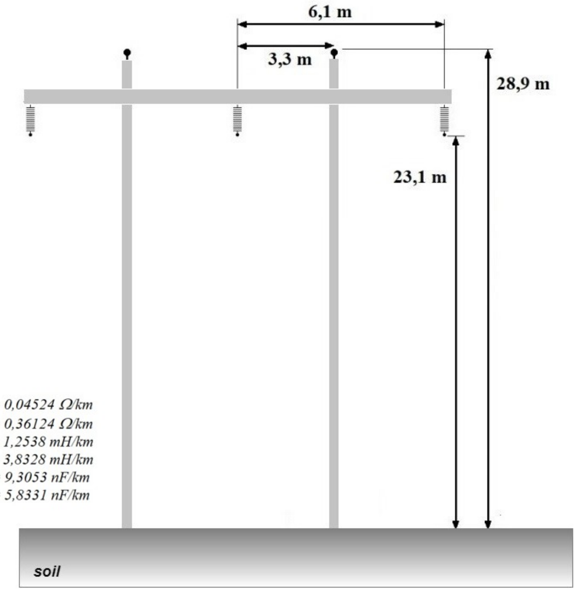


Figure 4. Tower silhouette and OHTL parameters.

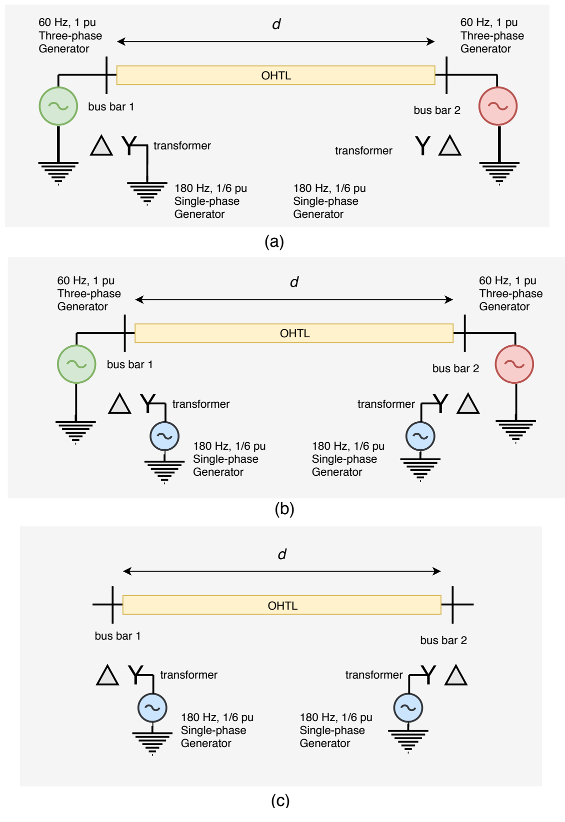


Figure 5. Configurations for this study: (a) Conventional OHTL; (b) OHTL with THV injection and (c) OHTL with THV injection at the OHTL.

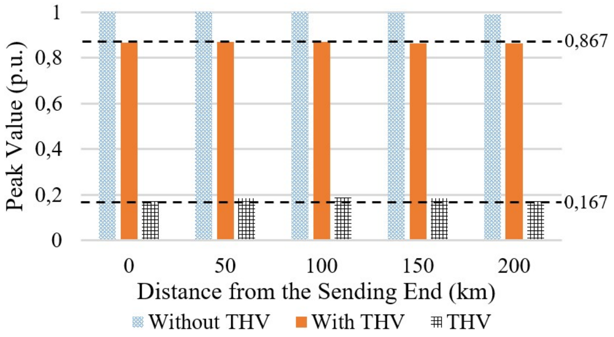


Figure 6. Voltage profile along the 200-km long OHTL.

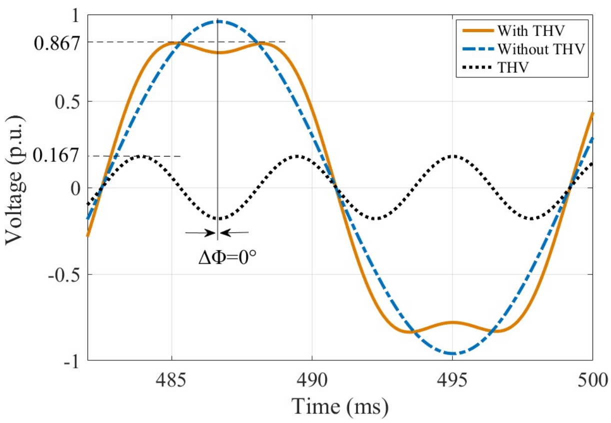


Figure 7. Voltage waveforms at the midpoint of the 200-km long OHTL.

*3.2 300-km long OHTL*

Fig. 8 shows the behaviour of the peak phase voltages, both in the presence and in the absence of THV along the length of a 300-km long OHTL. It also shows the amplitude of the THV separately. According to Fig. 8, phase voltage amplitude of a conventional OHTL remains in 1 p.u. at every sampled point.The phase voltage with THV injection maintains its peak values under 0.867 p.u. only at the line ends, and it reaches 0.9 p.u. at the midpoint of the structure. This result implies that, in order to avoid exceeding the limit of 1 p.u., the fundamental phase voltage increase must be limited to 11.1% instead of the expected 15.5%. The peak value of the isolated THV is noticeably over its nominal value of 0.167 p.u., which contributes to the overvoltage in the OHTLs with THV injection. In order to verify possible signal dispersion in the studied OHTL. The phase voltages and the THV waveforms at the midpoint of the line were monitored; the results are presented in Fig. 9. It can be noted that in the middle of the 300-km long OHTL uprated with injection of THV a minimal signal dispersion was detected, thus contributing to the slight deformation presented by the resulting phase voltage waveform. However, the main cause for the peak value of 0.9 p.u. is the third harmonic component amplitude, as stated before.

*3.3 400-km long OHTL*

Fig. 10 shows the behaviour of the same voltage amplitudes along the 400- km long OHTL. It can be observed

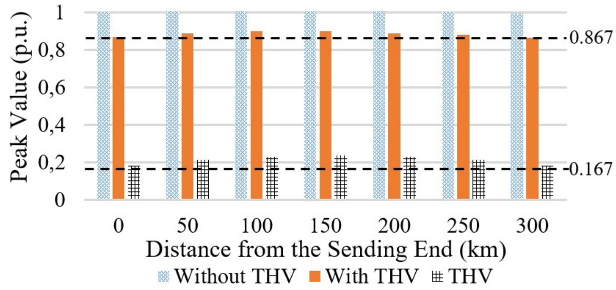


Figure 8. Voltage profile along the 300-km long OHTL.

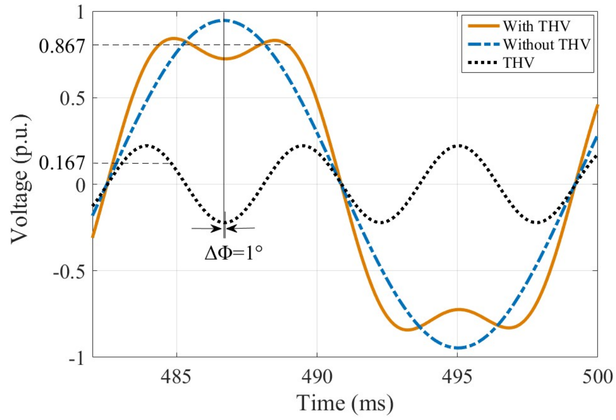


Figure 9. Voltage waveforms at the midpoint of the 300-km long OHTL.

that the peak value of the phase voltage with injected THV is higher than 0.867 p.u. in different points along the line, and it reaches 1 p.u. at the midpoint of the structure. As it can be seen, the THV amplitude is higher than its nominal value outside the terminals of the line, which contributes to the overvoltage of the resulting phase voltage. The peak phase voltage of a conventional OHTL increases in the middle of the conductors due to the distributed parameters of the line, this phenomenon tends to became more evident in longer lines. Fig. 11 shows the wave-forms of the phase voltages in the presence and the absence of THV at the midpoint of the 400-km long OHTL. Fig. 11 shows a phase shift of 2° between fundamental and the third harmonic components, this value is sufficient for a noticeable deformation in the resulting phase voltage waveform. Besides, the amplitude of the THV component reaches 0.36 p.u., that is approximately the double of its nominal value. These combined phenomena would limit the voltage uprating, as the peak value surpasses the expected 0.867 p.u., and approximates the limit of 1 p.u.

*3.4 500-km long OHTL*

Following the same analysis, Fig. 12 shows the peak phase voltages and THV along a 500-km long OHTL. One can notice that except the OHTL ends, the peak values of the phase voltages with THV are higher in comparison with the phase voltages of the conventional OHTL. At the receiving end, the peak value of the resulting phase voltage reaches 0.9 p.u. It can also be noticed that the THV peak value reaches 5.52 times its nominal value between the 200 and 300 km, where the higher peaks of the resulting phase voltage occur. Fig. 13 shows the

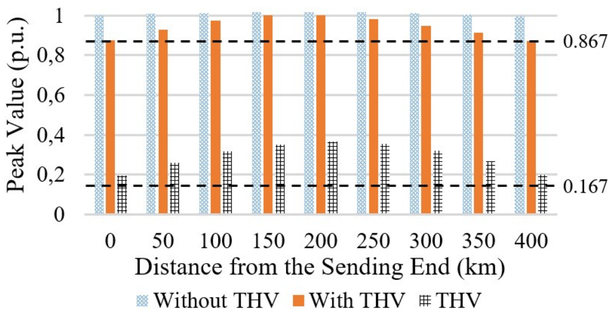


Figure 10. Voltage profile along the 400-km long OHTL.

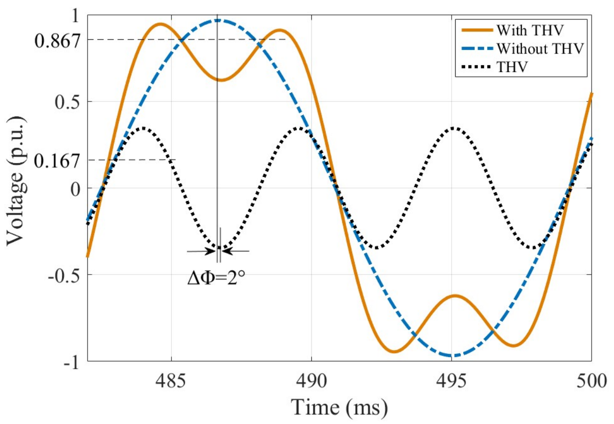


Figure 11. Voltages waveforms at the midpoint of the 400-km long OHTL.

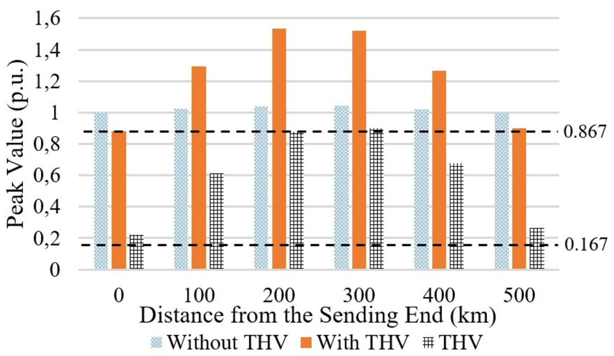


Figure 12. Voltage profile along the 500-km long OHTL.

phase voltage wave-forms at the midpoint of the OHTL. According to Fig. 13, the resulting phase voltage is highly deformed in relation to what is expected by the studied uprating method. Although phase shift contributes to this problem, the main cause for this is the high value of the THV amplitude.

### *3.5 600-km long OHTL*

The behaviour of the peak values of the monitored voltage waveforms along the line is shown in Fig.14. Voltage profiles presented by Fig.14 indicates that overvoltage in the OHTL with injected THV occurs all along the OHTL. In this case, even at the both OHTL ends, the resulting peak phase voltages surpass the theoretical value of 0.867 p.u. It can also be verified in Fig.14 that the amplitudes of the THV at both ends are below the nominal value

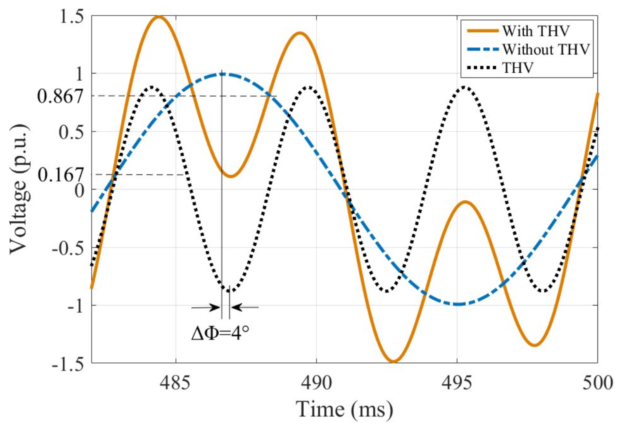


Figure 13. Voltages waveforms at the midpoint of the 500-km long OHTL.

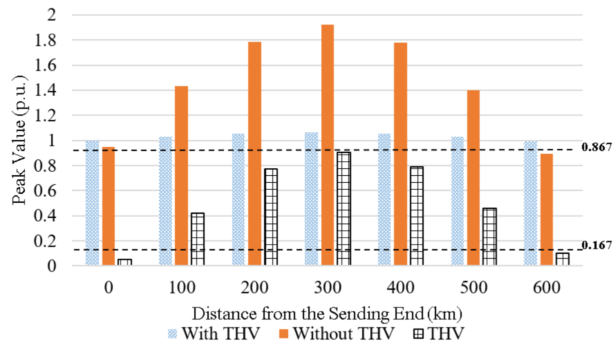


Figure 14. Voltage profile along the 600-km long OHTL.

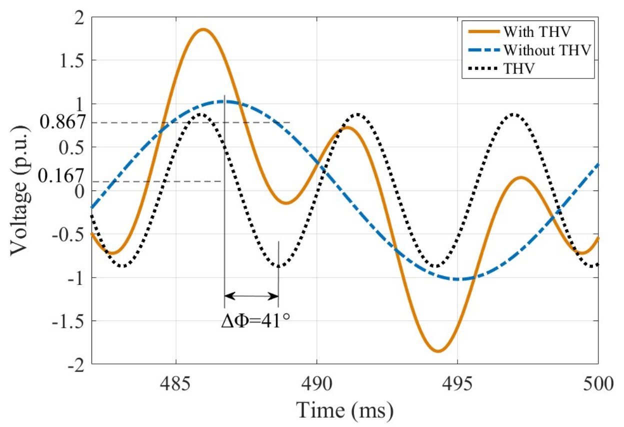


Figure 15. Voltages waveforms at the midpoint of the 600-km long OHTL.

(0.167 p.u.), which do not cause a proper phase voltage reduction at both OHTL ends. Besides, the most critical voltage value occurs at the midpoint of the OHTL, where this component reaches 5.62 times its nominal value. The voltage waveforms at the midpoint of the 600-km long OHTL are presented by Fig. 15. According to Fig.15, the peak value of the THV reaches approximately 0.90 p.u., which is the highest value presented by the THV component in this carried out study. Besides, fundamental and THV components present notable phase shift, resulting in a deformed phase voltage waveform. Because of these two combined phenomena, the resulting phase voltage greatly surpasses the peak voltage limit for the OHTL studied.

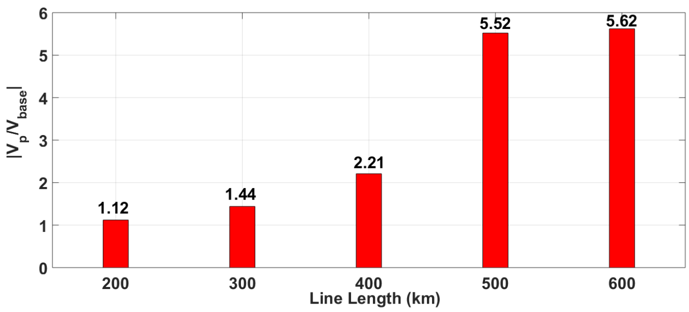


Figure 16. Normalized amplitudes of THV generator at the midpoints of OHTLs studied ($V_{base} = 31.3$ kV)

### *3.6 Discussions*

Results show a particular behaviour of the peak values of the third harmonic component, especially at the midpoint of every studied OHTL. For OHTLs with lengths up to 200 km, the resulting phase peaks are maintained under acceptable levels at the midpoint of these lines. In this scenario, the uprating THV technique reduces the phase voltages and then, the power transferred can be increased by 15.5% as seen in Fig7. However, longer OHTLs uprated with the THV technique do not present the necessary reduction at the phase voltage peaks due to high amplitude of the voltages imposed by the 180-Hz THV generator and the line length itself.

The normalized peaks of the 180-Hz THV generator at the midpoints of each OHTL were organized in a bar graph, as illustrated in Fig. 16, where $V_{base} = 31.3$ kV. It can be seen, for a 200-km OHTL, the peak is 1.12 higher than the nominal value, which is near of 15.5% increased in the phase voltages of the OHTL. As the line length increases, the amplitudes of the 180-Hz THV generator increases. At the midpoint of the 500 and 600-km lines, the THV peaks are more than five times its nominal voltage. These high peaks are related to approximated OHTL length to the quarter-wave-length imposed by the 180-Hz THV generator. As a consequence, even though phase shift between fundamental and THV voltages is minimal, the peak value of the resulting phase voltage reaches almost 1.90 p.u. Additionally, according to the previously presented results and Fig. 16, OHTLs with lengths that are higher than 400 km may present overvoltage due to phase shift between fundamental and third harmonic components, even though the THV amplitude is around its nominal value.

## 4. CONCLUSIONS

In this paper, the resulting phase voltages in several OHTLs with the uprating approach by a THV injection were studied. Results shows that the phase voltages for a 200-km OHTL uprated by the THV technique do not exceed the safety level along its length and the power transfer can be increased by 15.5% . However, for OHTLs longer than 300 km, phase voltages above the limit levels occurs due to phase shift between fundamental and third harmonic components, as well as due the variations in the amplitude of the 180-Hz generator. The maximum voltage peak observed is 1.90 p.u. at the midpoint of 600-km OHTL, where the amplitude of the THV generator reaches 5.62 times the nominal value. The results show that the uprating voltage technique by the injection of third harmonic voltage can be feasible for lines up to 200 km and, for longer line lengths, other techniques/studies must be carried out.


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