Impact of Renewable Energy Source Penetration on Total Harmonic Distortion Using Harmonic Power Flow

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Abstract –The importance of renewable energy increases in activities relating to new forms of managing and operating electrical power, such as wind power, solar source, which make the power system becoming morecomplex. In order to evaluate the impact of renewable resources on harmonic distortion, a balanced harmonic load flow program is applied to study the impact of renewable source penetration on magnitude busvoltage, total harmonic value(THDV), total harmonic currentvalue (THDI), this approach has been carried out on the IEEE 14 bus meshed transmission power system .

Index Terms –Renewable Energy Source, Transmission System, Harmonic, Nonlinear load, Harmonic power flow, Total Harmonic Distortion.

I. Introduction

Growing concern for environmental issues and advancement in power electronic technology resulted in fast development of energy production using renewable energy sources (RES). These natural resources play an important role on power system generation and one of the most promising energy resources nowadays is the wind and solar energy. Wind energy is one of the optimistic sources of energy generation among all the RES. Now a day's energy demand is increasing rapidly, due to the growth in population and economic development in the world leading to increase in environmental impact on conventional plants. Hence RES must be employed in order to meet the energy demand and have communal development and prolong growth [1].

Harmonic load-flow calculations can be performed on a deterministic basis, assuming that all the relevant parameters are well known and non-random. However, such studies provide a static and certain image of a varying and uncertain situation. In fact, the network configuration usually changes and its linear and nonlinear loads vary all the time; in addition, even if they were constant their parameters are not usually well known [2]. All these features make harmonic distortion a phenomenon involving uncertainty. Hence, harmonic power flow studies are important to quantify the voltage and current waveforms distortion at various points in a transmission and distribution system. The results are useful for corrective measures and troubleshooting the problems caused by the harmonics.

Harmonic power flow analysis is performed basically to determine the existence of dangerous resonant conditions and verify its compliance with the standard harmonic limit [3].Power flow calculations are most frequently performed by electric power utilities for static operating conditions such as contingency analysis, system security assessment, optimal dispatching and for dynamic operating conditions such as stability analysis. A large amount of work has been done in formulating methods for carrying out power flow studies. Power flow studies normally involve digital computers used as a tool to solve steady load flow equations [4]. The result of a power flow study is the magnitude and phase angle of the voltage at each bus, active and reactive power in each line. Another piece of important information obtained from the power flow study is the system active and reactive power loss.

Many researchers have been performed so far as well as some researches concerning how to tackle the resultant problems of harmonics load flow on power system. Some of these distinguished difficulties are as follows: Harmonic power flow determination using the fast fourier transform (FFT) in [5], Three phase AC/DC load and harmonic load flows in [6], Optimal harmonic power flow in [7], Harmonic frequency power flow in [8], Application ANN for balanced harmonic load flow in [9], study load flow solution on distribution system in [10], Application genetic algorithm (GA) for distribution system load flow solution in[11],Application harmonic power flow to determine the dominant source [12], Application possibility method for harmonic load flow in [13], and new model is developed to allocate the harmonic losses in the optimal power flow in [14].

Many researchers have been performed so far as well as some researches concerning how to tackle the resultant problems of RES integration on harmonics power system analysis. Some of these distinguished difficulties are as follows: Minimize line current harmonics in interfacing RES [15], Application of the three-level inverter for reduction THD value [16], Optimal RMS value and phase angle of the injection current to get the minimum THD of three-phase controlled converter [17], Optimal placement and sizing of capacitor of RES [18], Novel control strategy for active power filter in the presence RES connected to a 3-phase 4-wire network [19], Proposed control scheme of three-level NPC inverter for integration of RES for increasing harmonic frequencies [20], Optimal placement different types of RES considering control THD using the GA optimisation method [21], Harmonic emission versus active power from three individual RES [22], Study harmonics produced from multiple distributed RES in power distribution networks [23], and efficient harmonic and phase estimator for grid connected RES [24].

In this paper, the harmonic power flow algorithm based on Newton-Raphson method is applied to study the impact of RES penetration on voltage bus, voltage total harmonic distortion value, and three harmonic orders value (5th, 7th11th, 17th ,and 19th). This approach has been carried out on the IEEE 14 bus meshed transmission power system.

II. Impact of RES on Power Systems

Incorporation of great amount of RES, such as wind and PV energy, has a significant impact on power network, which are mainly related to environmental, economical and reliability aspects. Low wind penetration levels are usually accommodated in power networks considering that the network is passively controlled and operated. Although there are several available tools to be used for RES forecasting [25], wind energy is still considered as a non dispatchable and not centrally planned technology. Impact of RES on power systems is thus focused on several issues related to security, stability, power quality and operation of power systems [26].

- RES has several impacts on power flow that could lead to reverse power flow and, as a result, power systems operation will become more complex.

- Moreover, power injection by wind farms may cause power losses in the distribution systems.

- All the utilities have to keep stable and reliable the voltage supply to the customers within specific limits of frequency and magnitude. Connection of wind farms may result in voltage changes; consequently, some countries have defined a higher short circuit level at the connection point, normally between 20 and 25 times the RES capacity.

- Power quality is related to voltage variation and harmonic distortion in the network. However, the incorporation of RES in power networks could affect the quality of the supplied voltage to the customers. To reduce this impact, nowadays, variable speed wind turbines equipped with power electronics are widely used in wind energy conversion.

- Protection system is also affected by wind farms since the incorporation of wind power injection alters power flows; so that conventional protection systems might fail under fault situations.

- In the past, power network was passive operated and kept up stable under most circumstances. However, this statement is no longer valid if considering an increase of wind energy penetration. Recently, new requirements for RES units have been designed in order to keep power networks stable under several disturbances, such as low voltage ride through capability.

II. Total Harmonic Distortion

Before proceeding to discuss the nature of power system harmonics, it is worthwhile to briefly review the concepts of active power and reactive volt-amperes. For this purpose, the terminology in[27] is used. Consider a voltage $v(t)$ and current $i(t)$ expressed in terms of its RMS harmonic components,

$$v(t)=V_0+\sum_{k=1}^{\infty}\left[V_k\sin\left(k\omega_0+\theta_k\right)\right] \quad (1)$$

$$i(t)=c_0+\sum_{k=1}^{\infty}\left[c_k\sin\left(k\omega_0+\delta_k\right)\right] \quad (2)$$

The active and reactive power is given by flowing equations:

$$P=V_0c_0+\sum_{k=1}^{\infty}\left[V_kc_k\cos\left(\delta_k-\theta_k\right)\right] \quad (3)$$

$$Q=\sum_{k=1}^{\infty}\left[V_kc_k\sin\left(\delta_k-\theta_k\right)\right] \quad (4)$$

The apparent power level is given by equation:

$$S=\sqrt{\left(\sum_{k=1}^{\infty}V_k^2\right)\cdot\left(\sum_{l=1}^{\infty}V_l^2\right)} \quad (5)$$

In the case of sinusoidal v (t) and i (t), the S is become:

$$S=P^2+Q^2 \quad (6)$$

However in non-sinusoidal case, equation (6) does not hold well, the discrepancy is termed as distortion *(D)*:

$$D=\sqrt{S^2-P^2-Q^2} \quad (7)$$

It is imperative to size the overcurrent device to true Root Mean Square (*RMS*) as measured by a true *RMS* meter. Average sensing, *RMS* equivalent meters do not correctly respond to harmonic current. Harmonic-rich currents will have higher effective RMS as compared to non-distorted sinusoidal waveforms [28]. The *RMS* value of a pure sinusoidal voltage waveform (V_{RMS}) is defined by:

$$V_{RMS}=V_{1RMS} \quad (8)$$

Where,

$$V_{1RMS}=\sqrt{\frac{1}{2\pi}\int_0^{2\pi}V_{1\max}^2\sin^2(\omega t)dt} \quad (9)$$

$$\Rightarrow V_{1RMS}=\frac{V_{1\max}}{\sqrt{2}} \quad (10)$$

The *RMS* value of a non-sinusoidal voltage waveform ($V_{NS.RMS}$) is defined as:

$$V_{NS.RMS}^2 = \frac{1}{2\pi}\int_0^{2\pi} v^2(t)dt \quad (11)$$

$$V_{NS.RMS}^2 = \frac{1}{2\pi}\int_0^{2\pi} \begin{bmatrix} V_{1\max}\sin(wt+\varphi_1) + V_{2\max}\sin(2wt+\varphi_2) \\ + \ldots\ldots + V_{n\max}\sin(nwt+\varphi_n) \end{bmatrix}^2 .dt \quad (12)$$

Where, φ_n is phase angle of *n* harmonic, and *n* is rang of harmonic.

$$V_{NS.RMS}^2 = \frac{V_{1\max}^2}{2} + \frac{V_{2\max}^2}{2} + \ldots + \frac{V_{n\max}^2}{2} \quad (13)$$

Simplifying the above equation results in:

$$V_{NS.RMS} = \sqrt{\frac{V_{1RMS}^2 + V_{2RMS}^2 + \ldots + V_{nRMS}^2}{2}} \quad (14)$$

The total harmonic distortion (THD) quantifies the thermal effect of all the harmonics. THD applies to both current and voltage and is defined as the RMS value of harmonics divided by the RMS value of the fundamental, and then multiplied by 100%. THD of current varies from a few percent to more than 100%. THD of voltage is usually less than 5%[4-9], [29]. The voltageTHD is defined as:

$$THD_V = \frac{V_H}{V_{1RMS}} \times 100\% \quad (15)$$

Where,

$$V_H = \sqrt{V_{2RMS}^2 + V_{3RMS}^2 + \ldots + V_{nRMS}^2} \quad (16)$$

The limits on voltage harmonics are thus set at 5% for THD and 3% for any single harmonic. It is important to note that the suggestions and values given in this standard are purely voluntary. However, keeping low THD values on a system will further ensure proper operation of equipment and a longer equipment life span. Voltage THD below 5% is widely considered to be acceptable, but values above 10% are definitely unacceptable and will cause problems for sensitive equipment and loads[29], [12].

IV. Harmonic Power Flow

The Newton-Raphson method is powerful for solving nonlinear simultaneous equations due to its fast convergence. It is, indeed, the practical method of load flow solution for large power network. The set of power flow equations are formed to mathematically express the representation between the changes in real and reactive powers and the components of bus voltages.

Although the Newton-Raphson method, compared with the Gauss-Seidel method, uses more computer storage, it is more attractive for its fast convergence and for quite independence on the size of a power system in question[30].Power flow analysis by the Newton-Raphson method is based on Taylor's series expansion.

This method expands the power flow equations around initial values of state variables by Taylor's series by considering up to the first order derivative terms and then drives mismatches of active and reactive powers to zero by making adjustment of the corrector vector of the state variables.

A). Newton-Raphson method Recall

The Newton-Raphson method for power flow study solution is well known. The mismatch equations (i.e., active power and reactive volt-ampere balance) are forced to zero iteratively by forcing the bus voltages to the solution. Consider bus 1 to be the slack bus, busses 2 through *m*-1 are conventional load busses (linear loads-*V* or *P*-*Q* busses), and busses m through *n* as non-sinusoidal load busses. Busses 1 through *m*-1 are handled in the usual way. For busses m through *n* inclusive, the active power is specified and the apparent power is known. Also, the form of the non-linearity is known.

The power balance equations are that ΔP and ΔQ at all non-slack busses are zero for all harmonics. The functional form of ΔP and ΔQ as a function of $|V_{bus}|$ and $|\theta_{bus}|$ (i.e., bus voltage magnitudes and phase angles) is as in the conventional-case with the note that Y_{bus}must be modified at harmonic frequencies. The specified values of $P^s$and Q^s are known at busses 2 through *m*-1, but only P^1 is known at busses *m* through *n*. Note *s* = 1, 5,7,11, ..., etc. The missing harmonics are absent as a consequence of the voltage and current sequences which exist at *s* = 2, 3, 4, 6,..., etc. The mismatch vector (consisting of mismatch power and mismatch currents) for harmonic power flow is defined as:

$$\Delta\overline{M} = \left[\Delta\overline{W},\ \Delta\overline{I}^{(5)},\ \ldots,\ \Delta\overline{I}^{(L)},\ \Delta\overline{I}^{(1)}\right]^t \quad (17)$$

Where, ΔW is the mismatch power vector and ($\Delta I^{(5)}$, ..., $\Delta I^{(L)}$, $\Delta I^{(1)}$) is the mismatch current vector for the harmonics including the fundamental. Where the nonlinear load current components$G_{r,m}^{(h)}$and $G_{i,m}^{(h)}$are given (referred to swing bus) and the line current components $I_{r,m}^{(h)}$and $I_{i,m}^{(h)}$are the non linear injected currents.

The Newton-Raphson method is implemented by forcing the appropriate mismatches, ΔM, to zero using the Jacobian matrix [*J*] and obtaining appropriate correction terms $\Delta U^{(\varepsilon)} = U^{(\varepsilon)} - U^{(\varepsilon+1)}$,where$\varepsilon$represents the iteration number:

$$\Delta\overline{M} = \overline{J}.\Delta\overline{U}^{(\varepsilon)} \quad (18)$$

The matrix formulation of the problem is:

$$\begin{bmatrix} \Delta\bar{V}^{(1)} \\ \Delta\bar{V}^{(5)} \\ \Delta\bar{V}^{(7)} \\ \cdot \\ \cdot \\ \cdot \\ \Delta\bar{V}^{(L)} \\ \Delta\overline{\square} \end{bmatrix} = \begin{bmatrix} \bar{J}^{(1)} & \bar{J}^{(5)} & \ldots & \bar{J}^{(L)} & \ddot{0} \\ \overline{YG}^{(5,1)} & \overline{YG}^{(5,5)} & \ldots & & \bar{H}^{(5)} \\ \overline{YG}^{(7,1)} & \overline{YG}^{(7,5)} & \ldots & & \bar{H}^{(7)} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \overline{YG}^{(L,1)} & \overline{YG}^{(L,5)} & \ldots & \overline{YG}^{(L,L)} & \bar{H}^{(L)} \\ \overline{YG}^{(1,1)} & \overline{YG}^{(1,5)} & \ldots & \overline{YG}^{(1,L)} & \bar{H}^{(1)} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \Delta\bar{W} \\ \Delta\bar{I}^{(5)} \\ \Delta\bar{I}^{(7)} \\ \cdot \\ \cdot \\ \cdot \\ \Delta\bar{I}^{(L)} \\ \Delta\bar{I}^{(1)} \end{bmatrix} \quad (19)$$

And,

$$\Delta\bar{W} = \begin{bmatrix} P_2^1 + F_{r,2}^{(1)}, Q_2^{(1)} + Q_{i,2}^{(1)}, \ \ldots \ , P_{m-1}^{(1)} + F_{r,m-1}^{(1)}, Q_{r,m-1}^{(1)} + \\ Q_{i,m-1}^{(1)}, \ \ldots \ , \Delta P_m^{nonlinear}, \Delta Q_m^{nonlinear}, \Delta P_m^{nonlinear}, \Delta Q_m^{nonlinear} \end{bmatrix}^t \quad (20)$$

Where, $P_2^{(1)}$, $F_{r,2}^{(1)}$, $Q_2^{(1)} + Q_{i,2}^{(1)}$..., $P_{m-1}^{(1)}+F_{r,m-1}^{(1)}$, $Q_{m-1}^{(1)}$ applies to linear bus, and $\Delta P_m^{nonlinear}$, $\Delta Q_m^{nonlinear}$, $\Delta P_m^{nonlinear}$, $\Delta Q_m^{nonlinear}$, applies to nonlinear buses. The fundamental current mismatch is defined for nonlinear buses where all currents (e.g., line currents and nonlinear load currents) are referred to the swing bus:

$$\Delta\bar{I}^{(1)} = \left[I_{r,m}^{(1)} + G_{r,m}^{(1)}, I_{i,m}^{(1)} + G_{i,m}^{(1)}, \ \ldots \ , I_{r,n}^{(1)} + G_{r,n}^{(1)}, I_{i,n}^{(1)} + G_{i,n}^{(1)} \right]^t \quad (21)$$

The harmonic current mismatch is defined for linear and nonlinear buses including swing bus:

$$\Delta\bar{I}^{(h)} = \begin{bmatrix} I_{r,1}^{(h)}, I_{i,1}^{(h)}, \ \ldots \ , I_{r,m-1}^{(h)}, I_{i,m-1}^{(h)} + I_{r,m}^{(h)} + G_{r,m}^{(h)}, I_{i,m}^{(h)} \\ + G_{i,m}^{(h)}, \ \ldots \ , I_{r,n}^{(h)} + G_{r,n}^{(h)}, I_{i,n}^{(h)} + G_{i,n}^{(h)} \end{bmatrix}^t \quad (22)$$

Where all elements in this matrix equation are sub-vectors and sub-matrices partitioned from $\Delta M, J$, and $\Delta U^{(\varepsilon)}$.

B). Harmonic Newton-based power flow algorithm.

The solution procedure for the harmonic power flow algorithm is as follows:

***Step 1*:** Perform the fundamental load flow analysis (treating all nonlinear devices as linear loads) and compute an initial (approximate) value for the fundamental bus voltage magnitudes and phase angles. Make an initial guess for the harmonic bus voltage magnitudes and phase angles (e.g., 0.1$p.u$and 0 radians).

***Step 2*:** Compute nonlinear device currents $G_{r,m}^{(h)}$and $G_{i,m}^{(h)}$ (Referred to the swing bus) for nonlinear loads.

***Step 3*:** Evaluate $\Delta M(U)$using equations (19), and (20) If it is small enough then stop.

***Step 4*:** Evaluate J and calculate ΔU.

***Step 5*:** Update U.

***Step 6*:**Update the total (fundamental plus harmonic) powers at nonlinear buses $P_j^t$and$Q_j^t$and the specified total apparent power or total reactive whichever is known.

***Step 7*:** Go to Step 2.

V. Case Study and Simulation Results

The IEEE 14 bus transmission system network in the presence of RES as shown in Figure 1, It consist 14 bus, 2 synchronous machines, 10 loads, 3 winding transformers, and 20 lines. The nonlinear load study is connected at bus number 10 and the RES is connected at bus number 8 for different penetration. The data of nonlinear load and RES are in Appendix.

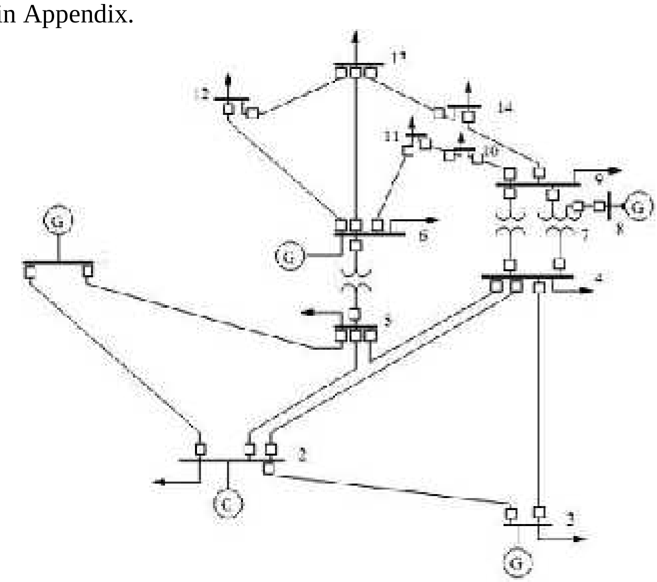


Fig. 1. Single line diagram of the IEEE 14-bus systemwith RES.

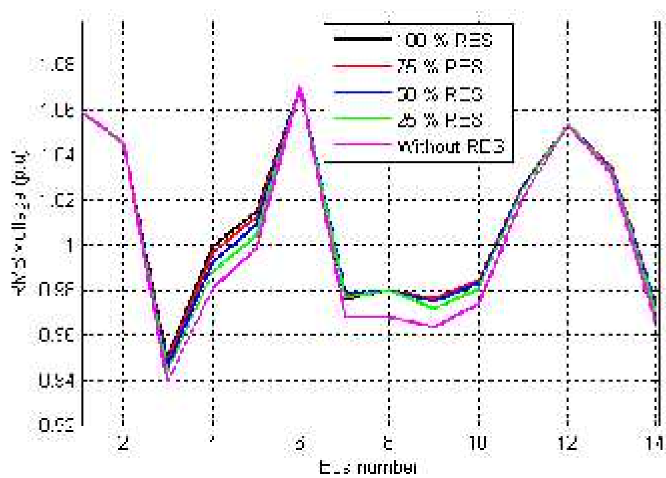


Fig. 2. Impact of RES penetration on voltage profile.

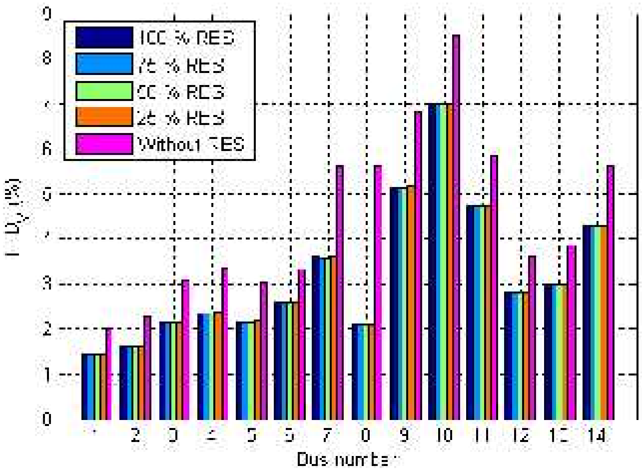
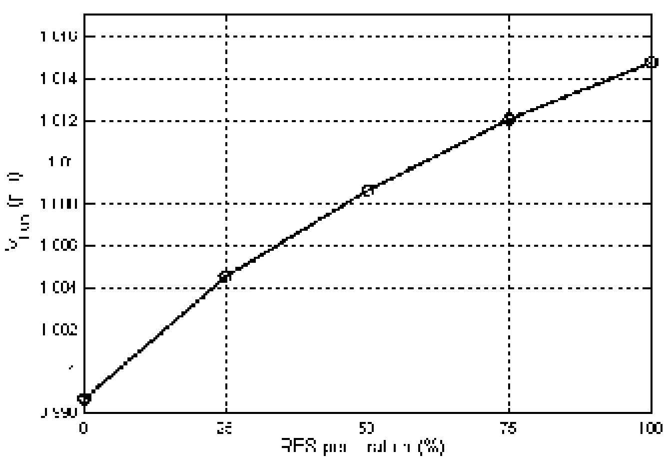


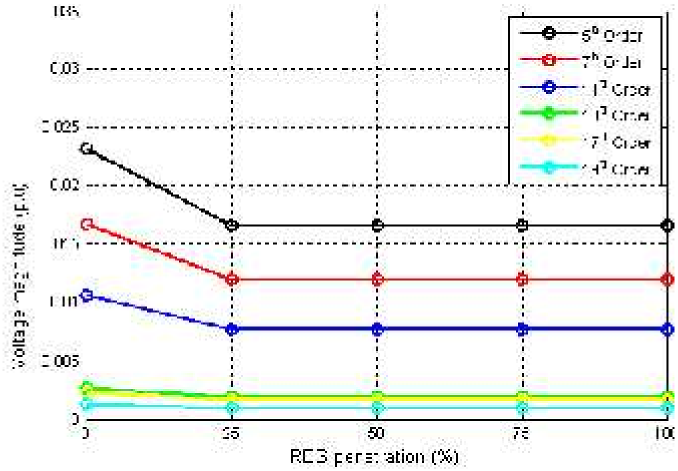
Fig. 3. Impact of RES penetration on THD_V.

From Figure 2, it is observed that the voltageprofile is improved with addition of the RES at bus number 8, and we notice that the gap between the RMS voltage without RES and for different penetrations is greater when the bus 8 becomes a PV bus.

It is also observed from figure 3 that the installation of the RES unit has significant impacts on the reduction of the voltage harmonic distortion value in the transmission system. The base value was 5.87 % at bus number 8, and after integration of the RES it decreases to 2 %.



(a)

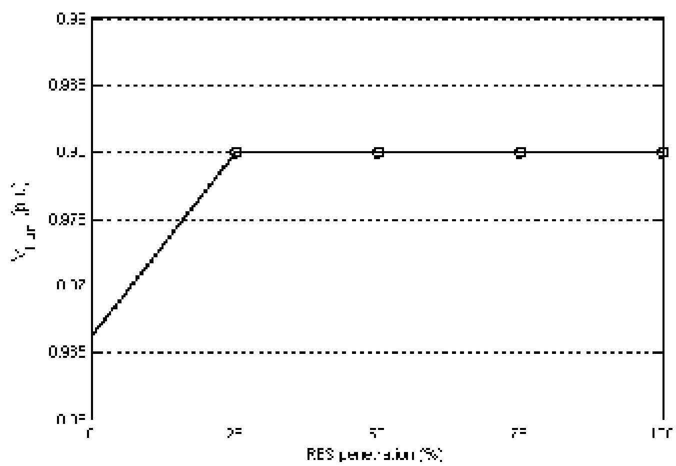


(b)

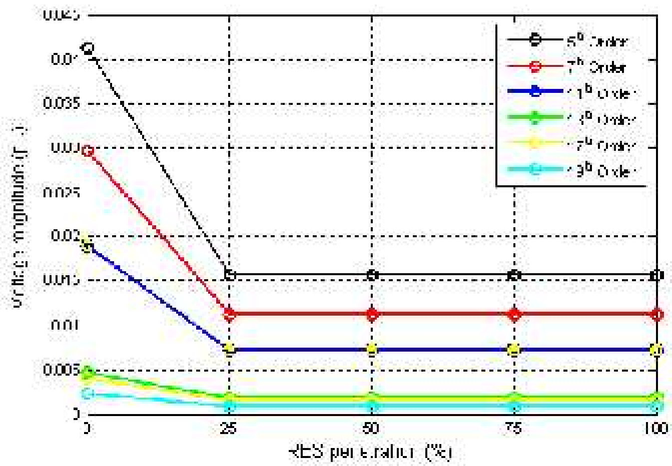
Fig. 4. Impact of RES penetration on bus voltage at bus no. 5 a). Fundamental voltage , b). 5th, 7th 11th , 17thand 19thharmonic orders.

The bus 5 has been chosen to illustrate the impact of RES penetration in the bus voltage. From figure 4, the presence of RES at bus 8 has a direct influence on the reduction of the harmonic order voltage and the voltage profile of the IEEE 14 bus system is greatly improvedwith power penetration increase.

It is observed from figure 5 that the fundamental voltage is improved and the harmonic voltage has also decreased after addition of the RES in the system where the bus 8 becomes a PV bus.



(a)



(b)

Fig. 5. Impact of RES penetration on bus voltage at bus no. 8 a). Fundamental voltage, b). 5th, 7th 11th , 17thand 19th harmonic orders.

VI. Conclusion

In this research work, the impacts of the renewable energy sources penetration on voltage bus, voltage THD_V, and six harmonic order valuesare investigated for a transmission power system using a harmonic power flow based Newton-Raphson method.

From the studied cases, it can be seen the addition of theRES in the network has a direct impact on the voltage RMS value, harmonic order, and THD_V factor. The fundamental voltage is improvedand isdepending of power penetration of the RES system; also the injection of RES has a significant impact on the harmonic reduction and THD_V value.

Further research study cases concerning multiple renewable energy sources connected to distribution network are currently under investigation and preparation for future publications.

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APPENDIX

Table A. Harmonic source data

Harmonic order	Mag(p.u)	Angle (deg)
5	0.0490	-74.1189
7	0.0251	-31.6672
11	0.0102	-10.7580
13	0.0021	-10.7843
17	0.0014	-8.1301
19	0.0007	-8.1301

Table B. Renewable energy source data.

Penetration	Power Injected
100 %	P_{RES} = 100 MW Q_{RES} = 50 MVar
75 %	P_{RES} = 75 MW Q_{RES} = 37.5 MVar
50 %	P_{RES} = 50 MW Q_{RES} = 25 MVar
25 %	*PRES = 25 MW* *QRES = 12.5 MVar*