# Total Harmonic Distortion Calculation in Modified Feeder Distribution System

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***Abstract –*** *With the growing demand for electric power, it is becoming necessary to ensure a continuous supply in both low and high-voltage distribution systems. Distribution systems integrated with modern distributed generation (renewable energy resources) enhance power reliability and comply with carbon emission policies worldwide. These policies benefit society by reducing greenhouse gases, promoting clean air, and encouraging sustainable practices and technologies. Flexible AC transmission systems devices like static VAR compensators are used to mitigate transmission power quality issues, while custom power devices like dynamic voltage restorers and distribution static synchronous compensators are used to address distribution-level problems. In this research article, a Photovoltaic (PV) with Distribution Static Synchronous Compensator (PV D-STATCOM) is employed, to enhance voltage stability, improve power quality, reduce power fluctuations in distribution feeder systems, and support grid reliability by providing reactive power compensation and dynamic voltage control. It reduces losses by injecting reactive power (Q) and active power (P) and measures total harmonic distortion (THD). The PSCAD/EMTDC software is used for modeling and IEEE-13 node test feeder systems is taken for multiple case scenarios.*

***Keywords*** – Total Harmonic Distortion (THD), Photovoltaic Distribution Static Synchronous Compensator (PV D-STATCOM), Custom Power Devices, FACTS.

## 1. INTRODUCTION

The distribution system is crucial for reliably and efficiently delivering electrical power to residential, commercial, and other consumer [1]. It comprises power lines, transformers, substations, and related infrastructure, operating at lower voltages compared to the transmission system. The distribution network aims to ensure reliable, efficient, and quality power delivery while maintaining system stability [2].

Electric power systems consist of three essential components: generation, transmission, and distribution [3]. Electric power generation in countries like India utilizes various sources, including coal, natural gas, and renewable energy, each with distinct environmental impacts [4]. Transmission moves electricity over long distances to areas of high demand using transmission lines and substations operating at high voltages. Distribution represents the stage of delivering electricity to end users through a network of power lines and transformers at suitable lower voltages for consumption [5][6].

Losses occur at each level of the power transmission. Efforts to reduce these losses through increasing generation efficiency and optimization to enhance quality at the distribution level [7]. Devices like FACTS in transmission and custom power devices at the distribution system are employed to mitigate losses. In distribution systems, losses include resistance loss in conductors, transformer loss during voltage conversion, and technical losses from inaccuracies in protective devices and meters [1]. Measures to minimize these losses involve using efficient materials, enhancing transformer design, and implementing advanced monitoring systems. FACTS devices optimize the efficiency, control, and reliability of electric power transmission systems by dynamically adjusting voltage, impedance, and phase angle in real time [8]. They enhance power transfer capabilities, mitigate voltage fluctuations, reduce transmission losses, and improve grid stability. Custom power devices resolve power quality problems in distribution systems including voltage sags, swells, harmonics, and voltage flicker [9]. PV D-STACOM improves quality and stability for end-users, ensuring uninterrupted operation of sensitive equipment and reducing downtime. PV D-STATCOM, a specific type of FACTS device, offers several advantages for power systems, including enhanced grid stability, refined voltage control, minimized power fluctuations, optimized power flow on transmission lines, improved power quality, reduced transmission losses, cost savings, and increased efficiency [10][11].

Moreover, FACTS devices can facilitate the integration of renewable energy sources and quickly respond to utility, manage congestion on transmission lines, and contribute to environmental sustainability by checking greenhouse gas emissions [9]. Finding Total Harmonic Distortion (THD) in electrical systems is crucial for ensuring power quality protecting equipment, and meeting regulatory standards [12]. High THD levels can lead to voltage distortion, equipment overheating, and interference with sensitive electronics. Monitoring THD helps ensure that electrical equipment operates within acceptable limits, preventing performance issues.

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A Photovoltaic Distribution Static Synchronous Compensator is integrated into the IEEE-13 node test feeder system presenting an opportunity for revenue generation. To effectively leverage this opportunity, the THD for taken system in both active power P and active and reactive power PQ modes is explored. A comparative study is conducted and the findings are presented in this article:

The grid-tied solar system operates in three modes.

1. True -Power Mode (P)
2. Reactive -Power Mode (Q)
3. (True and Reactive) Power Mode (PQ)

Modified IEEE-13 node test feeder system PV D-STATCOM operates in three modes. The first mode is Active power mode, where P is supplied. In the second mode, Reactive power mode Q is supplied and in the third mode which is a combination of P and Q compensation mode PQ is supplied.

The research challenge is related to increased Distributed Generation (DG) adoption, proposing to Optimize the placement of DG and D-STATCOM units on radial distribution systems to minimize losses. They use stability indices to determine optimal locations and a variation technique to optimize sizes. The paper conducts load flow and harmonic analyses on an IEEE-13 bus system to validate the approach [13].

The author presents an artificial intelligence approach that employs Particle Swarm Optimization for the optimal placement and sizing of DG in distribution systems. The goal is to enhance the voltage profile, reduce losses, and decrease THD. By considering sensitivity to fitness values in PSO, load flow and harmonic calculations are integrated [14].

## 2. PROBLEM FORMULATION

Minimizing power losses and total harmonic distortion in a distributed system depends on the placement of distributed generation.

This article aims to decrease power loss by regulating harmonics in the system through conventional methods. The objective function to minimize power losses is given by eq. (1):

$$F_{min} = (P_{losses}) + (THD_i) \tag{1}$$

Where F represents the fitness function, $(P_{losses})$denotes the total real power loss, and $(THD_i)$ indicates the average total harmonics distortion at all buses in the system.

The total amount of real power loss in eq. (2) is defined as:

$$\mathrm{P_{losses}} = \sum_{i=1}^{n} P_{Losses_i} \tag{2}$$

Here n indicates the number of lines. The mean THD in eq. (3) follows as:

$$THD_i = \sum_{i=1}^{n} THD_n \tag{3}$$

Here, n indicates the number of buses, and THD signifies [15]:

$$THD_i = \sqrt{\frac{Sum\ of\ square\ of\ amplitude\ of\ all\ harmonics}{Square\ of\ Amplitude\ of\ fundamental\ component}} \times 100\% \quad ....(4)$$

Bus voltage (V$_{\mathrm{bus}}$) limit: The magnitudes of bus voltages must remain within acceptable limits throughout the entire process.

$$V_{min} \leq |V_m| \leq V_{max}$$

$V_{min}$ and $V_{max}$ are the lower and upper limit of bus voltage defined, with $V_m$ representing the RMS value of the $i_{th}$bus voltage provide in eq.(5):

$$|V_m| = \sqrt{|V_m|^2} + \sum_{h=h_0}^{h_{max}} \left|V_m{}^{(h)}\right|^2 \tag{5}$$

**Table 1. IEEE standard for THD.**

| IEEE Standard for Total Harmonics Distortion(THD) | |
|---|---|
| Overall THD | Individual THD |
| Less than 5 Percentage | Less than 3 Percentage |

THD limit: The THD should be less than or equal to per standard value specified in Table.1 [16].

### 2.1 *Mathematical Model of PV module*

An equivalent circuit of a solar cell, as illustrated in Fig.1, includes a current source in anti-parallel with a diode, a shunt resistance $R_p$, and a series resistance $R_s$..

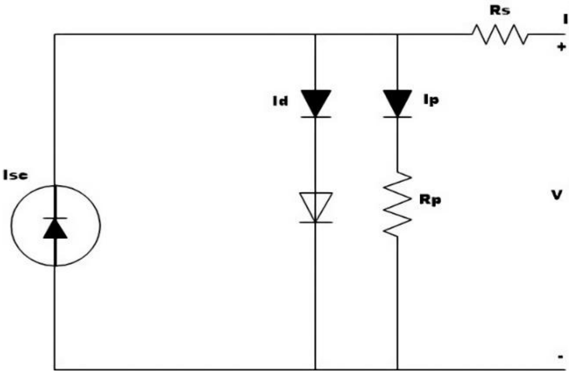

**Fig 1. Solar Cell Equivalent Circuit Diagram**

The fundamental equation that describes the V-I characteristics of a solar cell is constructed as follows[17]:

$$I = I_{sc} - I_d - I_p$$

The result of substituting in eq. (6) appropriate equations for the shunt branch current $(I_p)$ and the diode current $(I_d)$ is given below,

$$I = I_{sc} - I_o\left[\exp\left(\frac{V+IR_S}{\frac{nkT_C}{q}}\right) - 1\right]\left(\frac{V+IR_S}{R_p}\right) \tag{6}$$

The short circuit current $(Isc)$ depends on the irradiance and temperature (Tc) and the amount of solar radiation (G) plane given by eq. (7):

$$I_{sc} = I_{SCR}\frac{G}{G_R}[1+\alpha_T(T_c - T_{CR})] \tag{7}$$

where $T_{CR}$ is the reference temperature and $I_{SCR}$ is the circuit current resistance equal to zero under the standard radiation. The temperature coefficient of photocurrent is indicated by the parameter αT.

## 3. PROBLEM DESCRIPTION

### *3.1 Modeling of Simulated System*

The model for simulating a solar farm connected to the grid is shown Fig.2. In this, the test feeder system is modified by incorporating with the solar farm at buses 634 and 680. The parameter and rating of solar is shown be illustrated in Table 2.

In system configuration, a weak grid-tied solar farm is employed. The system comprises a capacitor bank and distribution damped load of 3.5 MW and 2.2 MVAR, respectively. The network operates at a voltage level of 4.16kV.

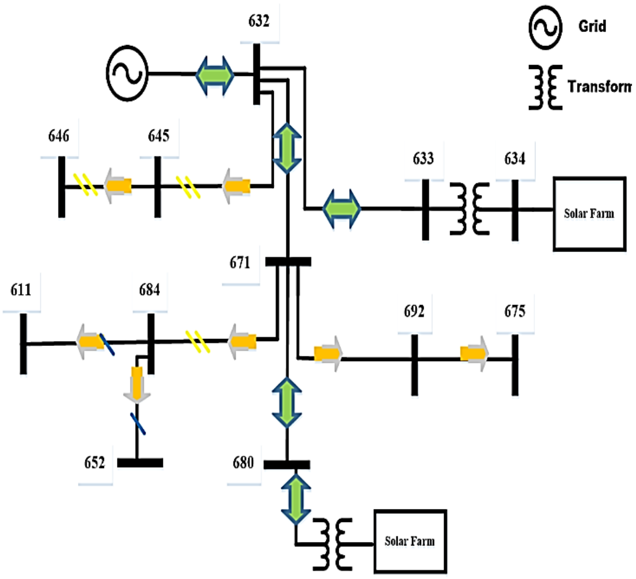

**Fig. 2. Single line representation of modified IEEE 13 Node Test Feeder System.**

**Table 2. Parameter for PV array.**

| S. No | PV Parameter Description | Value |
|---|---|---|
| 1. | Rated Power | 2MW |
| 2. | Number of cells connected in series within a module | 60 |
| 3. | Number of cell string connected in parallel | 1 |
| 4. | Open Circuit Voltage | 37.6V |
| 5. | Short circuit Voltage | 8.85A |
| 6. | Reference Irradiance | 1000 |
| 7. | Reference Cell Temperature | 25 |

In the modified simulated system, the PV power rating is 2MW at Bus 634 and 2.2 kW at Bus 680.

In a feeder system, an FFT analyzer (as depicted in Fig. 3) is utilized to transform voltage or current signals into their frequency-domain representation. The analysis focuses on the fundamentals of current (I) value.

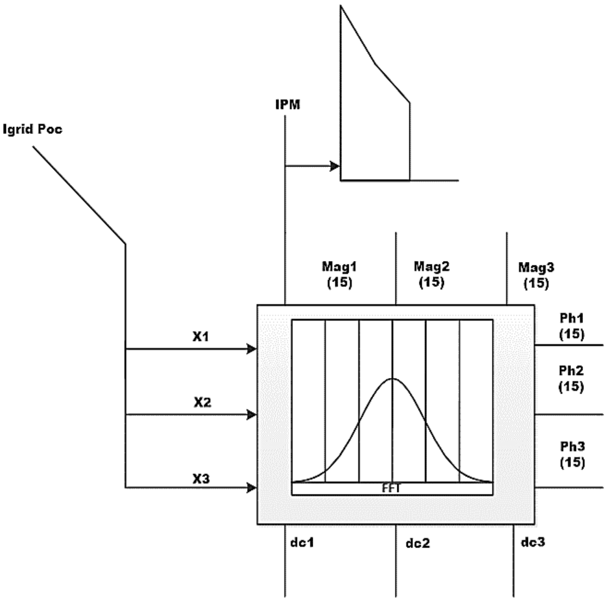

**Fig. 3. FFT Function Block.**

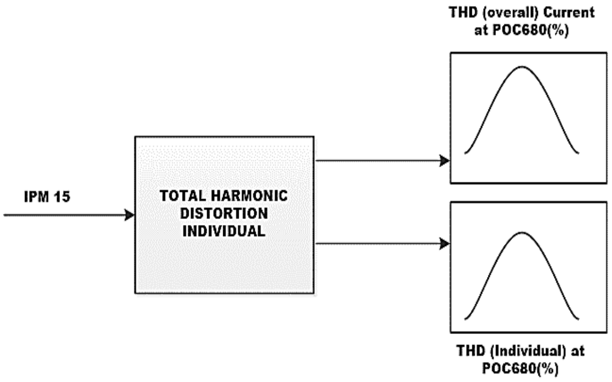

**Fig. 4. Visualization of THD to Show Harmonic Distortion at Point of Connection**

## 4. RESULT AND DISCUSSION

The total harmonic impedance of positive sequence impendence Z=|0.349|∠71.4293° ohms. Total Harmonic Distortion (THD) at Bus 634 and Bus 680 is evaluated under various scenarios including the presence of a PV D-STATCOM at the point of connection 634 and 680 as shown in Fig.4.

This paper assesses the impact of PV D-STATCOM based on THD within the IEEE-13 node feeder system considering various active and reactive power modes on Bus 634 and Bus 680. In the weak grid, the source impedance is considered to be 20% of |Z+|.While the rating of solar farms at Bus 634 (2 MW) and Bus 680 (2.2 kW) with PV D-STATCOM. The Controlling through PI controller, the value of THD has been calculated.

Eight different cases are studied to analyze Total Harmonic Distortion (THD):

1. PV D-STATCOM (P mode) with a capacitor bank at Bus 634, 680.
2. PV D-STATCOM (P mode) at Bus 634, 680

without a capacitor bank.

3. Bus 634 (P mode) and Bus 680 (PQ mode) with capacitor bank
4. Bus 634 (P mode) and Bus 680 (P-Q mode) without capacitor bank
5. P-Q mode at Bus 634 and P mode at Bus 680 with a capacitor bank.
6. P-Q mode at Bus 634 and P mode at Bus 680 without a capacitor bank.
7. P-Q mode at Bus 634, 680 with a capacitor bank.
8. P-Q mode at Bus 634, 680 without a capacitor bank.

Fig.5 at Bus 634 illustrates that the individual THD harmonics measured 3.81531% on the THD graph, reflecting performance under both P-Q and P-Q modes, while complying with IEEE standards for harmonic control.

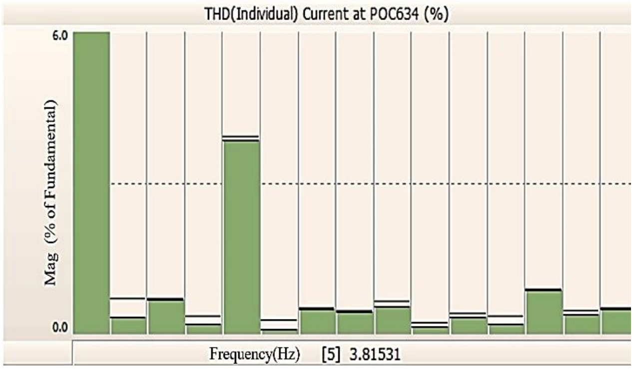

**Fig. 5. THD% of Individuals of BUS 634.**

Fig. 6 at Bus 680 illustrates that the individual THD harmonics measured 2.89421% on the THD graph, reflecting performance under both P-Q and P-Q modes, while complying with IEEE standards for harmonic control.

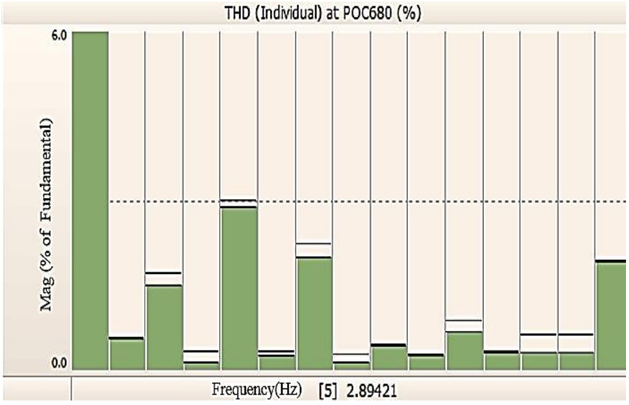

**Fig.6 THD% of Individuals of BUS 680**

In Fig.7, the THD graph for Bus 634 shows an overall Total Harmonic Distortion (THD) of 4.13035%.

Fig. 8 shows the THD graph for Bus 634 shows an overall Total Harmonic Distortion (THD) of 2.21697%.

The result analysis for Case-1, 2 to shown in table3:

The result analysis for Case-3, 4 to shown in Table 4:

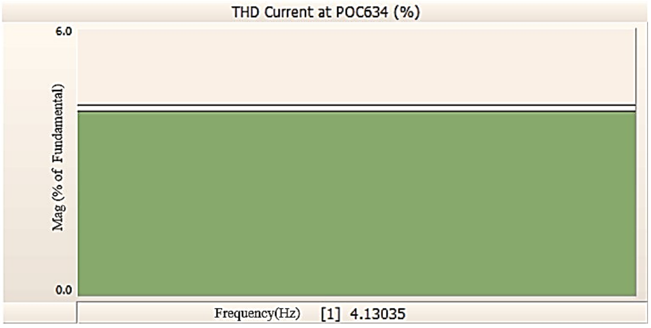

**Fig. 7. THD% of BUS 634.**

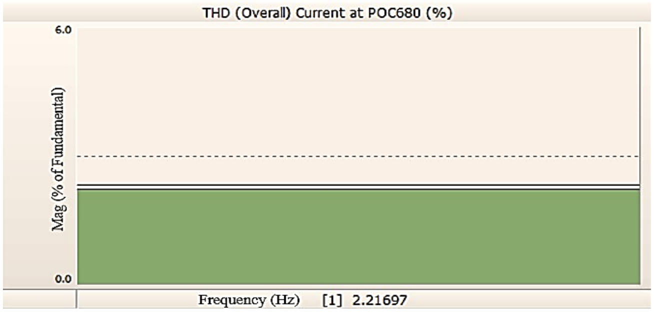

**Fig. 8. THD% of BUS 680.**

**Table 3. PV D-statcom in P mode at bus 634 and bus 680 with and without a capacitor bank.**

| | Case-1(With Capacitor Bank) | | Case-2(Without Capacitor Bank) | |
|---|---|---|---|---|
| S.no. | BUS 634 (P) (Overall THD) | BUS 680(P) (Individual THD) | BUS634(P) (Overall THD) | BUS 680(P) (Individual THD) |
| 1. | 3.93938 | 2.28968 | 4.06301 | 2.21985 |

**Table 4. PV D-statcom in P mode at bus 634 and PQ mode at bus 680 with and without a capacitor bank.**

| Case-3(With Capacitor Bank) | | | Case-4(Without Capacitor Bank) | |
|---|---|---|---|---|
| S.no | BUS 634 (P) (Overall THD) | BUS 680 PQ (Individual THD) | BUS 634(P) (Overall THD) | BUS 680 PQ (Individual THD) |
| 1. | 4.05918 | 3.0483 | 4.07823 | 3.05259 |

The result analysis for Case-5, 6 to shown in Table 5:

**Table 5. PV D-statcom in P-Q mode at bus 634 and P mode at bus 680 with and without a capacitor bank.**

| | Case-5(With Capacitor Bank) | | Case-6(Without Capacitor Bank) | |
|---|---|---|---|---|
| S.no. | BUS634 (PQ) (Overall THD) | BUS 680 P (Individual THD) | BUS 634 PQ (Overall THD) | BUS 680 (P) (Individual THD) |
| 1. | 4.15774 | 2.2908 | 4.13035 | 2.21697 |

The result analysis for Case-7, 8 to shown in TABLE.6.

**Table 6. PV D-statcom in P-Q mode at bus 634 and bus 680 with and without a capacitor bank**

| | Case-7(With Capacitor Bank) | | Case-8(Without Capacitor Bank) | |
|---|---|---|---|---|
| S.no. | BUS634(PQ) (Overall THD) | BUS680(PQ (Individual THD) | BUS634(PQ (Overall THD) | BUS680(PQ (Individual THD) |
| 1. | 4.10748 | 3.04065 | 4.13288 | 3.05259 |

Fig.9 represents the voltage (3-phase) and current (3-phase) waveforms at Bus 680. The graph illustrates the waveforms, highlighting peak values at specific points. The key measurements shown are $V_{rms}$ = 0.917pu, $V_{grid}$ = 3.26kV, $I_{grid}$ = 0.43kA, P_POC680 = 2.185kW, and Q_POC680 = 0.80MVAR. These values represent the root mean square voltage, grid voltage, grid current, active power at the POC, and reactive power at the POC, respectively. This graph provides a comprehensive view of Bus 680, essential for understanding its performance and behavior at POC.

Fig. 10 shows the voltage and current waveforms at Bus 634, with peak values highlighted at certain points. The main measurements are $V_{rms}$ = 0.999pu, $V_{grid}$= 3.47kV, $I_{grid}$ = 0.41kA, P_POC634 = 1.94kW, and Q_POC634 = 0.0259MVAR. These values represent the average voltage, grid voltage, grid current, active power at the POC, and Q at the POC, respectively. This graph provides a clear view of Bus 634, which is important for understanding its performance and behavior at POC.

## 5. CONCLUSION AND FUTURE SCOPE

In conclusion, this study examines the harmonic performance of a feeder system with PV D-STATCOM under various operational scenarios. The findings demonstrate that deploying PV D-STATCOM with precise PI control effectively reduces THD at bus 634 and bus 680 to within 5%, aligning with regulatory requirements. However, challenges remain with uncontrolled 5th-order harmonics in some instances, indicating the necessity for further mitigation strategies. Future research could explore the implementation of harmonic filters, optimization of control strategies such as fine-tuning PI controller parameters, enhancing system design considerations, and implementing comprehensive monitoring and maintenance practices to effectively address harmonic distortions.

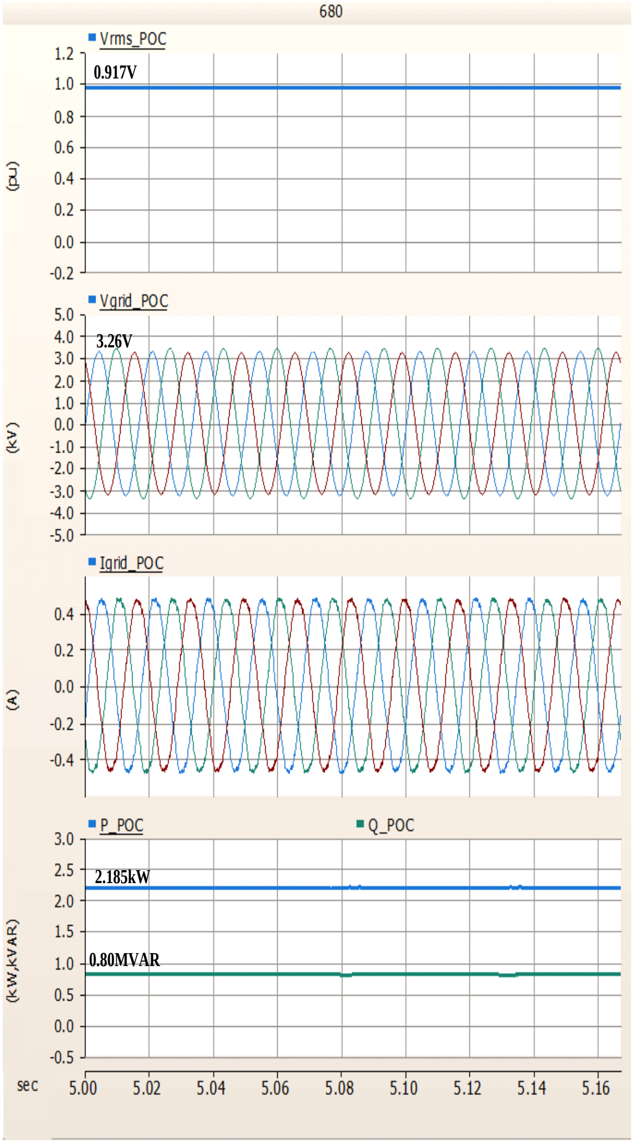

**Fig. 9. Analyzing Voltage and Current Waveform of Bus 680**

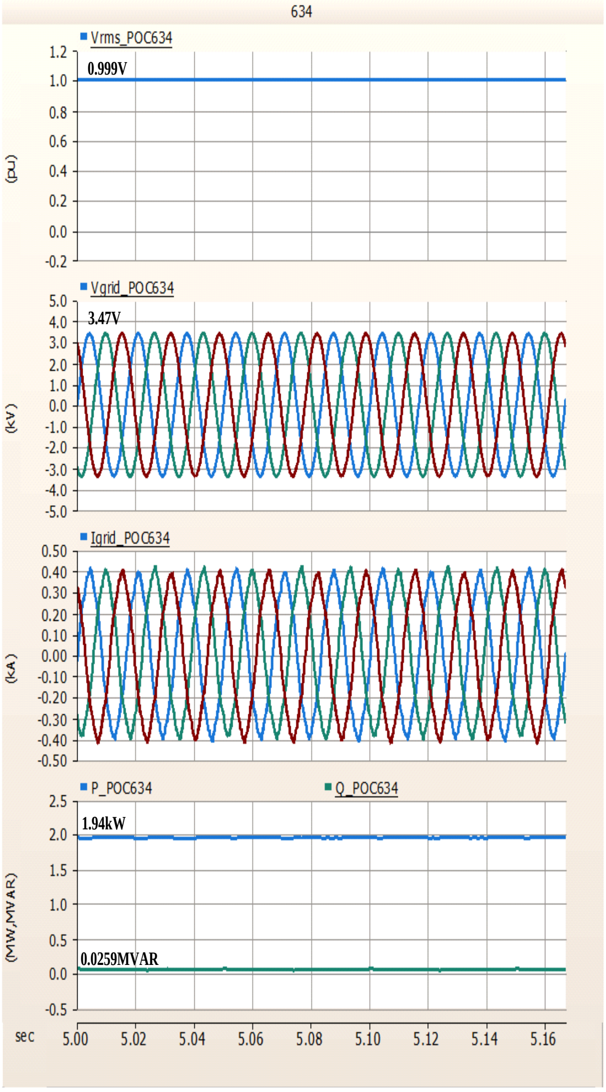

**Fig. 10. Analyzing Voltage and Current Waveform of Bus 634.**

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