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Harmonic Damping in DG-Penetrated Distribution Network

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***Abstract*—Grid background harmonics may be amplified, propagate through a long distribution feeder and even lead to power system instability. In this paper, harmonic propagation issue is investigated and mitigation of the harmonics is analyzed by using transmission line theory which has already been applied in power systems. It is demonstrated that a specific harmonic will not be amplified if the feeder's length is less than one quarter of the harmonic wavelength meanwhile the terminal impedance is less than characteristic impedance. Besides, three scenarios will be considered in accordance with the relationship between the feeder's length and harmonic wavelength. Harmonic suppression control strategies will be respectively designed considering 5th and 7th harmonics coexisting in the distribution line. Finally, a simulation study has been performed to verify the theoretical analysis and demonstrate the effectiveness of the proposed strategy.**

Keywords—virtual impedance; harmonic damping; distributed generation;

I. INTRODUCTION

Recently, high penetration of nonlinear loads, such as rectifier diodes and switching power electronic devices that interfaces into the power system result in significant harmonic pollution in distribution networks. These harmonics that exist in the upstream of power distribution network are propagated and amplified through a transformer to the downstream of low voltage distribution feeder, which implies the harmonics may exist at the beginning node of downstream feeder. These background harmonics in low voltage feeder may affect the sensitive loads operation and even the stability of power system. In order to suppress harmonic voltage propagation and amplification, passive or active damping methods have been chosen in the power distribution system [1]. However, passive damping of harmonic propagation is fading out due to power losses, bulky volume and additional cost.

On the other hand, resistive active power filter (R-APF) has been extensively adopted in the power system to damp out harmonic. For instance, it is proposed in [1] to install R-APF at the end of a radial distribution line to damp out the amplification of harmonics, where harmonic propagation was suppressed by controlling virtual impedance of R-APF to be equal with the line characteristic impedance (LCI) at the selected harmonic frequency. Similar approach was proposed by [2] where a discrete frequency-tuning APF operated as a variable conductance at the selected frequency to mitigate the power system harmonics. Additionally, in [3] multiple R-APFs were implemented by designing droop control strategy to achieve harmonic sharing ability among multiple converters. Recently, R-APF has been successfully implemented in distribution power system and loop power systems. Reference [4] proposed a site selection method for R-APF to damp the harmonics in radial distribution system. It can achieve better harmonic damping performance if the R-APF's installation site is properly selected. Moreover, a hybrid series filters control strategy was proposed by [5] in the loop power system where the R-APF could be located anywhere in the loop line to improve THD of the system.

Meanwhile, nowadays, the concept of Renewable Energy Source(RES) based distribution generation(DG) units with the function of addressing power quality issues has drawn much attention [6]. In [7] R-APF function has been incorporated into primary DG power control by utilizing Current-Controlled Method (CCM). Besides, Voltage-Controlled Method(VCM) is also implemented in the literature in achieving power quality improvement with nonlinear load connecting at the Point of Common Coupling (PCC). Recently, a virtual impedance based control algorithm with DG unit was proposed by [8] at the terminal of the feeder to mitigate harmonic propagation and resonance issue. However, only one or two DG units that are connected at the terminal of long feeder can not achieve effective harmonic damping. Harmonic voltage mitigation methods should be customized based on the length of the feeder. According to transmission line theory, harmonic mitigation methods that are effective for one specified feeder's length may deteriorate and propagate the harmonics when feeder's length varies. However, customized harmonic mitigation methods according to feeder's length variation have not been investigated until now.

In this paper, a virtual impedance based method is proposed for damping main voltage harmonics (5th and 7th). Three scenarios for harmonic suppression will be presented based on relationship among the feeder's length and harmonic wavelengths. Comparison among the proposed harmonic suppression method and surge impedance loading of the line will be exhibited. Finally, a case study will be illustrated to prove the effectiveness of the proposed methods.

II. Harmonic damping performance with DG units

A. Distributed Parameter Model of long feeder

Fig.1 shows a lumped-parameter model of distribution feeder while TABLE I provides the system parameter information. Besides, for the sake of simplicity, it is assumed that feeder inductance, resistance and capacitance are evenly distributed in the feeder.

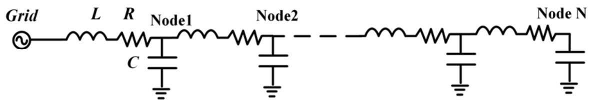


Fig.1. Diagram of simplified distributed parameter model

TABLE I. Distributed Feeder Parameters

	Value
Line Inductance L	1.98 mH/km
Line Capacitance C	$25\mu F/$km
Line Resistance R	0.25Ω
Characteristic impedance Z_0	$Z_0 = 8.9\Omega$

According to transmission line theory, characteristic impedance Z_0' of a general feeder is given by:

$$Z_0' = \sqrt{\frac{R+jwL}{jwC}} \tag{1}$$

Where R, L and C are feeder equivalent resistance, inductance and capacitance, w is the angular frequency. To analyze the harmonic propagation phenomenon, the worst case ($R = 0$) will be considered in the following analysis as the feeder resistance will provide inherent damping for the harmonic propagation. Therefore, (1) will be expressed as:

$$Z_0 = \sqrt{\frac{L}{C}} \tag{2}$$

Moreover, from microwave transmission line theory [9], propagation constant γ and wavelength λ are defined as:

$$\gamma = j\beta = jw\sqrt{LC} \tag{3}$$

$$\lambda = \frac{2\pi}{w\sqrt{LC}} \tag{4}$$

Finally, Table II outlines the relationship between harmonic frequency and wavelength.

B. Analysis of Harmonic-Voltage Propogation

The distributed-parameter model is illustrated in Fig.2, where *kth* harmonic voltage is assumed to be stiff. As the harmonics come from the upstream distribution network, V_{pcck}, $V_k(x)$, and $I_k(x)$ indicates the *k*th voltage harmonics at the source, harmonic voltage and current at the location of x, respectively. As in this paper, the DG is controlled in VCM mode, Z_L is considered to be *kth* harmonic virtual impedance.

From[1], it is demonstrated that the *kth* harmonic voltage at the location *x* is expressed as:

$$V_k(x) = A_1 e^{-j\beta x} + A_2 e^{j\beta x} \tag{5}$$

where A_1 and A_2 are respectively defined as the forward moving wave coefficient and backward moving wave coefficient and are expressed as:

$$A_1 = \frac{(\cosh(rl)+\sinh(rl))(Z_L+Z_0)}{2(Z_L\cosh(rl)+Z_0\sinh(rl))} \tag{6}$$

$$A_2 = \frac{(\sinh(rl)-\cosh(rl))(Z_0-Z_L)}{2(Z_L\cosh(rl)+Z_0\sinh(rl))} \tag{7}$$

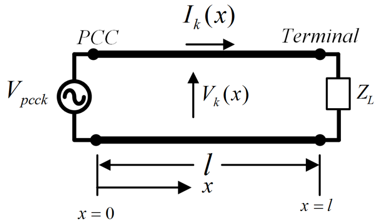


Fig.2. Diagram of simplified distributed parameter model

TABLE II. Illustration of frequency and wave length

Frequency f	Wavelength λ	$\frac{\lambda}{4}$
250Hz (5th)	17.97km	4.49km
350Hz (7th)	12.84km	3.21km

Substituting (6) and (7) into (5) formulates the harmonic voltage expression:

$$V_k(x) = \frac{Z_L\cosh(r(l-x))+z\sinh(r(l-x))}{Z_L\cosh(rl)+z\sinh(rl)} \tag{8}$$

According to microwave transmission line theory [9], if the Origin Point is set at the terminal, as is shown in Fig.3, the *kth* harmonic voltage is expressed as:

$$V_k(z) = A_1 e^{j\beta z} + A_2 e^{-j\beta z} \tag{9}$$

Where *z* is the distance from terminal, A_1 and A_2 are the same as (6) and (7).

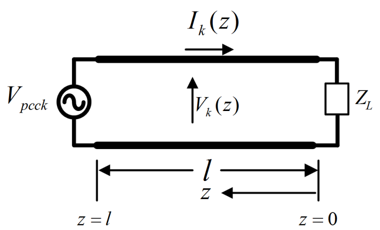


Fig.3. Diagram of simplified distributed parameter model

Moreover, the terminal harmonic reflection coefficient(THRC) is defined as [9]:

$$\Gamma_L = \frac{V_r(0)}{V_i(0)} = \frac{Z_L-Z_0}{Z_L+Z_0} \tag{10}$$

where $V_i(0)$ and $V_r(0)$ are defined as forward and backward travelling wave at the position of *z=0*. In addition, Z_L and Z_0 are terminal impedance and line impedance, respectively. When the terminal is connected to the resistance whose value is smaller than Z_0 ($Z_L = R_L < Z_0$), substituting R_L into (10) leads to:

$\Gamma_L = \left|\frac{R_L - Z_0}{R_L + Z_0}\right| \angle \varphi_L$ where $\Gamma_L < 0$, $\varphi_L = \pi$,

The harmonic voltage is expressed as:

$$V(z) = V_i(z)(1 + |\Gamma_L| e^{-j(2\beta z - \varphi_L)}) \quad (13)$$

The absolute value of $V(z)$ is given by:

$$|V(z)| = V_i(z)\sqrt{(1 + |\Gamma_L|^2 + 2|\Gamma_L|\cos(2\beta z - \varphi_L)} \quad (14)$$

It is demonstrated in (14) that harmonic voltage waveform along the feeder appears non-sinusoidal periodic behavior. The peak harmonic voltage occurs at the position $2\beta z - \varphi_L = 2n\pi$. By replacing $\lambda = \frac{2\pi}{\beta}$ into (14), it can be concluded that the maximum harmonic voltage occurs at $z = \frac{\varphi_L \lambda}{4\pi} + \frac{\lambda}{2}$n. Therefore, if the feeder's length l is less than $\frac{\lambda}{4}$ of the selected harmonic voltage (n=0), the harmonic will not propagate along the feeder, which can be explained by observing Fig.4, during 0<l< $\frac{\lambda}{4}$, $|V(z)|$ exhibits monotonically characteristic as shown in Fig.4 red curve, which implies amplitude of harmonic voltage grows as distance of z increases by setting Origin Point to be at terminal. In contrast, if the feeder's length is greater than $\frac{\lambda}{4}$ of the harmonic, the harmonic voltage appears propagation characteristic, meanwhile the maximum voltage occurs at the position of $\frac{\lambda}{4}$ from the terminal, as is shown in blue curve in Fig.4.

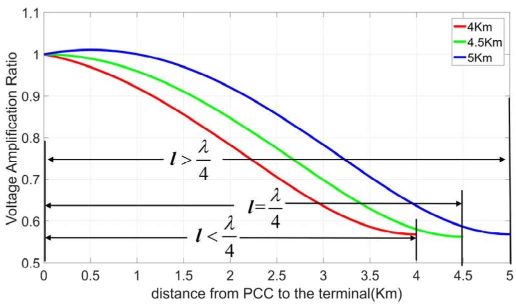


Fig.4. Diagram of single phase distributed parameter model

Based on the aforementioned discussion, harmonic voltage suppression can be achieved if terminal damping impedance is less than characteristic impedance while the distance from the connecting point of the damping resistance to PCC is less than $\frac{\lambda}{4}$ of the harmonics. Therefore, in the following section, different harmonic suppression strategies will be proposed and discussed based on the above conclusion considering 5th and 7th harmonics co-existence in the distribution feeder.

III. Flexible Site Selection for Harmonic Damping

One quarter of 5th and 7th harmonic waveforms are respectively 4.49km and 3.21km, as shown in Table II. In conformity with the correlation between feeder's length and harmonic wavelength, three scenarios will be considered for harmonic voltage mitigation.

Scenario 1: if the feeder's length is less than one quarter of 7th harmonic, which indicates $l < \frac{\lambda_7}{4} = 3.21km$, It is found that only one DG connecting at the terminal (as shown in Fig.5) can achieve harmonic mitigation by controlling the virtual resistance of DG unit at the selected frequency to be less than the characteristic impedance ($R_{5th,} < Z_0$, $R_{7th,} < Z_0$). Therefore, in this scenario, virtual impedance of $R_{5th,} = R_{7th,} = \frac{Z_0}{2}$ is proposed to damp out the harmonics. The 5th and 7th harmonic voltage along the feeder is expressed as:

$$V_{5th}(x) = \frac{R_{5th}\cosh(r(l-x)) + z_0\sinh(r(l-x))}{R_{5th}\cosh(rl) + z_0\sinh(rl)} V_{pcc5th}$$

$$V_{7th}(x) = \frac{R_{7th}\cosh(r(l-x)) + z_0\sinh(r(l-x))}{R_{7th}\cosh(rl) + z_0\sinh(rl)} V_{pcc7th}$$

$$0 < x \leq l \quad (13)$$

where V_{pcc5th} and V_{pcc7th} is considered as 5th and 7th harmonic voltage at PCC,

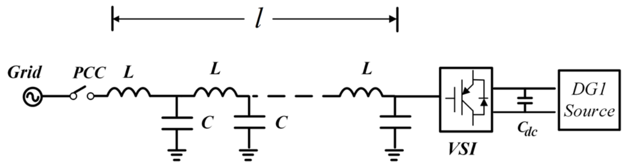


Fig.5. Diagram of two DG's installation points.

Figs. 6 and 7 depict harmonic voltage amplification ratio (HVAR) along the feeder with comparison of proposed methods and conventional methods. It is shown that both 5th and 7th harmonics severely amplifies when no DG is installed at the terminal. When a DG with loading impedance ($R_{5th,} = R_{7th,} = z_0$) is installed at the end bus, HVAR equals one. On the contrary, it is shown that with proposed methods both 5th and 7th harmonics are greatly attenuated when DG is installed on the end bus with virtual impedance $R_{5th,} = R_{7th,} = \frac{Z_0}{2}$.

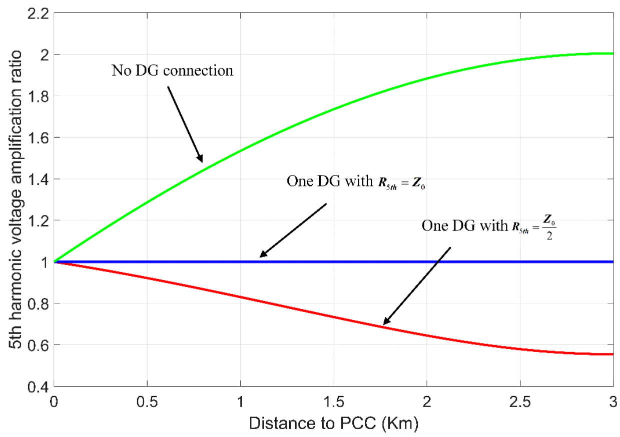


Fig.6. Fifth harmonic mitigation along the feeder

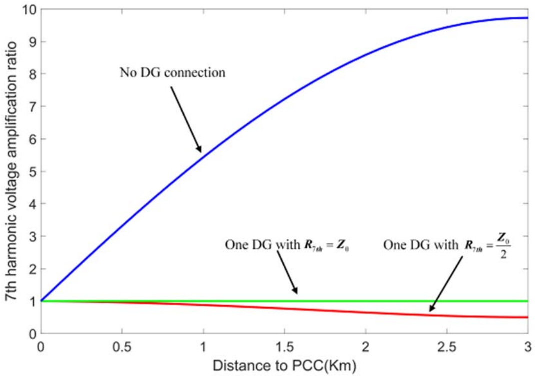


Fig.7. Seventh harmonic mitigation along the feeder

Scenario 2*:* if the feeder length is between one quarter of 5th harmonic and one quarter of 7th harmonic ($3.21km = \frac{\lambda_7}{4} < l < \frac{\lambda_5}{4} = 4.49km$,here, feeder length is 4km), only one DG interfacing at the terminal cannot ease both 5th and 7th harmonic voltage as $l > \frac{\lambda_7}{4}$ causes 7th harmonic amplification on the bus. Therefore, we proposes two DG units with virtual impedance to damp out harmonics, as shown in Fig.8, where DG1 unit is linked within $\frac{\lambda_7}{4}$ while DG2 is attached at the end of the bus

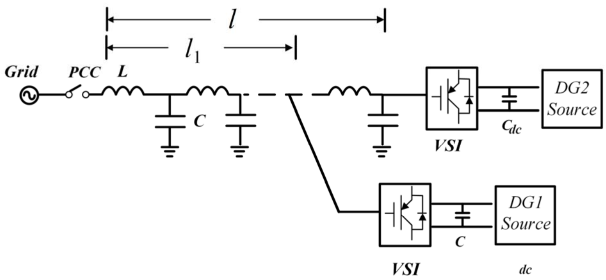


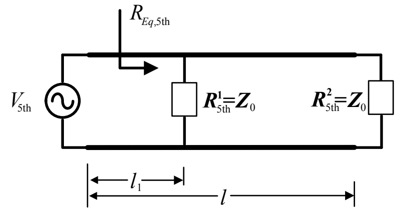
Fig.8. Diagram of two DG's installation points

The equivalent model of feeder with two DG units is shown in Fig. 9, where both DGs' 5th and 7th virtual impedances are set to be characteristic impedance. Therefore, the total impedance seen at l_1 will be $R_{eq\ 5th} = \frac{Z_0}{2}$, $z_{eq\ 7th} = \frac{Z_0}{2}$. The 5th and 7th harmonic voltages along the feeder are expressed as:

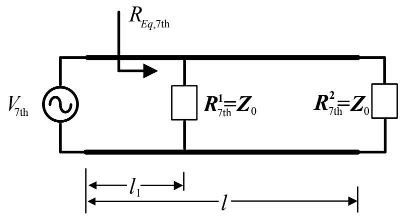
$$V_{5th}(x) = \begin{cases} \frac{R_{5th}\cosh(r(l-x))+z_0\sinh(r(l-x))}{R_{5th}\cosh(rl)+z_0\sinh(rl)} V_{pcc5th}, & 0 < x \le l_1 \\ V_{l1}, & l_1 < x \le l \end{cases}$$

$$V_{7th}(x) = \begin{cases} \frac{R_{7th}\cosh(r(l-x))+z_0\sinh(r(l-x))}{R_{7th}\cosh(rl)+z_0\sinh(rl)} V_{pcc7th}, & 0 < x \le l_1 \\ V_{l1}, & l_1 < x \le l \end{cases} \tag{14}$$

Harmonic voltage amplification curves of different methods are shown Figs. 10 and 11, it is observed that 5th and 7th harmonic are extremely amplified and propagated when no DG is interfaced along the feeder while one DG connection on the end of the bus equipped with characteristic impedance result in HVAR=1. Furthermore, HVAR is effectively attenuated to around 0.5 by adopting the proposed method.



(a) 5th harmonic equivalent model of feeder



(b) 7th harmonic equivalent model of feeder

Fig.9. Equivalent model of feeder with virtual impedance in scenario 2

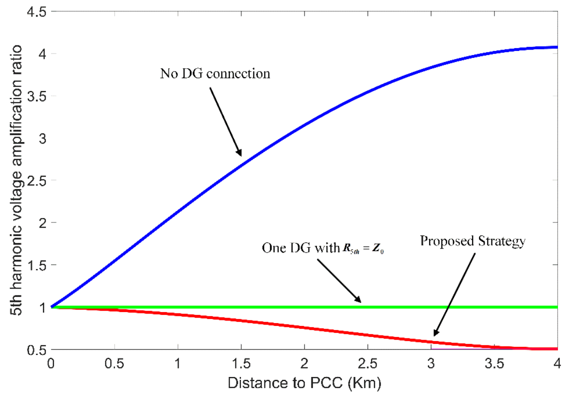


Fig.10.5th harmonic mitigation along the feeder

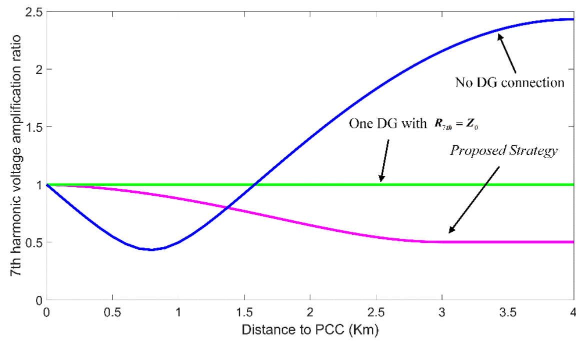


Fig.11.7th harmonic mitigation along the feeder

Scenario 3: if the feeder length is greater than half of fifth harmonic ($l_1 > \frac{\lambda_5}{2} = 8.98km$), we proposes that DG1 and DG2's connection points are respectively selected at the position of half of 5th harmonic and half of 7th harmonic from the terminal to achieve the best harmonic suppression [9](as shown in Fig.12). According to the impedance transformation theory [9], open circuit will keep its characteristic after half of the wavelength. Therefore, as is seen from the equivalent feeder model in Fig.13, open circuit property will not change, the 5th and 7th harmonic voltage are respectively expressed as:

$$V_{5th}(x) = \begin{cases} V_{pcc}, & 0 < x \le l_1 \\ \frac{\cosh(r(l_1-x))}{\cosh(rl_1)} V_{l1}, & l_1 < x \le l \end{cases}$$
$$V_{7th}(x) = \begin{cases} V_{pcc}, & 0 < x \le l_2 \\ \frac{\cosh(r(l_1-x))}{\cosh(rl_1)} V_{l2}, & l_2 < x \le l \end{cases} \tag{15}$$

Where $l_1 = l - \frac{\lambda_5}{2}$, $l_2 = l - \frac{\lambda_7}{2}$

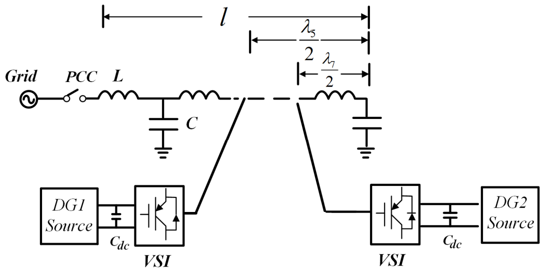
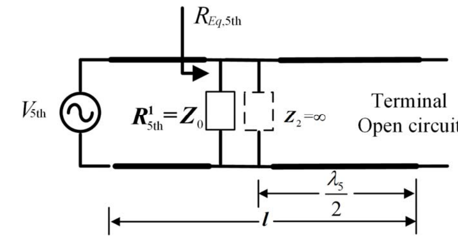
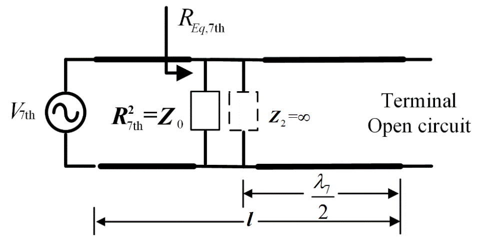


Fig.12. Diagram of three DGs' installation points



(a) 5th harmonic equivalent model of feeder



(b) 7th harmonic equivalent model of feeder

Fig.13 Equivalent model of DG units in scenario 4

From Figs.(14) and (15), it is observed that the proposed methods (two DGs connection) can achieve harmonic damping in all the nodes along the feeder. However, the conventional methods will cause harmonic voltage propagation.

TABLE III. DG CONTROL PARAMETER

Parameter	Value
Droop Coefficient	$D_p = 1/250$ $D_Q = 1/250$
Sampling frequency	10kHz
LC filter	$L_1 = 2\text{mH}, L_2 = 3.5\text{mH}, C_{DG} = 20uF$

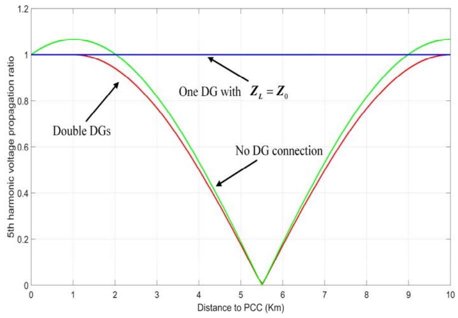


Fig.14. 5th harmonic mitigation along the feeder

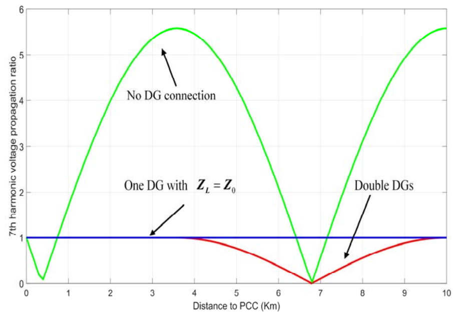


Fig.15. 7th harmonic mitigation along the feeder

IV. VERIFICATION OF PROPOSED METHODS

Simulation results have been obtained by case study. The simulated system parameters are shown in TABLE III. Three scenarios in Section III will be verified in this section. Grid voltage is stiff with 5% distortion of low order harmonic frequencies (5th and 7th harmonics).

Scenario 1

In scenario 1, feeder's length is chosen to be 3km, only one DG connected at the terminal, 5th and 7th virtual impedances are controlled to be half of the characteristic impedance, as can be seen from the Fig.16, the THD of PCC voltage is 7.1%, while the THD decreased along the feeder and THD of the terminal voltage is reduced to 3.99%, which correspond to Figs.6 and 7.

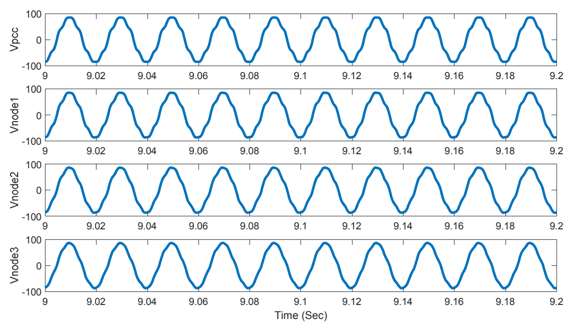


Fig.16. Harmonic voltage amplification when the feeder length is 3km the proposed method is exploited, (a)PCC voltage THD=7.1%;(b)node1 voltage THD 6.28%;(c) node2 voltage THD=4.96%;(d) node3 voltage THD=3.99%

Scenario 2

In scenario 2, the feeder length is chosen to be 4 km, two DGs are connected at node 2 and node 4, respectively. DG1 and DG2's 5^{th} and 7^{th} harmonic virtual impedances are both controlled to be equal with characteristic impedance. In Fig. 17, it is shown that the THD of voltage greatly drops from V_{pcc} to Vnode2 due to this reason that the equivalent impedance is half of the characteristic impedance. From Vnode 2 to Vnode 4, THD of harmonic voltage slightly decreased from 4.61% to 4.10% because of the line impedance damping.

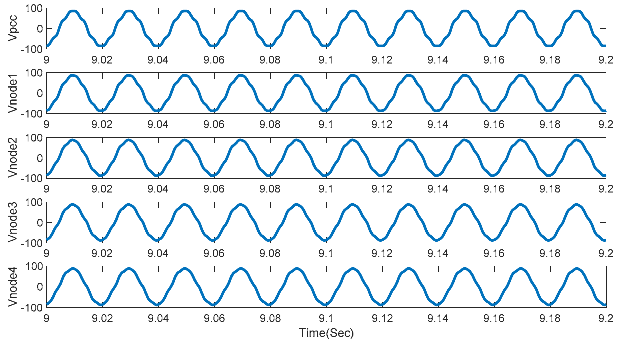


Fig.17. Harmonic voltage amplification when the feeder length is 4km,the proposed method is exploited, (a)PCC voltage THD=7.1%;(b)node1 voltage THD 5.49%;(c) node2 voltage THD=4.61%;(d) node3 voltage THD=4.44%(e) node4 voltage THD=4.10%

Scenario 3

In scenario 3, the total feeder length is chosen to be 10km, two DGs are connected at the distance of one half of 5^{th} and 7^{th} harmonics. From Fig.18, it is found that the site selection with virtual impedance has obvious damping effect on the harmonic propagation.

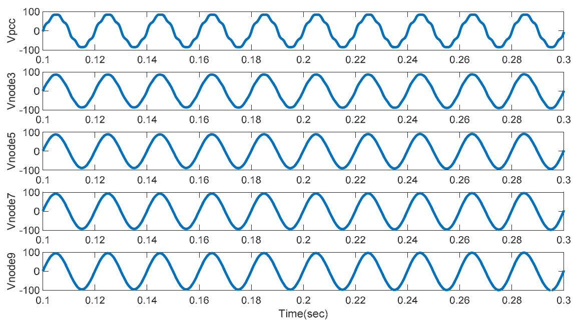


Fig.18. Harmonic voltage amplification when the length is 10km, the proposed method is exploited, (a)PCC voltage THD=7.11%;(b) node3 voltage THD 4.02%;(c) node5 voltage THD=3.33%;(d) node7 voltage THD=3.87%(e) node9 voltage THD=3.85%.

V. Conclusion

In this paper, harmonic propagation along the distribution feeder issue has been analyzed. It is concluded that harmonic voltage will not propagated if the feeder's length is less than one quarter of selected harmonic wavelength meanwhile the damping impedance is less than the characteristic impedance. Moreover, harmonic damping methods are proposed and compared with conventional methods in three different scenarios. Finally, Simulation results shows the effectiveness of the proposed control strategies.

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