Operation of a Power Transmission Line with Injected Third Harmonic Voltage

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Abstract: The mandatory requirements for constructing new transmission line such as land acquisition, Rehabilitation and Resettlement, Rights of Way and Compensation, Environmental Problems Due to Design. Alternative for that upgrade low efficient existing transmission or construct new lines with minimum impact on mandatory factors. The objective of injection of third harmonic voltage in transmission lines to reduced peak amplitude of phase voltages. In this proposed method, 13.4 % of peak amplitude of phase voltage is reduced by injecting third harmonic voltage in fundamental component of phase voltage and line to line voltage remains intact. The third harmonic voltage could be injected through line or neutral of transformer. Injected third harmonic voltage does not affect or generation or load side. In this method impact of third harmonic voltage only in phase voltage And does not affected on line to line voltage. With this approach, the existing transmission line can be upgraded by increasing voltage level. In proposed method required less ground clearance compared to practical transmission lines by injecting third harmonic. Furthermore, the capital investment of new construction transmission line could be reduced by shorter length of tower. The loadability of existing transmission lines can be increased, if clearance of new phase to phase is met. In this paper, operation of a power transmission line with injected third harmonic voltage and practical consideration for its implementation is studied.

Index Terms - **power transmission, third harmonic voltage, ground clearance, line upgrading, and line loadability**.

I.INTRODUCTION

High Voltage Direct Current (HVDC) transmission lines are more economical for Trans- mitting a bulk power over very long distances. Some superior advantage of HVDC over HVAC, higher efficiency, lower electrical losses, less stress. In addition, HVDC provides instant and precise control of the power flow. HVDC has some limitation for short and medium transmission lines. In the past decades, transmission line are proposed Half-wavelength [2], four-phase [3] and combined AC-DC [4].yet they have not become practical. In fact, conventional HVAC lines are still a common solution to transfer power at short or medium distances. In power load has tremendous growth in day by day and capacity of generation also increasing. Power utility have to transfer the bulk amount power from source to load sites required high power transmission capability. For that some method are used to increased transmission line capability. These methods are:

1. Increased loading of existing lines.
2. Building of new lines or circuits at existing voltages.
3. Superposition of higher voltages on existing systems.

The building of new lines has more expensive as compared to superposition of higher voltages on existing systems. But increasing voltage or loading of existing transmission line it is required large ground clearance for that increasing tower heights, adding midspan towers [5]. All these approaches require tower or conductor modifications which are costly and time consuming. In this paper, the proposed design of power transmission line design method is reduces the required conductor-to-ground clearance by injecting Third Harmonic Voltage (THV). As a result, this system can be implemented using less-expensive and shorter transmission towers. The existing conventional HVAC lines could also be upgraded with this method to increase their ground clearance, if desired. Injection of THV can also increase the loadability of existing AC lines, if the new phase to-phase clearance is met. In section II discussed about requirements for constructing new transmission lines. In section III, explain the proposed design transmission line and influence of third harmonic voltage. This is followed by a discussion of possible practical issues to consider when injecting THV into section VI. The Alternative method for long transmission lines is explained in section V and case study and conclusion is discussed in section VI.

II. REQUIREMENTS FOR CONSTRUCTING NEW TRANSMISSION LINE

1. Sanction:

The sanction authorize company to plan and coordinate activities to commission the new project .Under the Section 68 (1) of the Indian Government Electricity Act, 2003, there is a mandatory requirement for adoption of any new power transmission project. Electricity Act clearly does not deal with the environmental impact of activities related to power transmission.

2. Forest Clearance:

When the transmission projects go through forest land, the forest (conservation) Act, 1980 has to get approval from concerned authorities. This act was increasingly implemented to prevent deforestation and environmental degradation.

When incorporating forest areas, MOEF has to go through detailed review and approval procedures to obtain a forest clearance certificate.

3. Environmental Clearances:

Transmission line projects are clean and environmental clearance of solid waste, land, air and water, pollution and hazardous substances.However, recent amendments in the Environment (Protection) Act, 1986 made it necessary to obtain MOEF approval for power transmission projects.

4. The Biological Diversity:

Under United Nations Conference on Biodiversity, signed on 5th of June, 1992 in Rio de Janeiro, India is also a party, MOEF has implemented the Organic Diversity Conservation Act, 2002 for the conservation of biological diversity, whose permanent use Components of the benefits generated for the use of biological resources, knowledge and related matters and fair and equitable sharing. According to the provisions of the Act some areas which are rich in biodiversity and unique and representative ecosystems have been identified and have been named as Biosphere Reserve for facilitating its safety. Power Company will abide by the provision of act wherever applicable and try to totally avoid these biosphere reserves while finalizing the route alignment.

5. Rehabilitation and Resettlement:

Ministry of Rural Development, Government of India, has notified national policy on R & R for PAF in February 2014, where 500 or more households enter simple areas or 250 or more families in hilly areas are displaced due to project.It is necessary to provide support for poor poverty assets, to support the rehabilitation efforts of resources and provide comprehensive canvas for effective consultation between officials responsible for PAF and their R & R. However, the benefits of the rights listed in the National Policy for PAF are accepted by POWERGRID in the "Social Entitlement Framework" where the substation is being implemented while the land is acquired.

6. Rights of Way and Compensation:

Under this Act, there is a provision to inform the broadcasting company under Section 164 (B) for availing the benefits of the eminent domain under the Indian Telegraph Act, 1885. MOP, GOI has stated in the Gazette Notification dt 23rd Dec'03 that under this section the Power grid Act. Therefore, with the aim of keeping any strings, poles etc., POWERGRID contains all the powers which are held by the Telegraph Authority. Thus, Power grid can actually build and construct towers without acquiring land. However, all losses caused by power grid activity are metered at the market rate. Power transmission schemes are always employed in such a way that empowered domain power is used responsibly.

7. Land Acquisition:

When the land is acquired for sub-stations, then the power grids will follow the procedures prescribed under the Land Acquisition Act (LA Act), 1894. Power grid sub-stations have never suffered mass displacement or livelihood. The LA Act specifies that in all cases of land acquisition, no rewards of land can be given by government officials unless all the compensation has been paid.

8. Impact Due to Project Location and Design:

The ecological effects of transmission line projects have not reached far and most are localized in ROW. However, the Transmission Line project has some impact on natural and social-culture resources. In order to reduce the environmental impact, especially the sensitive areas such as water bodies, temples, school buildings etc. have been avoided by installing special towers.To reduce the cutting of trees in the garden, extension towers have been provided at different places. These effects can be minimized by careful route selection. Thus, it required large no of tower and capital cost of transmission line increased. The transmission company have to handle some problem such as Resettlement, Land value depreciation, Historical value, Encroachment into other valuable lands, Interference with other utilities and traffic.

9. Environmental Problems Due to Design:

9.1. Polluting Materials:

Instruments installed on lines and substations are static in nature and they should not produce any fumes and waste materials. One section has been included in the contract section to avoid / reduce construction phase and the site engineers are regularly supervising.

9.2. Fire/Explosion Hazards:

During survey and site selection for transmission lines and sub-stations, it has been ensured that they are kept away from the oil / gas pipelines and other sites which are susceptible to explosion or fire. Due to the flashover from the lines, there may be a more serious problem in the fire forest. However, adequate safeguards will be taken to avoid such incidents. Besides this, forest officials also include measures like making fire lines to prevent fire spread in affected forest areas.

9.3. Environmental aesthetics:

Since spacing between the towers in case of 400 KV D/C lines is approx. 300-400 meters these will not affect the visual aesthetics of the localities particularly when it is ensured to route the lines as far away from the localities as possible. Since the spacing between the towers in the case of 400 KV D / C lines approx. This will not affect the distance between 300 and 400 meters on the visual beauty of sites, especially when ensuring that routes are routed away from local areas as much as possible.

In this section, discussed about mandatory requirements for constructing new transmission line. There are lot of constraints to fulfil for construction of new transmission lines. Therefore, the existing AC transmission lines can be upgrade by injecting third harmonic voltages. In next section, the explanation of the proposed line design method are given.

III. EXPLANATION OF THE PROPOSED LINE DESIGN METHD

Fig.1 shows the simplified diagram of proposed transmission lines with injected third harmonic voltage.

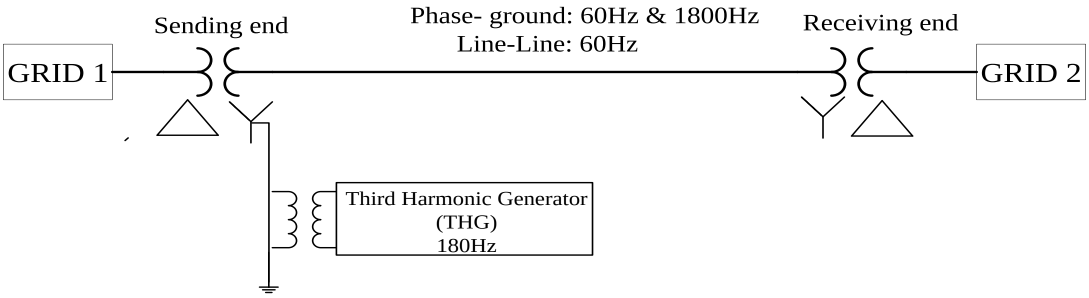


Fig.1 shows the simplified diagram of proposed transmission lines with injected third harmonic voltage.

The third harmonic voltage is injected to transmission lines through sending end neutral by single phase third harmonic generator. Third harmonic generator (THG) nothing but generator frequency could be three times the fundamental frequency. The THG can be fulfil by single phase inverter or synchronous machine. The receiving side transformer neutral is not grounded, thus third harmonic current does not get return path and would not present to power flow. Adding third harmonic voltages are cophasal, thus THV vanish in line to line voltage.

1. Third harmonic injection in power electronics:

Generally, undesired frequency such that any frequency except fundamental frequency and its try to removed out from the system. However, power electronics engineers have benefited from undesired frequency such as third harmonic voltage to pulse width modulation in an inverter for few decades [6]-[7]. it is achievable to get a peak to peak line output voltage of inverter is 15 % more than DC link voltage by adding third harmonic voltage. While line to line voltage undistorted.

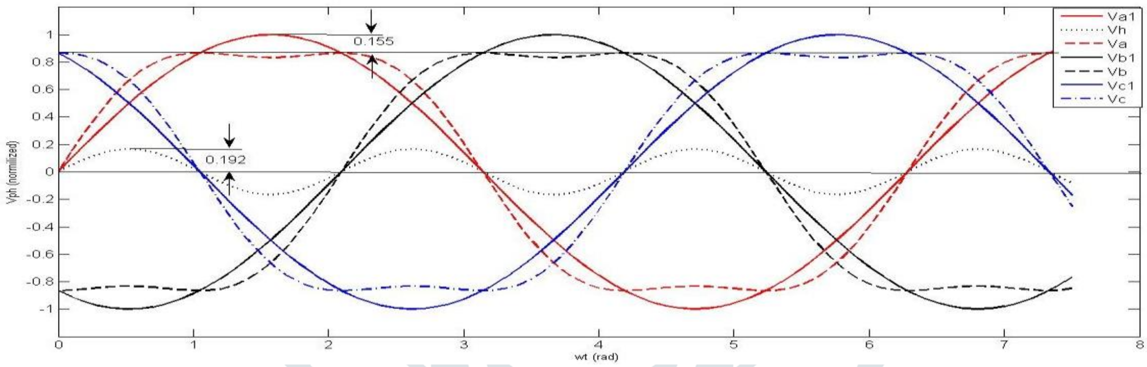


Fig. 2. Increasing inverter gain by THV injection

Shown in fig. 2, the output of three phase inverter are Va, Vb and Vc and Vh is third harmonic voltage. However, third harmonic voltage injected to output of three phase inverter thus their fundamental component Va1, Vb1, Vc1 are increased by 15.5%. To conclude, third harmonic voltage injection is used in an inverter system to increase the modulation index range and without increasing the voltage rating of these devices, the inverter voltage rating is increased.

2. Third Harmonic Injection, a proposal in Power Systems:

The key determinant of transmission line investment is its voltage level and thus may be the cost of any improvement in the sector-benefits. In section A-1, The injection was given to increase the peak amplitude of phase voltage in THV. The same concept could be implemented to reduce the peak amplitude of phase voltages. The implementation of third harmonic voltage injected through sending end transformer shown in fig.3.

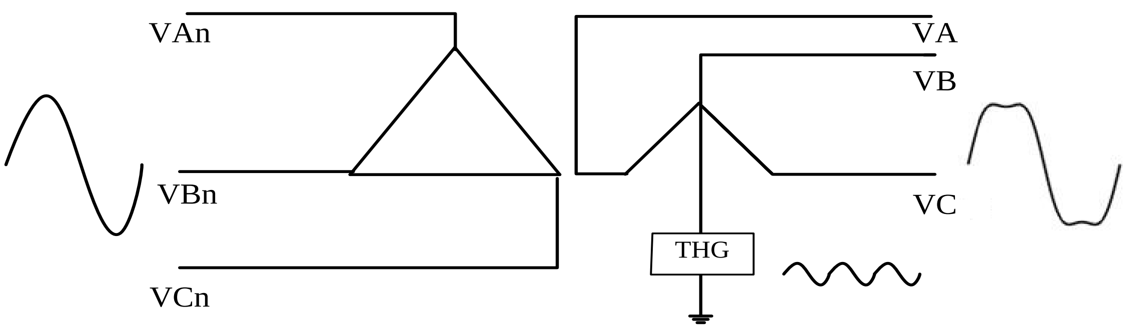


Fig. 3 Sending-end transformer with THV injection.

In Fig.3, the third harmonic voltage Vh injected through neutral of sending end transformer secondary winding and got a phase voltage VA, VB and VC which has peak amplitude decreases by 13.3 %. The mathematical expression of fundamental and third harmonic voltages as follows:

$$V_A = V_{An} + V_h = V\sin(\omega t) + V_h \sin(3\omega t),$$
$$V_B = V_{Bn} + V_h = V\sin\left(\omega t - {}^{2\pi}/_{3}\right) + V_h \sin(3\omega t), \qquad (1)$$
$$V_C = V_{cn} + V_h = V\sin\left(\omega t + {}^{2\pi}/_{3}\right) + V_h \sin(3\omega t),$$

Where, $\mathbf{V_A}$, $\mathbf{V_B}$ and $\mathbf{V_C}$ are the total components of phase voltages. And $\mathbf{V_{Kn}}$ (K = A, B, C) are fundamental components of phase voltages, ω is the system angular frequency. The third harmonic voltage is denoted by $\mathbf{V_h}$ which has one sixth of peak amplitude of fundamental phase voltages V. It should be remembered that line to line voltage remains intact. . Fig.4. shows that injecting THV could decrease the peak amplitude of phase voltages by 13.4%.

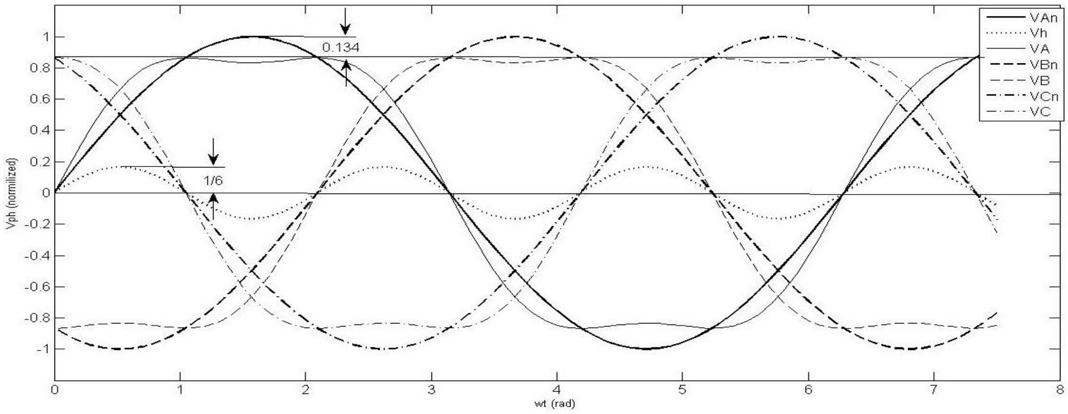


Fig. 4. Decreasing voltage peak amplitude by THV injection**.**

3. Third Harmonic Generator (THG):

The third harmonic generator nothing but it has frequency three times of the fundamental frequency. The single phase synchronous machine or inverter can be implemented as third harmonic generator. In case of synchronous machine, higher pole number (**P**) or mechanical speed ($\mathbf{n_s}$) must be selected. The mathematical relation between electrical frequency and number of pole could be expressed as:

$$n_s = \frac{120f}{p} \qquad (2)$$

Here, f= 150 Hz: $n_s \times p = 18000$.

Therefore, small scale synchronous machine could be reduced speed by increasing no of pole and another approach is to use single phase inverter by using step up transformer shown in fig. 1. To ensure the correct combination of fundamental and THV components, a phase lock loop (PLL) [8] unit must be connected to THG. Function of PLL is generate output signal whose phase is related to the phase of an input signal.

4. Influence of Third Harmonic Injection on Ground Clearance:

One of the important components of any overhead transmission line are transmission towers. Their work is to keep high-voltage conductors separated from each other and provide some kind of approval. To know the effect of third harmonic injection on the needed clearances, they are first presented as follows:

4.1. Phase-to-Phase Clearance:

It is adequate clearance between two phase conductors of electrical transmission line. It is adequate clearance between two Phase conductors of electrical transmission line. It is required to prohibit swinging contacts and flashovers between conductors. For calculating phase to phase clearance line to line voltage is main deciding factor [9].

4.2. Clearance between phase conductor and earth wire:

It is also known as clearance between Air Clearance. To ensure the clearance of air, the conductor is able to withstand the overvoltage due to electric power frequency and switching or lighting sources[10].

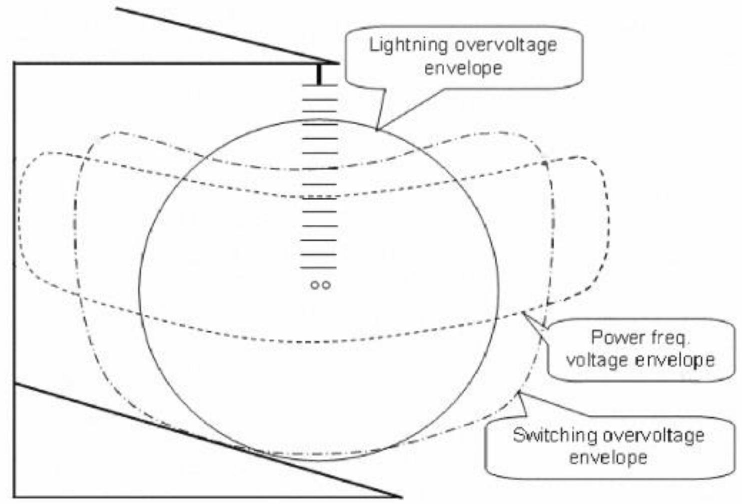


Fig. 5. Clearance envelopes for various overvoltages.

4.3 Ground Clearance:

The clearance between ground and mid-span of lowest conductor of transmission lines is known as ground clearance. It is required to maintain safety clearance of phase conductor to ground for prevent accident. It is dependence on the type of surrounding area and operating maximum phase to ground voltage. For example ,]RUS Bulletin 1724E-200, "Design manual for high voltage transmission lines," Electric Staff Division, Rural Utilities Service, U.S. Department of Agriculture, Washington, USA, Tech. Rep., 2009.For example As per Indian Electricity Rule 1956, Clause No 77, the minimum distance between bottom conductor and ground of a 33KV uninsulated electrical conductor is 5.2 meter, is increased by 0.3 meter for every 33KV above 33KV.for example of 230kv transmission line would be

230KV – 33KV = 197KV and 197KV/33KV ≈ 5.9696

Now, 5.9696 X 0.3 = 1.79 meter.

So, as per logic, the ground clearance of 220KV bottom conductor would be, 5.2 + 1.79 = 6.99 ≈ 7 meter.
The proposed method reduces the peak amplitude of phase voltages and leaves the line-to-line voltages intact. Thus, the ground clearance requirement could be reduced while air and phase-to-phase clearances continue to be fulfilled. Transmission Companies could be cut the line investment by using shorter electrical transmission towers and narrower ROW.

4.4Influence of Third Harmonic Injection on Line Loadability:

The without exceeding the ground clearance, the rms-value of the phase voltages can be increased by 15.5% as shown in figure 2. This increases the surge impedance loading (SIL) of the line by 33%, which relates directly to line loadability [1]. The design transmission lines could be increased up to 15.5 % without affecting ground clearances. Since the peak-amplitude of phase voltages remain same. The loadability of transmission line can be increase by increasing phase voltage but phase to phase clearance also increases. In fact, many transmission tower types are capable of providing high phase to phase approvals and they are mostly limited by their air clearances. Air clearance remains intact due to injecting third harmonic voltage. Thus, it can be concluded that the transmission tower is likely to be eligible for THV upgrade by injections compared to conventional voltage uprating. H.P. St. Clair introduced the concept of line loadability expressed as a percentage of surge impedance load (SIL) in 1953 through St. Clair curves [11]. The universal loadability curve was used in approximately calculating the loadability of transmission lines of the network. There are three factors that limit the power through a transmission line, the thermal limit, limit of voltage drop and small-signal stability limit .The value of SIL was calculated,

$$\mathrm{SIL} = \frac{\mathrm{VLL}}{Z_{\mathrm{surge}}} = 3\,\frac{\mathrm{Vph}^2}{Z_{\mathrm{surge}}} \quad (3)$$

V_L Is the rated line to line voltage of the transmission line and Z_c is the characteristic impedance of the line [11].

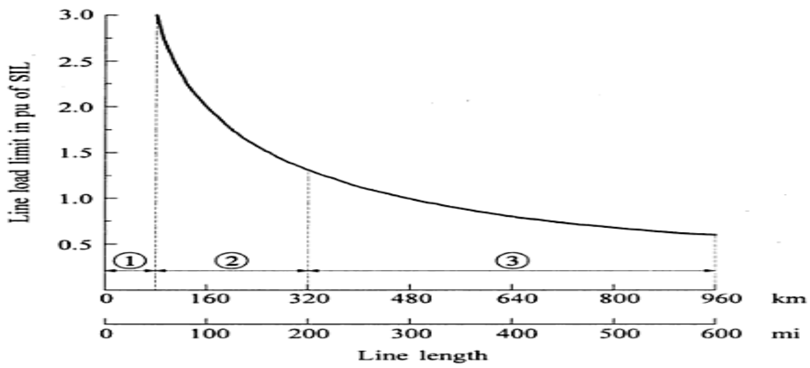


Figure 6: Transmission line loadability curve

It can easily suggest the maximum loading capability of transmission line for different line length using the above power transfer capability curve or Universal Line Loadability Curve. For example, if line length is 300 km, then line loadability will be around 1.5 times of Surge Impedance Loading.

IV. CONSIDERATION IN INJECTION OF THIRD HARMONIC VOLTAGES

In the previous section, how to generate third harmonic voltage and influence of third harmonic voltage into electrical transmission line was discussed. In this section, the practical valuation of electrical power transmission line with injected third harmonic voltage is studied.

1. Magnetic coupling with oil/Gas pipelines:

In the last few decades, the development in electric power, petroleum and underground pipelines are increasing rapidly. They are crossing each other or parallel to each other most of times. One of the reason of corrosion occurs between them is AC current. One of the most recent standards on this topic has specifically stated: “the contribution of the third harmonic to induction on pipelines has been observed in some situations. Industry understanding of the impact on pipeline induction from harmonics on the transmission system is not mature at this time; material on the subject will be considered in a future update to this Standard.” The corrosion also dependence on AC power supply frequency. When frequency less than 130 Hz then AC corrosion mainly occurs. And the corrosion rate could be decrease by increasing frequency [12]. In the power transmission line third harmonic voltage frequency more than 130Hz Therefore, the influence of insignificant third harmonic current on magnetic coupling with adjacent pipeline and its corrosion rate seems to be negligible.

2. Charging Current in the proposed transmission Line:

In a transmission line, air acts as a dielectric medium between the conductors. When the voltage is applied across the sending end of the transmission line, current starts flowing between the conductors (due to imperfections of the dielectric medium). This current is called the charging current in the transmission line**.** The charging current shown in figure (7).

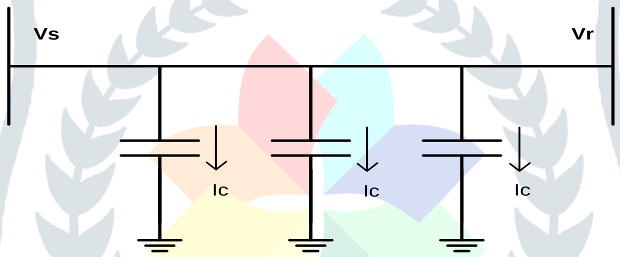


Fig. 7. Charging current of transmission line.

In transmission lines, the two sources of capacitance. One of them is capacitance between two phases is called mutual capacitance Cm other is capacitance between phase and ground is called self-capacitance Cg shown in fig. 8. Injection of third harmonic voltage in transmission lines,

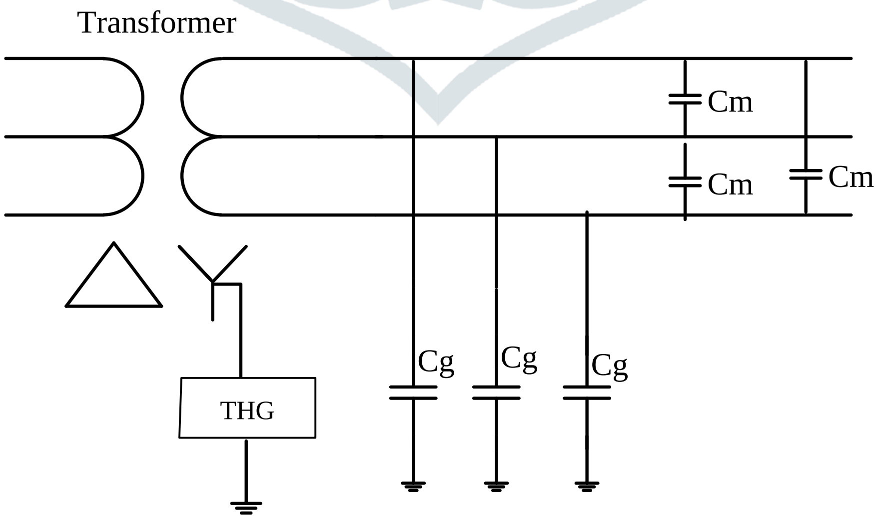


Fig. 8. Different sources of transmission line capacitance.

Only affects the phase voltages and thus phase-to-ground charging currents. A key determinant of charging current amplitude is the voltage profile over the line which depends on the line loading and whether the line is compensated or not. Here, it is assumed that the voltage has a uniform profile over the line. In conventional transmission lines, total reactive power generated from mutual capacitance and phase to ground obtained as:

$$\begin{aligned} Q_1 &= Q_{Cm} + Q_{Cg} \\ &= 3\omega C_m {V_{LL}}^2 + 3\omega C_g (V/\sqrt{2})^2 \\ &= 4.5\omega C_m V^2 + 1.5\omega C_g V^2 \end{aligned} \quad (4)$$

Where, V is the peak amplitude of phase voltage and V_{LL} is the line to line rms voltage value. In the system, V_{LL} is the rms-value of line-to-line voltage and V is peak-amplitude of the phase voltage. In the proposed system, Q_3 is an additional reactive power, associated with injected third harmonic voltage (i.e. $V_h = V/6$). Thus:

$$Q_3 = 1.5(3\omega)C_g\left(V/6\right)^2 = 0.125\omega C_g V^2 \quad (5)$$

According to Eqs. (4) and (5), the ratio of Q_3 to Q_1 is obtained as:

$$Q_{tf} = \frac{Q_3}{Q_1} = \frac{1}{12+36K_c} \quad (7)$$

$$\text{Where, } K_c = \frac{C_m}{C_g}$$

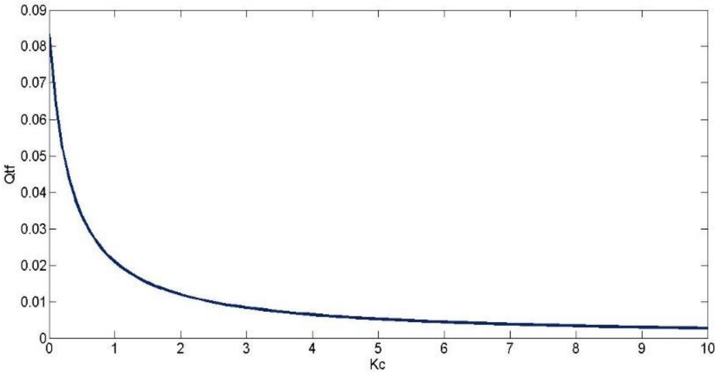


Fig. 9. Ratio of charging volt-amperes vs. ratio of sequence capacitances.

In fig.9 shows the relationships between Ratio of charging volt-amperes and ratio of sequence capacitances by using equation (5) .Increasing value of K_c the ratio of Q_{tf} is decreasing.

4) Displacement of Third Harmonic Voltage:

In proposed system, at the end of sending the adjusted phase with the difference, between them two volts between 60 Hz and 180 Hz are combined. In fig. 10 shows how to vary peak amplitude of phase voltage after injecting third harmonic voltage at difference phase angle. Fig. 11 shows the relation between peak amplitude of phase voltage variation (ΔV_{peak}) and phase-angle difference (Δt).

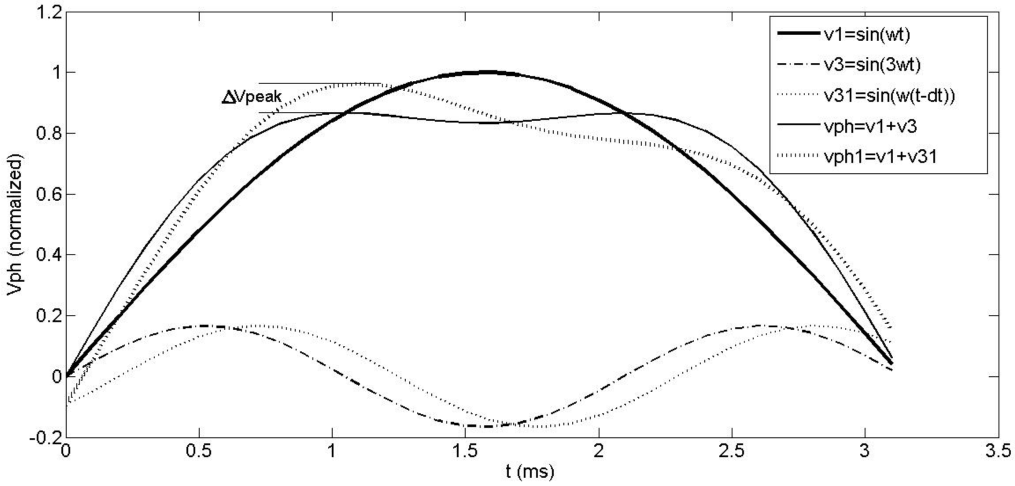


Fig. 10. Different combination of fundamental and third harmonic voltages.

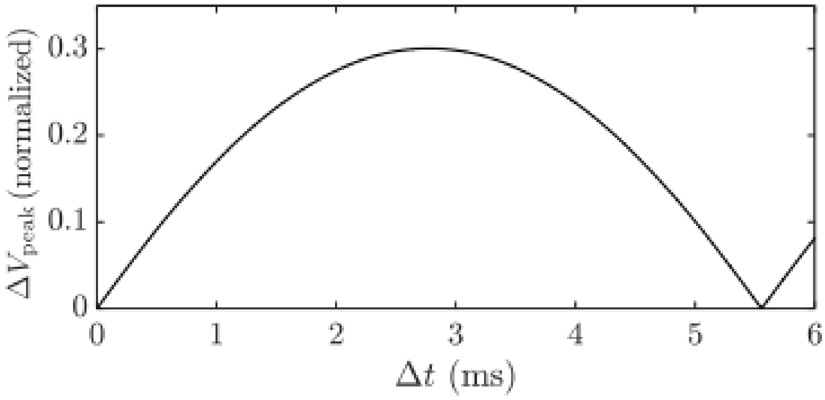


Fig. 11. The impact of phase-angle shift on voltage peak variation

To achieve the lowest peak amplitude of phase voltage (i.e. $\Delta V_{peak}= 0$), it is required to have $\Delta t = 0$ at both sides of the line However, in practice, this cannot be obtained for two reasons:

1) Signal Dispersion:

The electromagnetic waves travel through a transmission line with the propagation speed (V_p) or speed of phase velocity. For a lossless line, Vp equals 1/√LC which is the independent from frequency and line's inherent characteristic. In practice, a transmission lines are lossy and V_p is frequency-dependent. Consider a signal that is constructed at sending-end of a long transmission line by combining multiple signals with different frequencies. As a result of difference in their velocities, the constructed signal will arrive at the receiving-end distorted. This phenomenon is known as signal dispersion that is a similar challenge in an optic line transmitting data by combining signals in different frequencies [14]. v_p Is calculate as [15]:

$$v_p = \frac{\omega}{Im\left\{\sqrt{(R+j\omega L)(G+j\omega C)}\right\}} = \frac{1}{Im\left\{\sqrt{\left(\frac{R}{\omega L}+j\right)\left(\frac{G}{\omega C}+j\omega C\right)}\right\}} \times \frac{1}{\sqrt{LC}} \quad (8)$$

$\frac{G}{\omega C}$ Equal to zero in an overhead line. Thus:

$$v_p = k \times \frac{1}{\sqrt{LC}}, K = \frac{1}{Im\{\sqrt{-1+i\alpha}\}}, \alpha = \frac{R}{\omega L} \quad (9)$$

The value of ω is three times in 180 Hz as compare to 60 Hz. the value of series resistance R is equal to root three times larger than in 180 Hz as compare to 60 Hz due to skin effect. For overhead HVAC line, α_{60Hz} is a small value $(0 \le \alpha_{60Hz} \le 1)$ which is depends on the conductor type [13]. It is consider that propagation speed in lossless overhead line almost equal to the speed of ligh t[15]. Shown in fig. 11 for minimized impact of signal dispersion on both ends, the transmission line design such that least peak amplitude of phase occurs in the middle of line. Thus, the arrival time difference for 180Hz and 60Hz voltages in receiving-end which is caused by signal dispersion, is calculated as:

$$\Delta t_{sd} = \frac{l/2}{v_{p\_60Hz}} - \frac{l/2}{v_{p\_180Hz}} \quad (10)$$

In equation (10) l is the line length of line. In fig.14 shows the relation between Δt_{sd} and length of line when α_{60Hz} is varied. By comparing figs.11 and 13, it is conclude that, signal dispersion could become negligible, if the accurate controlled the injection of harmonic voltage.

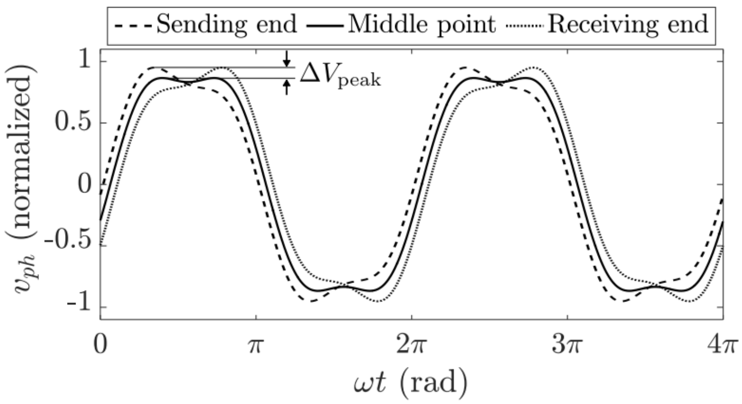


Fig. 13. Distributing ΔV_{peak} variation in the proposed system.

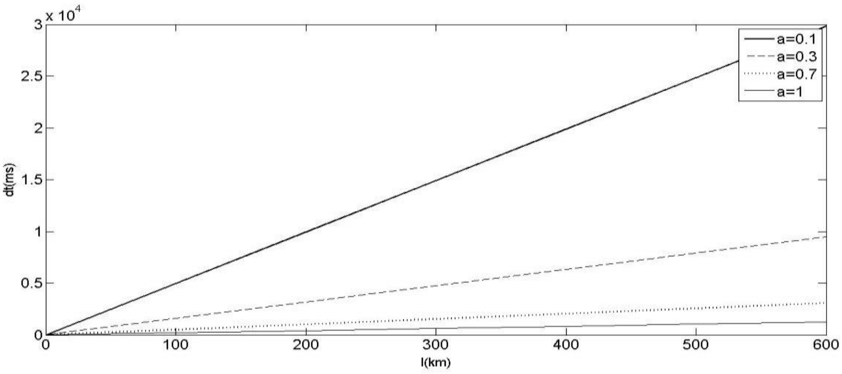


Fig. 14. The variation of phase voltage peak amplitude vs. line length.

2) Load Angle:

Assume a lossless transmission line represented using its nominal Π model and Xi is the transmission line's series impedance. The power transferred through the transmission line is calculated as:

$$p = \frac{3V_sV_r}{X_i}\sin\delta \qquad (11)$$

Where, Vr and Vs are the rms-value of receiving and sending phase voltages, δ is known as load angle. In short transmission line, the thermal limit of conductor has main factor of limiting power which is almost 2.3 SIL. In this case, the δ value depends on the line length. For example, consider a 240 kV with Xi = 0.3681 Ω/km and surge impedance of Z_{surge} = 286 Ω. Thus,

$$P = 2.3\ SIL = 2.3\frac{V^2}{Z_{surge}} = \frac{V^2}{124.3} \qquad (12)$$

where, V is the rms-value of line-to-line voltage. If it is assumed Vs = Vr = V/√3, from Eq. (11):

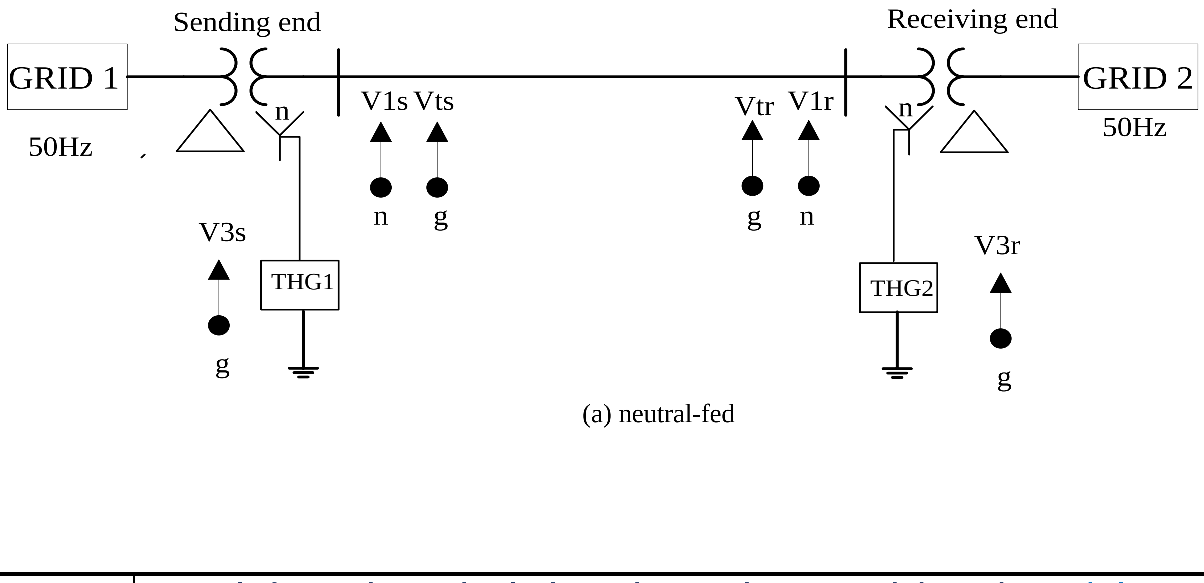
$$\frac{V^2}{124.3} = \frac{V^2 sin\delta}{0.3681 \times l}$$

$$\delta = \sin^{-1}(2.961 \times 10^{-3} l) \qquad (13)$$

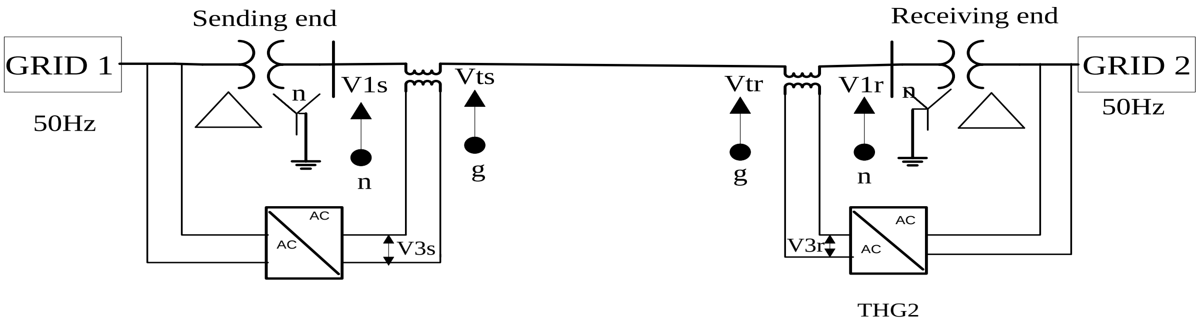
Where, l is the line length in Km. this line operates with injected THV in its thermal limit and it is designed to have the least peak amplitude in the middle of the line (see Fig. 13). Thus, the value of δ in the receiving end which could be obtained by Eq. (13). Third harmonic voltage could not contribute power transfer because of receiving side third harmonic remains intact and does not have phase angle with sending end. For long AC transmission lines, load angle should not exceed 44° due to angular stability limit. Consider long transmission line with injected third harmonic voltage at sending end has time difference between 60Hz and 180Hz voltage is almost equal to 1 ms caused due to load angle. To sum up, the proposed system with one THG at the sending-end is suitable for short transmission lines. As for longer AC lines, the arrival time difference is considerable and the variation of phase voltage peak amplitude may not be tolerable. In the next section, to tackle this problem in the long transmission line two modified versions of line with injected THV are suggested.

V.SUBSTITUTE FOR LONGER TRANSMISSION LINES

In this section, the proposed two alternative method for overcome arrival time difference and variation of peak amplitude of phase voltage in transmission lines. Two alternative method shown in fig. 15.



(a) neutral-fed



(b) Line-fed

Fig. 15. Single line diagram of the proposed alternatives for longer transmission lines.

The two third harmonic voltages could be injected sending and receiving end side. Shown in fig. 15 (a), Third harmonic voltages injected by third harmonic generator through neutral of star winding of both sides of transformer and fig. 15 (b), third harmonic voltages injected by two AC/AC converter in transmission lines. Therefore, the least peak amplitude of the phase voltages is ensured along the line. Voltage distribution of the line with injected two third harmonic generators shown in fig. 16.

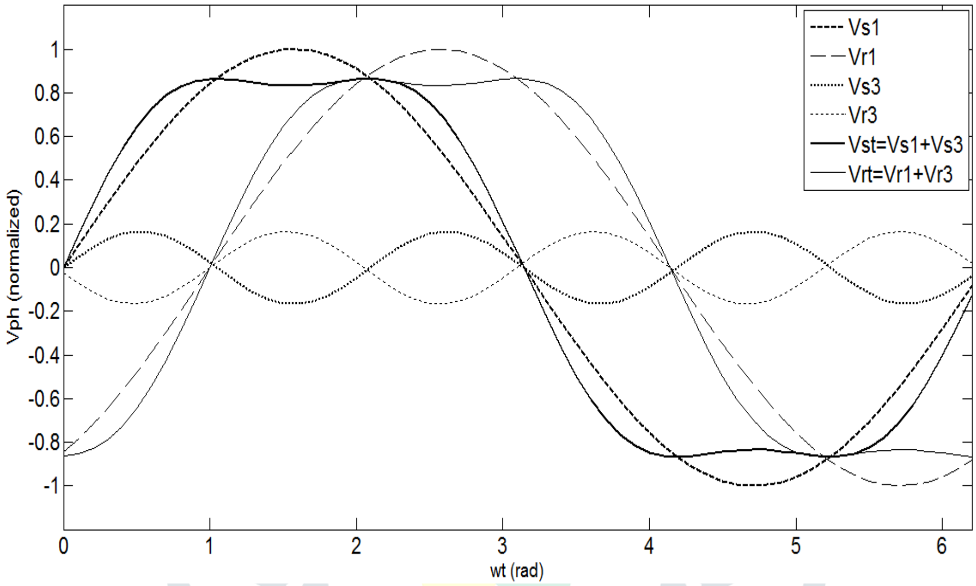


Fig. 16. Voltage distribution of the line with two THGs

In this scenario, the active power transfer both fundamental and third harmonic voltage component. How much power transferred by each component in lossless lines can calculated as equation 14 and 15.

$$P_1 = \frac{3V_{1s}V_{1r}}{X_{il\_60Hz}} \sin\delta \qquad (14)$$

$$P_3 = \frac{3V_{3s}V_{3r}}{X_{io\_180Hz}} sin3\delta \qquad (15)$$

Where, P_1 and P_3 are the active power transferred of fundamental and third harmonic voltage components and δ is the load angle. V_{1s} And V_{1r} are the rms-value of fundamental phase voltage at sending and receiving ends. V_{3s}And V_{3r} are the rms-value of injected THV at sending and receiving ends, respectively. X_{il_60Hz} And X_{io_180Hz} are positive and zero-sequences of the transmission line impedance. In transmission lines zero sequence impedance is three times of positive sequence impedance and also inductive reactance directly proportional to the frequency. It could be written as $X_{io\_180Hz} = 9X_{i1\_60Hz}$. The ratio of fundamental and third harmonic components power is calculate as:

$$P_{tf} = \frac{P_3}{P_1} = \frac{V_{3s}}{V_{1s}} \times \frac{V_{3r}}{V_{1r}} \times \frac{X_{i1\_60Hz}}{X_{i0\_180Hz}} \times \frac{\sin3\delta}{\sin\delta}$$

$$= \frac{1}{6} \times \frac{1}{6} \times \frac{1}{9} \times \frac{X_{i1\_60Hz}}{X_{i0\_180Hz}} \times \frac{\sin3\delta}{\sin\delta}$$

$$= 3.086 \times 10^{-3} \times \frac{\sin 3\delta}{\sin\delta} \qquad (16)$$

If the line operates in its stability limit, then:

$$\delta = 44 \circ \rightarrow P_{tf} = 3.302 \times 10^{-3} \qquad (17)$$

If the line operates with light loading (i.e. small δ), then:

$$\sin 3\delta \approx 3 \sin \delta \rightarrow P_{tf} = 9.259 \times 10^{-3} \qquad (18)$$

Power delivered rating of third harmonic component much smaller than fundamental component. . For example, consider a 200 MW line with allowable load angle between 0 ◦ and 44 ◦. The maximum active power transferred by the AC/AC converters occurs when δ = 30 ◦ (sin3δ = 1) and it is equal to 0.88 MW.

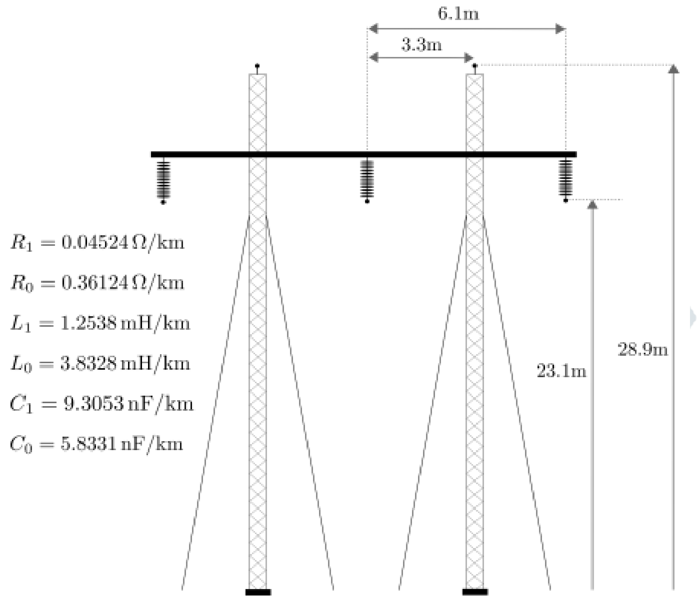


Fig. 17. 230 kV H-frame transmission line [1]

VI. CASE STUDY

A fully-transposed 230 kV H-frame transmission line (see Fig. 17) is selected for the power system shown in Fig. 18.

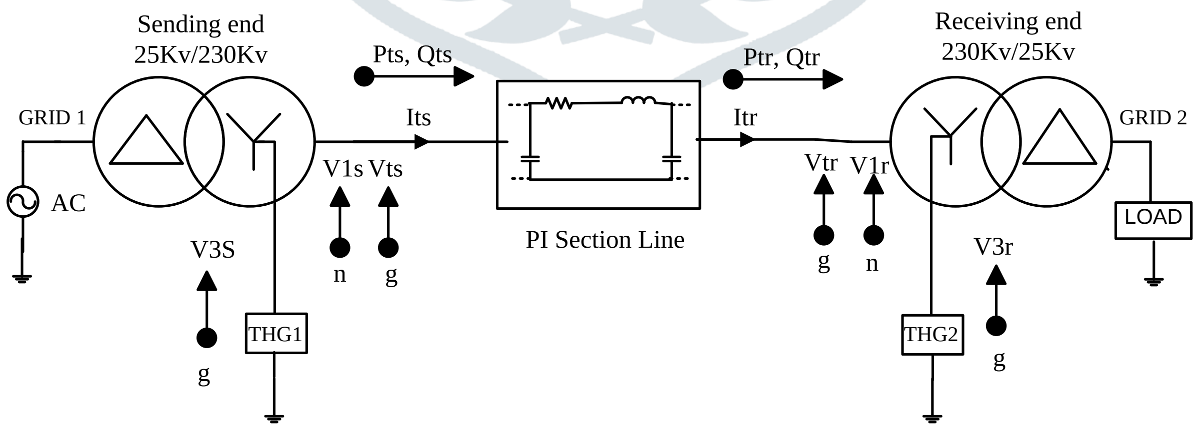
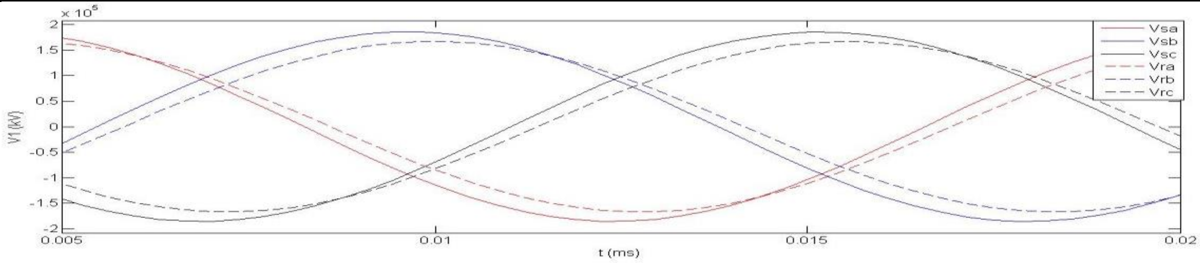
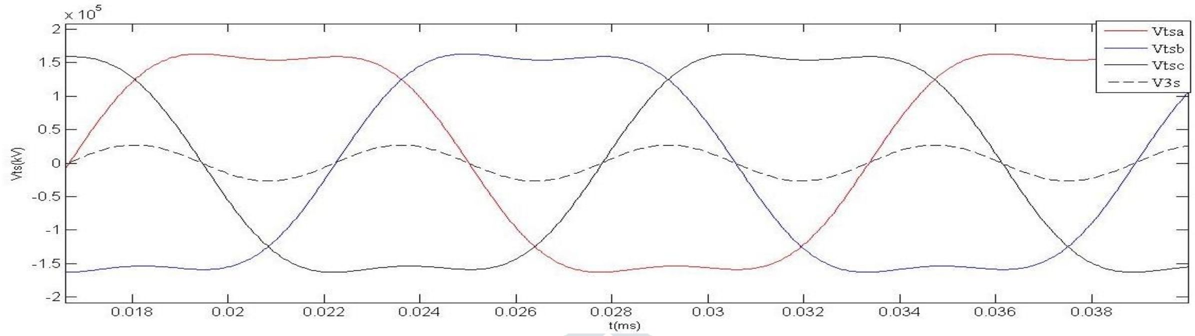


Fig. 18. Single-line diagram of the studied transmission line.

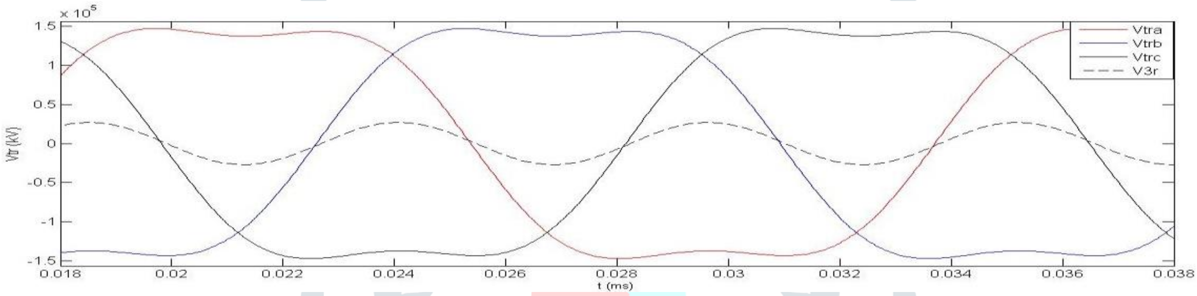
The 230kV, 150MVA long transmission line is designed with 300 Km of length and using single bundle conductor of martin. The 230kV, 150MVA long transmission line is designed with 300 Km of length and using single bundle conductor of martin. The MATLAB/Simulink results shown in fig.16. In this the fundamental component of phase voltage of sending end and receiving end are shown in fig 16(a). After the injection of third harmonics voltages on both ends, peak amplitude of sending end voltages drops from 184.68kV to 159.4kV as shown in fig.16(b)and peak amplitude of phase voltages drops from 167.16kv to 145.4kV as shown in fig.16(c) and also comparison between total phase voltage and fundamental phase voltage presents in fig.16(d). Theoretically and practically verify the peak amplitude of phase voltages are reduced by 13.3% after injecting third harmonic voltage. According to [1], phase to ground clearance reduced while line to line voltage remains intact. Therefore, existing transmission line could be upgraded or new transmission line can be constructed by shorter transmission tower.



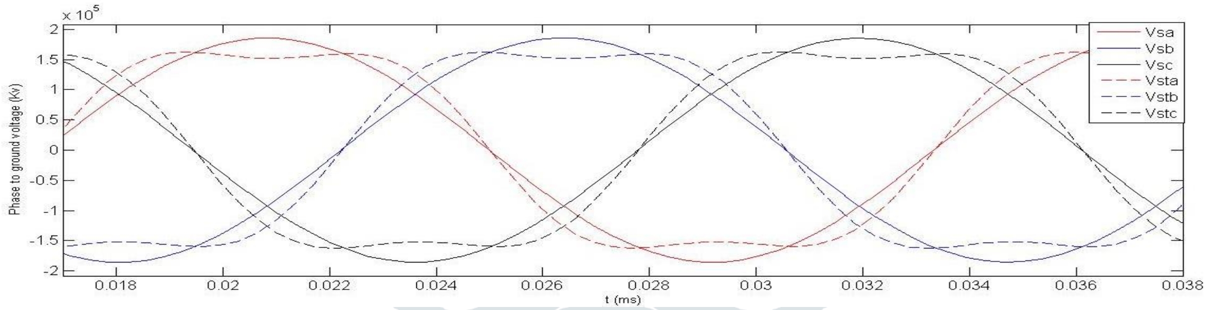
(a) Fundamental component of the phase voltages.



(b) Sending end phase voltage by injecting third harmonic voltage.



(c) Receiving end phase voltage by injecting third harmonic voltage.



(d) Compare fundamental and total phase voltage at sending end.

Fig.16. simulation result.

With this approach,loadability of transmission line could be increased 33% [1]. In long transmission line up to 320 km, the power is limited by voltage drop and thermal limit [] which will be around 1.5 SIL[23].In studied transmission line , phase voltage Vph=132.79 kV, series reactance = 137.01 Ω and surge impedance loading Z_c =357.66 Ω. Assume that Vsph=Vrph=Vph. Thus,

$$\text{SIL} = 3\,\frac{\text{Vph}^2}{Z_{\text{surge}}} \qquad (19)$$

$$\text{Loadability} = 1.5\ \text{SIL} \qquad (20)$$

From equation (19), SIL of transmission line is 147.90 MW and from equation (20) loadability is 221.85 MVA. After injecting third harmonic voltage, the rms value of phase to ground voltage can be increased up 15.5 percent without increasing phase to ground clearance [1]. Therefore, transmission line voltage could be increased up to 153.37 kV. From equation (19) and (20), the new SIL and loadability are 197.30MW and 295.95MVA. After Injecting third harmonic voltage, the line loadability can be increased up to 33.4%.

VI. CONCLUSION

The proposed method is discussed that injection of third harmonic voltage in transmission line to reduce peak amplitude of phase voltage and ground clearance dependence on peak amplitude of phase voltage. Thus, reduces the required conductor-to-ground clearance by injecting third harmonic voltage. The loadability of transmission line can be increased by injecting third harmonic voltage. Thus, transmission line could be upgraded. To reduces the required conductor-to-ground clearance by injecting third harmonic voltage.

REFERENCES

[1] Ramiar Alae and S. Ali Khajehoddin, "The operation of a power transmission line with injected third harmonic voltage," *IEEE Trans. On Power Delivery Volume: 32, Issue: 1, Feb. 2017.*

[2] F. Hubert and M. Gent, "Half-wavelength power transmission lines," *IEEE Transactions on Power Apparatus and Systems*, vol. 84, no. 10, pp. 965–974, 1965

[3] G. Samorodov, "Four-phase transmission systems and estimation of effectiveness of their application for power transmission from the Three Gorges Plant to East China," in *Proc. International Conference on Power System Technology (POWERCON)*, Beijing, China, Aug. 1998, pp. 146 – 150.

[4] H. Rahman and B. H. Khan, "Power upgrading of transmission line by combining AC-DC transmission," *IEEE Transactions on Power Systems*, vol. 22, no. 1, pp. 459–466, 2007.

[5] B Reisdorff, "Increasing transmission capacity case studies and techniques, increased transmission capacity by increasing ground clearance - a manufacturers perspective," in *Proc. IEEE International Conference on Transmission & Distribution Construction, Operation and Live-Line Maintenance (ESMO)*, Albuquerque, USA, Oct. 2006, pp. 1–7.

[6] J. A. Houldsworth and D. A. Grant, "The use of harmonic distortion to increase the output voltage of a three-phase PWM inverter," *IEEE Transactions on Industry Applications*, vol. IA-20, no. 5, pp. 1224–1228, 1984.

[7] M. A. Boost and P. D. Ziogas, "State-of-the-art carrier PWM techniques: a critical evaluation," *IEEE Transactions on Industry Applications*, vol. 24, no. 2, pp. 271–280, 1988.

[8] G.-C. Hsieh and J. C. Hung, "Phase-locked loop techniques. A survey," *IEEE Transactions on Industrial Electronics*, vol. 43, no. 6, pp. 609–615, 1996.

[9] RUS Bulletin 1724E-200, "Design manual for high voltage transmission lines," Electric Staff Division, Rural Utilities Service, U.S. Department of Agriculture, Washington, USA, Tech. Rep., 2009.

[10] S. Venkatesan, R. Bhattarai, M. Osborne, A. Haddad, H. Griffiths, and N. Harid, "A case study on voltage uprating of overhead lines air clearance requirements," in *Proc. International Universities Power Engineering Conference (UPEC)*, Cardiff, Wales, Sep. 2010, pp. 1 – 5

[11] P. Kundur, N. J. Balu, and M. G. Lauby, *Power system stability and control*. New York: McGraw-Hill, 1994.

[12] Y.-B. Guo, C. Liu, D.-G. Wang, and S.-H. Liu, "Effects of alternating current interference on corrosion of X60 pipeline steel," *Petroleum Science*, vol. 12, no. 2, pp. 316–324, 2015.

[13] L. L. Grigsby, *Electric Power Generation, Transmission, and Distribution*, 3rd ed., ser. Electric Power Engineering Series. Boca Raton, USA: CRC Press, 2012.

[14] P. G. Huray, *the Foundations of Signal Integrity*. Hoboken, USA: Wiley-IEEE Press, 2009.

[15] A. L. Shenkman and M. Zarudi, *Circuit Analysis for Power Engineering Handbook*. New York City, USA: Springer US, 1998.