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Harmonic Analysis Comparison between PV Integration in High Voltage and Medium Voltage Networks

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ABSTRACT: *Integration of large-scale renewable energy (RE) sources in particular, photovoltaic (PV) sources into the electric grid introduces current and voltage harmonics due to power electronics devices as well as inverter connected into the RE sources. Ensuring adequate harmonics in the line currents of RE integrated power system is one of the biggest challenges today. Harmonic is mostly caused by non-linear loads that form a distorted sine wave, which leads the equipment to become hotter faster, adding losses and reducing the equipment lifetime. Therefore, this study investigates the potential impacts in particular current and voltage harmonics causes due to integration of photovoltaic into high voltage (HV) and medium voltage (MV) networks and the interaction with other non-linear loads and the network voltage. The simulation method uses ETAP software to obtain values from Total Harmonic Distortion (THD) on the 11kV and 132 kV sides with several scenario simulations of photovoltaic integration.*

KEYWORDS *PV, Total Harmonic Distortion (THD),nonlinear loads, ETAP software, High Voltage (HV), Medium Voltage (MV)*

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I. INTRODUCTION

Nowadays, because of the rapidly increasing world's power demand, it is required to have energy sources which are clean, impregnable and economic. This need of energy sources can be obtained by solar, wind, tidal, waves, etc. power. Solar PV is available in abundance and thus it can become an alternative substitute for conventional energy. There is a big concern of poor power quality of the grid which is due to harmonic distortion caused by these PV's [1].

Harmonics are common in distribution networks. Harmonic can be known in the form of waves with different frequencies that produce new frequencies by multiplying the integer base frequency which has a boundary value, in the form of an original wave where the multiplier is used as a harmonic sequence number [2-4].

Linear load indicates the load class, which, if supplied by a sinusoidal source at fundamental frequency, the resulting form is a fundamental sinusoidal current [5-7]. In contrast to linear loads, electronic loads such as drive speeds that can be adjusted as desired are examples of nonlinear loads, which produce harmonic values [8]. All electric and electronic devices like transformers, compact fluorescent lamps (CFL), light emitting diodes (LED) lamps, high intensity discharge (HID) lamps, fluorescent tubes (FT), high voltage fluorescent lamps, air conditioners, rectifiers, inverters, lifts, mobile chargers, transformers cores, arc furnaces, switch mode power supplies (SMPS) and adjustable speed drives (ASD) produce harmonics [9]. SMPS are used in laptops, televisions, computers and a wide range of consumer electronic devices. SMPS are major source of harmonics in homes, offices and industries. Residential and nonlinear loads vary from 38% to 42% of the utility loads. Fluorescent lighting loads in the buildings vary from 40% to 70%. Adjustable speed drives (ASD) which used by wide range of industries consist of three phase current source and voltage source (PWM) converters [10].

Total harmonic distortion (THD) is a measure of the effective value of the harmonic voltage (THDv) or current (THDi) in a distorted waveform. Total harmonic distortions (THDs) are referred to the fundamental values of voltage and currents. Voltage and current THDs are given by

$$THD_V = \frac{\left\{\sqrt{\sum_{h>1}^{hmax} V_{h,rms}^2}\right\}}{V_1} \qquad (1)$$

$$THD_i = \frac{\left\{\sqrt{\sum_{h>1}^{hmax} I_{h,rms}^2}\right\}}{I_1} \qquad (2)$$

Where, voltage and current THDs are given by voltage and current harmonics vary from h=2 to h_{max} and V_1 or I_1 refer to rms values of fundamental voltages or currents [10].

IEC Standard 61000, part three, describes harmonic limits in MV and HV power systems. IEEE standards describes as function of ratio of short circuit level and load currents (ISC/IL). IEEE Standard 519–1992 also describes voltage and current limits in terms of total harmonic voltage (THD_V) and current distortion (THD_i) limits [11].

Energy losses due to harmonics, in well maintained power systems, varies from 1% to 1.5% of total energy consumption which including technical losses may increase up to 2– 25% in harmonics rich power systems [12]. Technical losses are less than 7% in developed utilities and more than 20% in third world utilities. Harmonics may increase losses by 2.1% in industrial feeders [13]. Harmonics worsen the power factor, increase utility apparent power supply demand and influence electromechanical meters as well as some types of smart meters using Rogowski coil transducers [14-16]. Harmonic currents increase hysteresis, eddy current and core losses in generators, transformers and induction motors; multiply line losses in conductors and cables due to higher frequencies; causing malfunction of circuit breakers, fuses, protective relays and control systems [17].

Inverter is a heart of modern renewable energy system providing DC to AC conversion for synchronization of renewable energy sources with existing electrical grid networks [18]. Harmonic distortion in grid connected PV systems is caused by non-linear loads [19-23], frequency switching variables in inverters [22- 23], and fluctuations in solar radiation [24-25]. The characteristics of current harmonic emissions in PV inverters under different voltage supplies have been evaluated by [26]. Similarly, the characteristics of harmonic distortion in distribution feeders were due to the inclusion of PV is stated by [27]. Also, increase in THD_V occurs at the PV terminals connected to the distribution network during cloudy weather is presented in [28].

Another power quality problem arises at the interface between PV inverters and the grid is harmonic resonance phenomenon. Harmonic resonance phenomena will occur at a resonant frequency where the inductive impedance is equal to the capacitive impedance. The number of PV units connected to the grid affect harmonic resonance. Th effect of harmonic resonance not only presents a severe power quality problem but also can trip protection devices and cause damage to sensitive equipment [29]. The experimental results indicate that the values of total harmonic distortion THDi depend on the output power of the inverter. This dependence decreases proportionally with reduced power converter rating. The interaction between grid components and a group of PV units can amplify harmonic distortion [30]. In addition, PV placement also contributes to harmonic distortion levels in a power system. PV placement at higher voltage circuit produces less harmonic distortion compared with PV placement at low voltage level [31].

In this paper, two study cases are presented to compare the effect of PV integration on harmonic levels in both MV and HV networks. The first study case is measuring and analysis of harmonic contents in sub-feeder in Assiut university distribution grid without and with PV integration with different rate, different inverter models and different point of common coupling (PCC). The second study case is analysis of harmonic level in cement factory without and with PV integration with different PCC at MV and HV sides. The different cases are simulated by ETAP software for harmonic load flow analysis. This paper is organized as follow: section II presents the studied systems description; results and discussions are presented in section III and finally, a conclusion is presented in section IV.

II. STUDIED SYSTEMS DESCRIPTION

A. NBS4 Sub-Feeder

Assiut university distribution grid is shown in Fig. 1. It consists of 18 sub-feeders (9 rings) and feeds 95 transformers with different ratings each ring consists of 2 sub-feeders which can be connected by isolator in case of fault or maintenance for any of the two bus bars. Each transformer is delta/grounded star connected and with voltage rating (11KV/400V). Cables in the medium voltage side are 3-cores AL cable (3*240 mm2 and 3*150mm2) with PVC insulation.

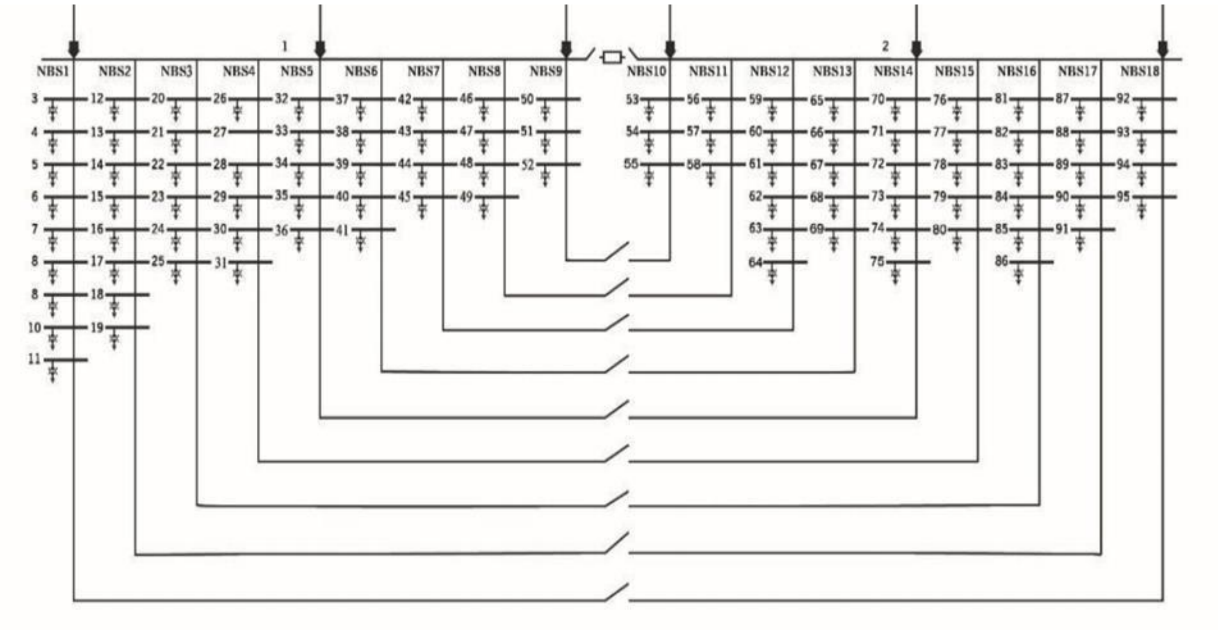

Fig.1. Assiut University Distribution Grid

The NBS4 studied sub-feeder is one of Assiut university distribution grid sub-feeders. It feeds 5 transformers, 4 of them 500 KVA and the fifth Transformer is 1MVA. The lengths of cables of in the studied sub- feeder are (44,135,110,130) m. NBS4 sub-feeder ETAP model is shown in Fig. 2

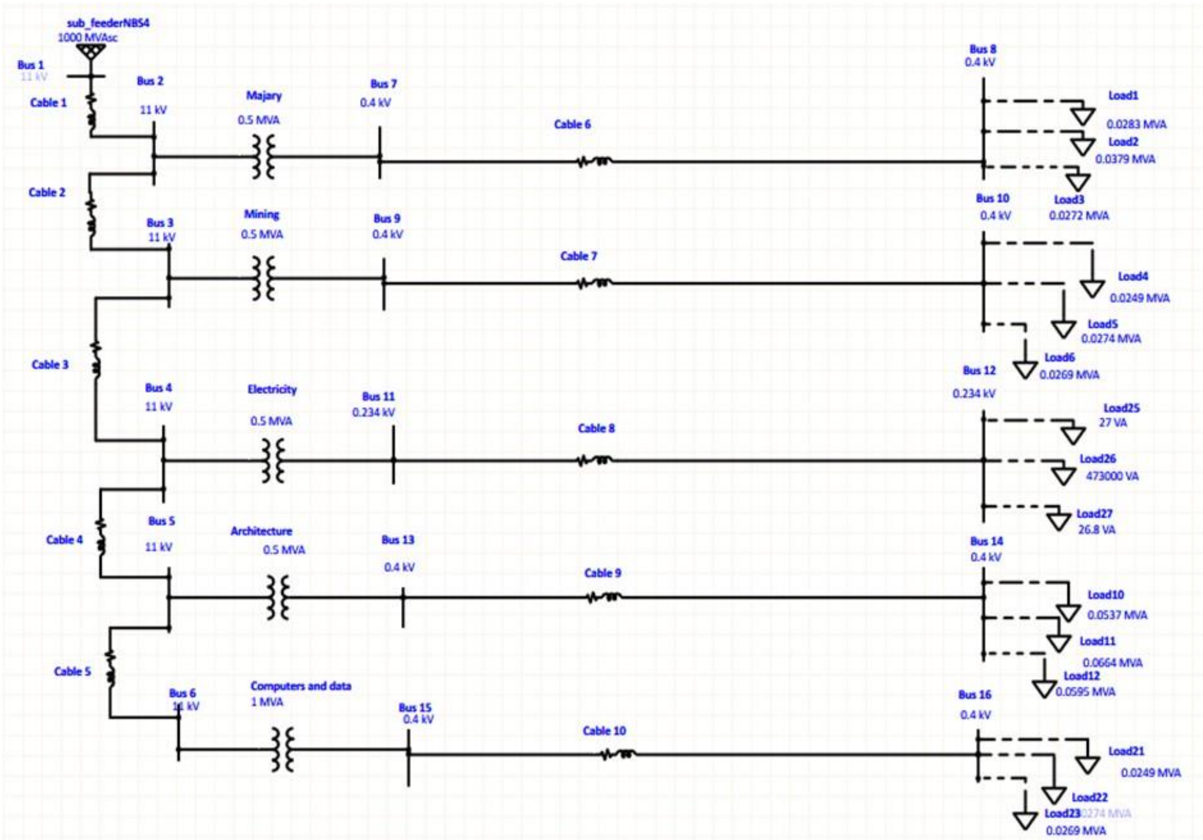

Fig. 2. NBS4 Studied Sub-feeder

Harmonic contents in each phase of low voltage (LV) side in NBS4 sub-feeder of Assiut university distribution grid are measured and monitored using FLUKE 435 power quality and energy analyzer. These data are used as input to harmonic load flow study by ETAP software to calculate the harmonic contents in MV side due to sub- feeder loads. PV integration with (LV) side in different buses for studying its effect on harmonic contents is presented. PV converter is considered six pulse converters harmonic choice.

B. 132 KV Transmission Line Feeding Circuit

Cement factory is fed from 132 KV Transmission line with total length 105 Km. Two circuits feeder 500KV are stepped down to 132KV and double 132KV transmission line circuits feed each cement factory. Also, there are two generation units feed both cement factories through 132 KV transmission line. The feeding circuit is shown in Fig. 3.

ETAP simulated circuit is shown in Fig. 4. Three feeders (buses 1,11 and 12) feed cement factory through 132KV HV transmission line and (Δ/Y) transformer with rate of 35 MVA, 132/6.3 kV. The loads of cement factory are simulated according to [32]. The main sources of harmonics in cement factory are variable speed drives (VFDs), UPS and different types of motors. Since all the VFDs and the DC drive are using 6-pulse converter, the dominant harmonic components are 5^{th}, 7^{th}, 11^{th} and 13^{th} order.

Harmonic load flow analysis is performed by ETAP software to study the harmonic contents in MV and HV sides according to loading condition. Effect of PV connection to MV side and HV side on harmonic content is studied.

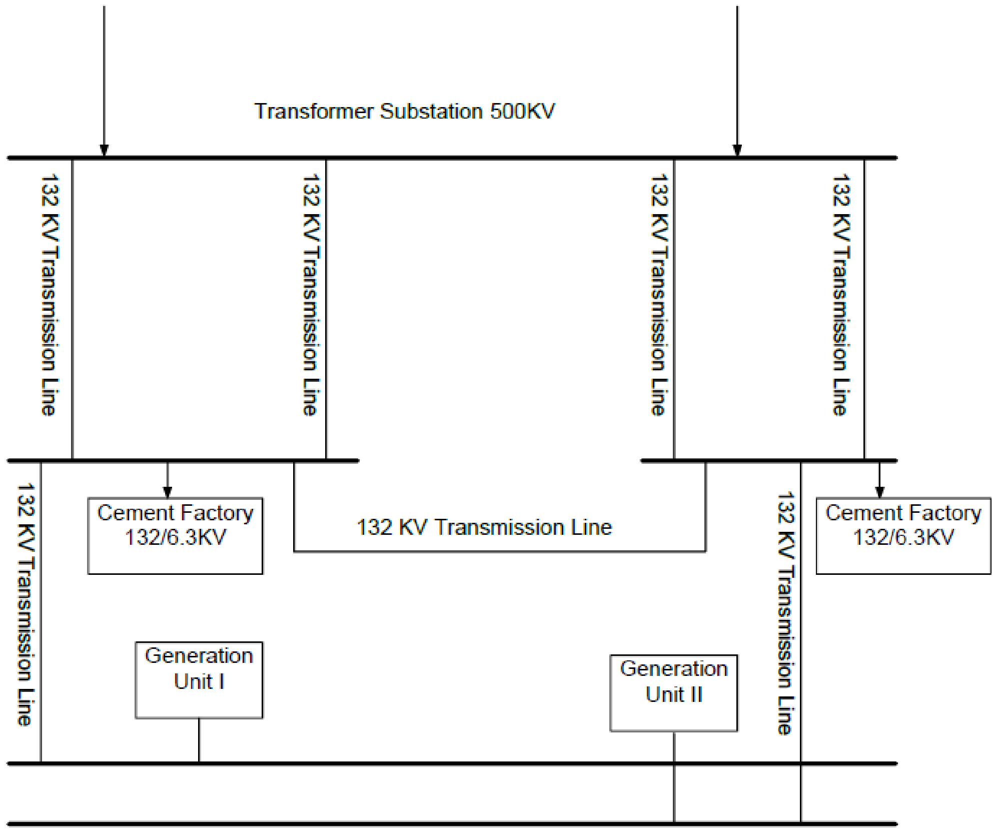

Fig. 3. Cement Factory 132KV Feeding System

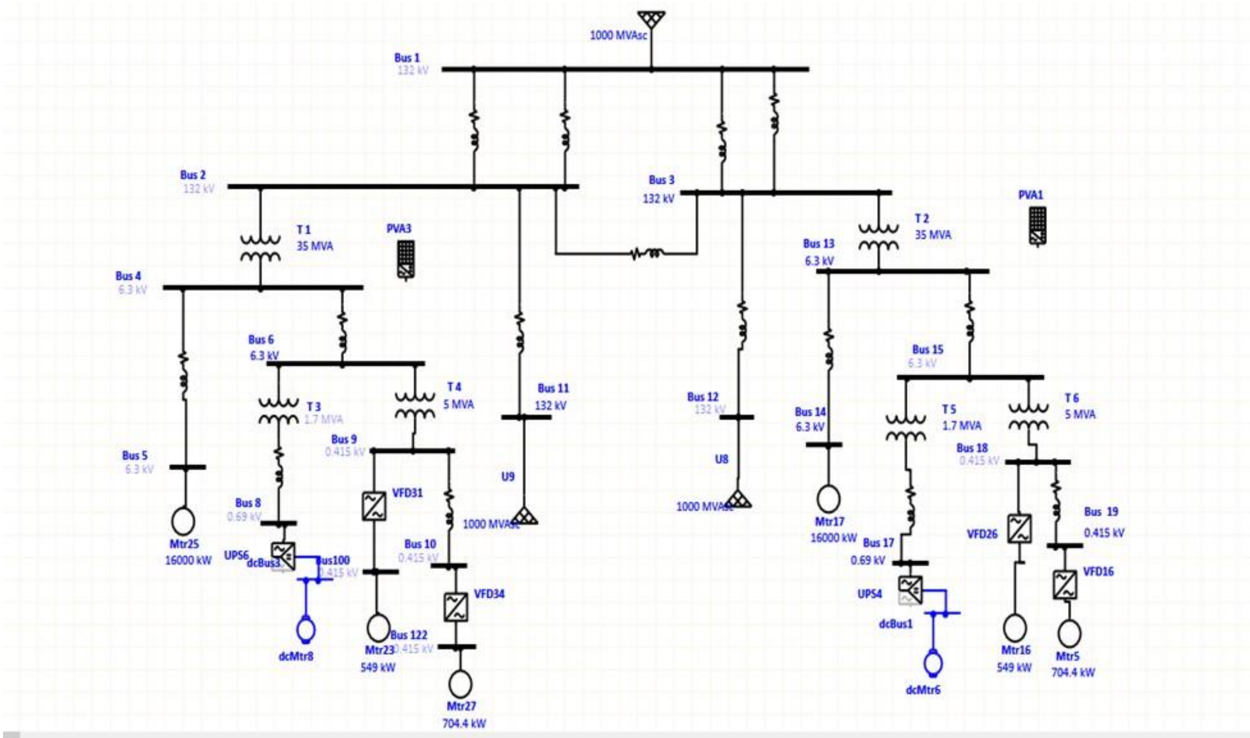

Fig. 4. Cement Factory Feeding System

III. RESULTS AND HARMONIC ANALYSIS

A. NBS4 Sub-Feeder Results

Harmonic contents in each phase of LV side in NBS4 sub-feeder of Assiut university distribution grid are measured and monitored using FLUKE 435 power quality and energy analyzer.

The measured loads, THD_i and THD_V of phase (A) in bus 10 with time for around 2 hours is plotted and shown in Fig. 5. The measured THD_i and harmonic current contents in each phase in bus 10 is shown in Fig.6. Also, THD_V and harmonic voltage contents in each phase in bus 10 is shown in Fig.7. THD_V and THD_i for each LV side bus is shown in Fig. 8 and Fig. 9 respectively.

From the measured data, the following can be observed:

- THD_i is dependent on loading current and load types while THD_V is nearly steady and dependent on grid voltage.
- THD_i is inverse proportional to loading condition
- Harmonics level is agreeing with IEEE Standard 519–1992
- The dominant harmonic contents are odd harmonic in voltage and current.

Analysis of harmonics without and with solar PV integration at different buses is performed. The analysis is classified into four cases. Analysis without PV integration is presented in case I while analysis with PV integration is presented in case II, effect of PV penetration on THD is presented in case III and effect of different PV converter harmonic models is presented in case IV.

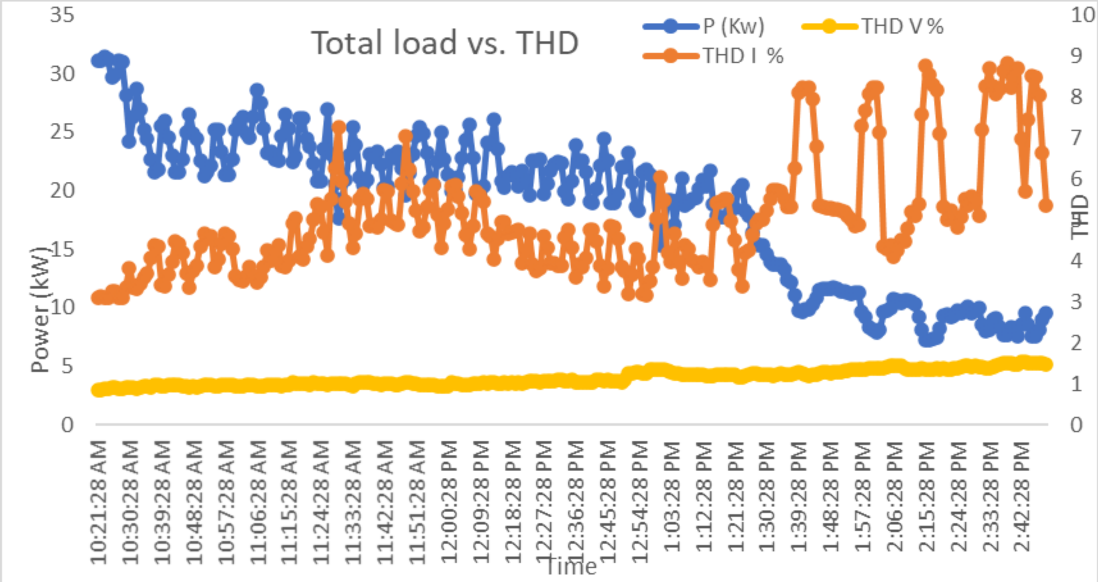

Fig. 5. Total load vs. THD at Bus 10

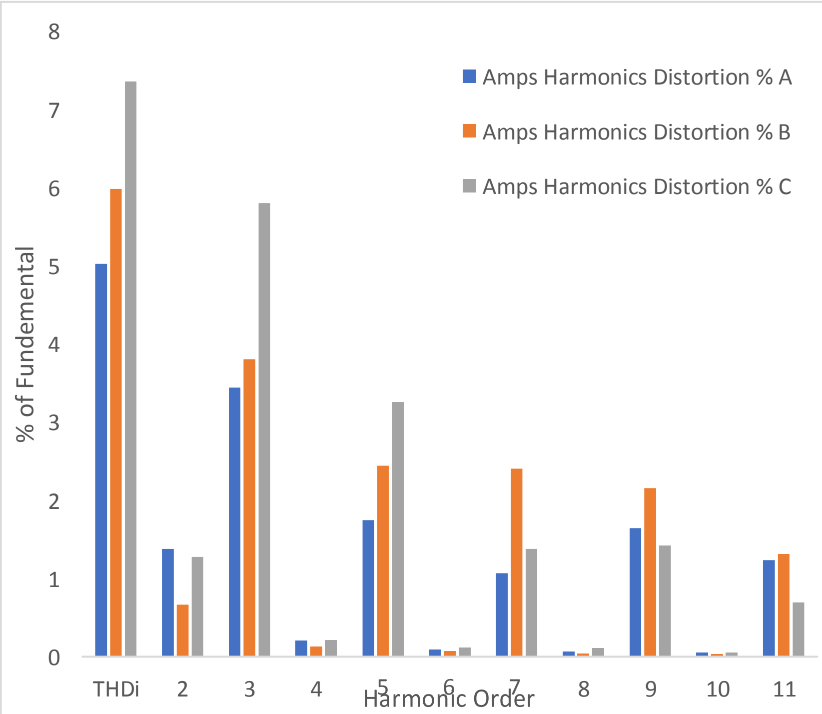

Fig. 6. Harmonic currents Content at Bus 10

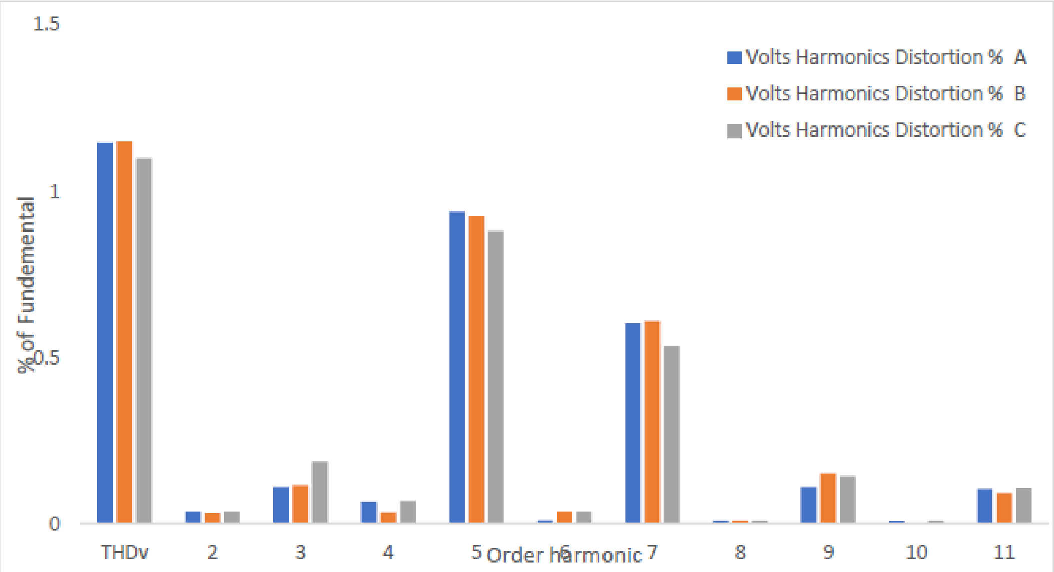

Fig. 7. Voltages Harmonic Content in Bus 10

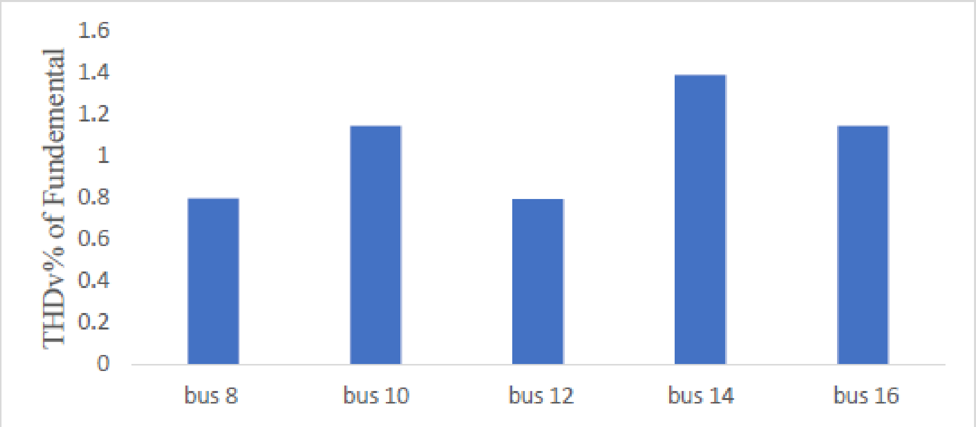

Fig. 8. THDV vs. Bus

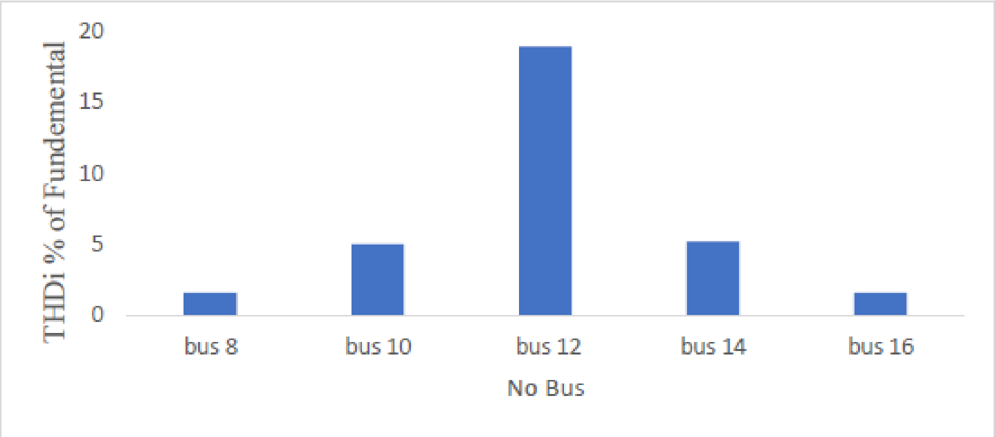

Fig. 9. THDi vs. Bus

Case I:
In this case the analysis of harmonics without PV integration is performed by ETAP software. The measured harmonics are used as input to harmonic load flow study by ETAP software to calculate the harmonic content in MV side due to sub-feeder loading.

The harmonic voltages and harmonic currents spectrum are shown in Fig. 10 and Fig. 11 respectively

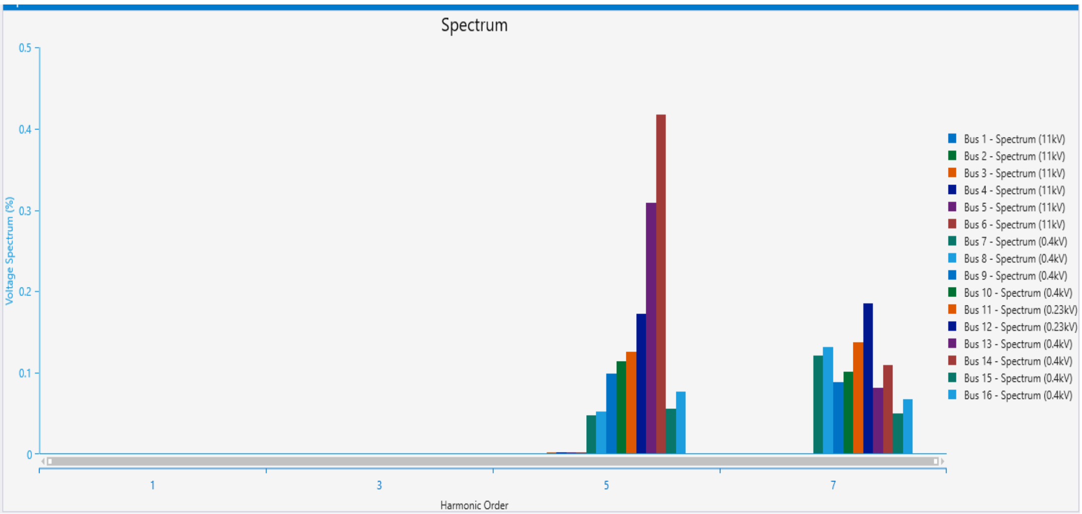

Fig. 10. Harmonic voltage spectrum in NBS4 sub-feeder of Assiut university distribution grid

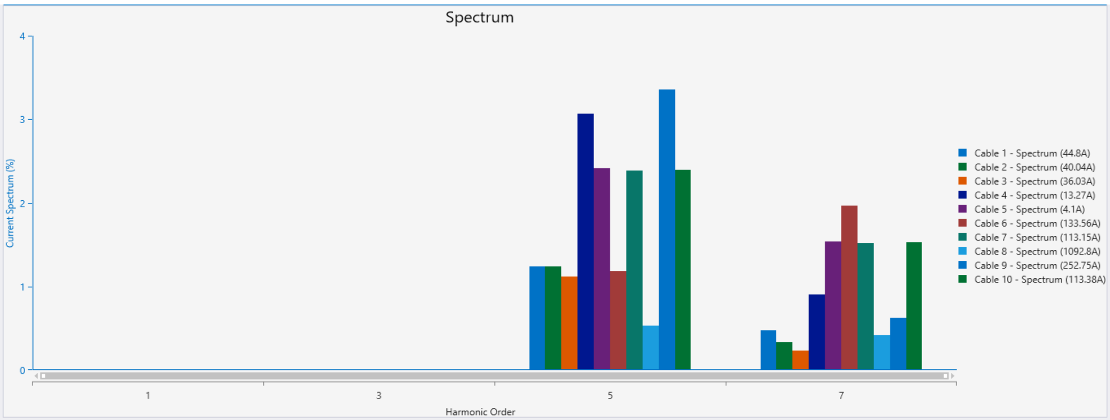

Fig. 11. Harmonic current spectrum in NBS4 sub-feeder of Assiut university distribution grid

- **Case II**

The goal of this case is studying the effect of PV integration on the THDV and THDi in NBS4 sub-feeder. The harmonic load flow is performed when the PV connected into bus 8, then bus 10, then bus 14, and finally bus 16. Each time there is one PCC connect PV to the grid.
Table 1 presents THDi in LV and MV sides for different PV integration PCC.
From Table 1, It is found that the harmonic distortion in current increased after PV integration.

Table 1 THDi without and with PV integration with different PCC

From-To	% THD without PV	% THD with PV at bus 8 only	% THD with PV at bus 10 only	% THD with PV at bus 14 only	% THD with PV at bus 16 only
Bus 1-Bus 2	1.326189	17.58639	17.63848	16.88939	18.49047
Bus 2-Bus 3	1.288749	1.286993	19.49233	18.67016	20.43889
Bus 2-Bus 7	2.295779	30.90693	2.298068	2.297749	2.297581
Bus 3-Bus 4	1.14425	1.142353	1.143279	20.2643	22.18689
Bus 3-Bus 9	2.826018	2.825141	30.22226	2.826881	2.826465
Bus 4-Bus 5	3.200128	3.19708	3.198154	38.26942	41.33373
Bus 4-Bus 11	0.678567	0.681614	0.682871	0.683063	0.683319
Bus 5-Bus 6	2.861081	2.860592	2.862791	2.864053	31.4349
Bus 5-Bus 13	3.411915	3.407773	3.408279	34.85947	3.407171
Bus 6-Bus 15	2.843488	2.84255	2.844593	2.845689	31.42387
Bus 7-Bus 8	2.295779	30.90693	2.298068	2.297749	2.297581
Bus 9-Bus 10	2.826018	2.825141	30.22226	2.826881	2.826465
Bus 11-Bus 12	0.678567	0.681614	0.682871	0.683063	0.683319
Bus 13-Bus 14	3.411915	3.407773	3.408279	34.85947	3.407171
Bus 15-Bus 16	2.843488	2.84255	2.844593	2.845689	31.42387

- **Case III**

The goal of this case is studying the effect of the PV penetration on the THDi within the system. The harmonic load flow is performed when the PV connected to all buses 8, 10, 14, and 16.

Table 2 shows the THDi with and without PV penetration. Fig.12 presents the effect of PV penetration on THDi

Table 2 shows that, the interaction between grid and number of solar PV units increases the harmonic distortion and all other buses are also affected by harmonics

Table 2 THDi without and with PV connection in each LV side buses

From -To	% THDi without PV	% THDi with PV at buses 8, 10, 14 and 16
Bus 1-Bus 2	1.326189	33.27001
Bus 2-Bus 3	1.288749	33.19953
Bus 2-Bus 7	2.295779	30.89322
Bus 3-Bus 4	1.14425	31.90923
Bus 3-Bus 9	2.826018	30.20693
Bus 4-Bus 5	3.200128	33.1636
Bus 4-Bus 11	0.678567	0.696281
Bus 5-Bus 6	2.861081	31.42002
Bus 5-Bus 13	3.411915	34.83219
Bus 6-Bus 15	2.843488	31.40728
Bus 7-Bus 8	2.295779	30.89322
Bus 9-Bus 10	2.826018	30.20693
Bus 11-Bus 12	0.678567	0.696281
Bus 13-Bus 14	3.411915	34.83219
Bus 15-Bus 16	2.843488	31.40728

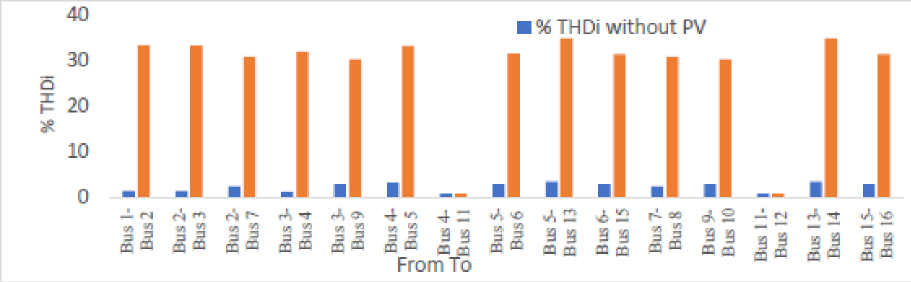

Fig. 12. THD$_i$ in MV and LV sides without and with PV penetration

- **Case IV**

The goal of this case is studying the effect of different PV converter harmonic models on THDi when PV connected to bus 14 in NBS4 sub-feeder. Table 3 and Fig. 13 show the THDi without PV connection and with PV connection to bus 14 with different converter harmonic models.

Table 3. THDi without PV connection and with PV connection to bus 14 with different converter harmonic model

To	% THD without PV	IEEE 519 Equation of 6 pulse	IEEE 519 Equation of 12 pulse	Typical- IEEE model XFMR Magnet	ABB Model ACS600 6 p
Bus 1-Bus 2	1.326189	16.88939	7.016623	13.01816	27.20934
Bus 2-Bus 3	1.288749	18.67016	7.732599	14.3048	30.07258
Bus 2-Bus 7	2.295779	2.297749	2.295884	2.294943	2.295113
Bus 3-Bus 4	1.14425	20.2643	8.394732	15.38927	32.66049
Bus 3-Bus 9	2.826018	2.826881	2.826262	2.823716	2.822302
Bus 4-Bus 5	3.200128	38.26942	15.71139	29.26896	61.49393
Bus 4-Bus 11	0.678567	0.683063	0.678711	0.683655	0.688969
Bus 5-Bus 6	2.861081	2.864053	2.861448	2.859677	2.859686
Bus 5-Bus 13	3.411915	34.85947	14.3305	26.42761	56.04646
Bus 6-Bus 15	2.843488	2.845689	2.843843	2.84134	2.840532
Bus 7-Bus 8	2.295779	2.297749	2.295884	2.294943	2.295113
Bus 9-Bus 10	2.826018	2.826881	2.826262	2.823716	2.822302
Bus 11-Bus 12	0.678567	0.683063	0.678711	0.683655	0.688969
Bus 13-Bus 14	3.411915	34.85947	14.3305	26.42761	56.04646
Bus 15-Bus 16	2.843488	2.845689	2.843843	2.84134	2.840532

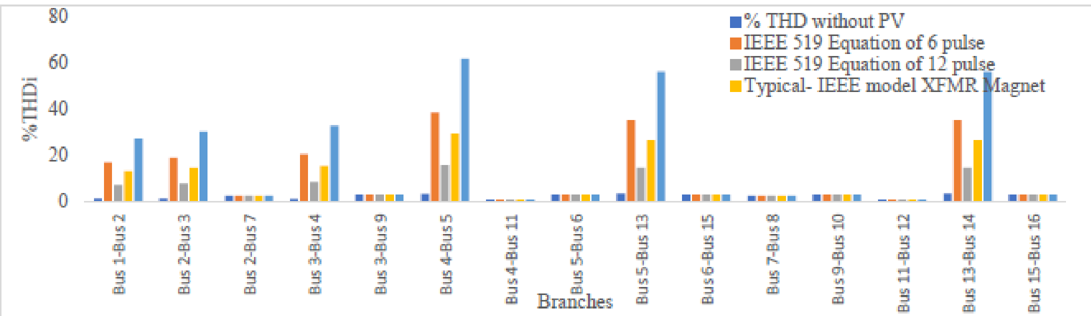

Fig.13. THD$_i$ without and with PV connection with different types of converter harmonic models

From case II, case III and case IV, the following can be observed:

- THDi increases with PV integration.
- THDi increases with increase number of PV connected
- THDi increases with increase rating of PV connected
- The connection of PV in LV side has high effect of THDi in both MV and LV sides

B. 132KV Transmission Line Feeding Circuit

Harmonic load flow analysis is simulated by ETAP software to study effect of non-linear load on harmonic contents in both MV and HV sides. The harmonic spectrum of voltage and current are shown in Fig.14 and Fig.15 respectively.

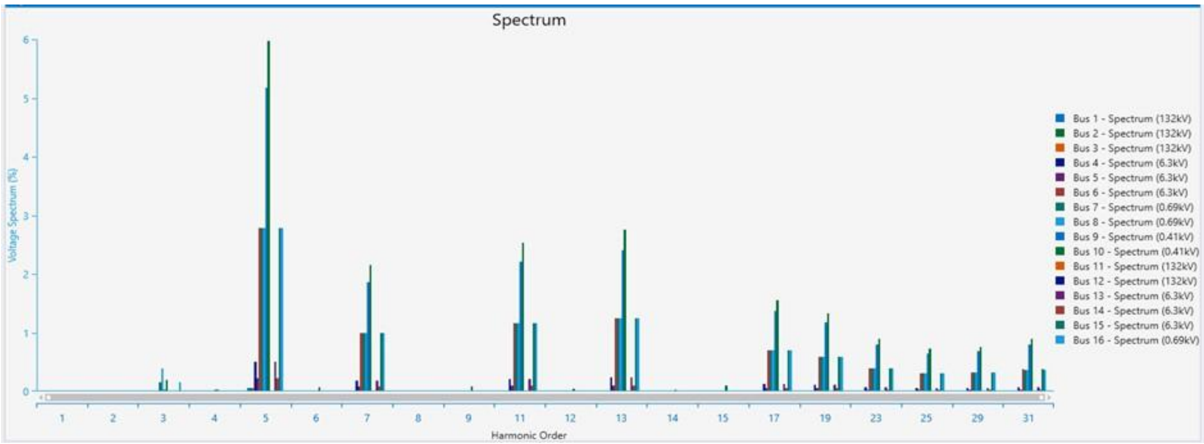

Fig. 14. Harmonic voltage spectrum

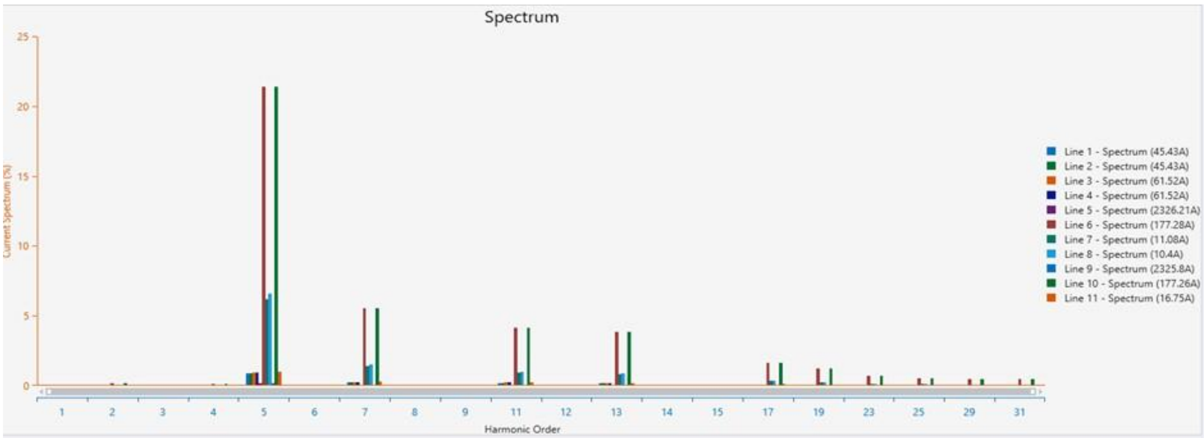

Fig. 15. Harmonic current spectrum

Effect of PV integration on harmonic contents is simulated with ETAP software. The PCC is MV bus and HV bus. THDi in MV and HV side is presented in Table 4. THDv in MV and HV side is shown in Fig. 16.

Table 4 THDi in MV and HV side with different PCC PV integration

From-To	% THDi without PV	% THDi with PV at HV (132kV)	% THDi with PV at MV (6.3 kV)
Bus 1-Bus 2	0.983069	0.98153	0.896697
Bus 1-Bus 3	1.014396	1.012815	0.925273
Bus 2-Bus 11	6.474824	6.464649	5.905001
Bus 2-Bus 3	1.049689	1.04797	0.957415
Bus 2-Bus 4	1.42895	1.428955	1.303311
Bus 3-Bus 12	6.864053	6.853268	6.259966
Bus 3-Bus 13	1.429252	1.429257	1.303603
Bus 4-Bus 5	0.218619	0.218611	0.199398
Bus 4-Bus 6	22.91044	22.91044	20.89653
Bus 6-Bus 7	0.756811	0.756806	0.690258
Bus 6-Bus 9	23.24308	23.24308	23.32494
Bus 7-Bus 8	50.22326	50.22326	50.2223
Bus 7-Bus 6	50.22326	50.22326	50.2223
Bus 9-Bus 10	22.48793	22.48793	22.59437
Bus 11-Bus 2	8.736651	8.722937	7.967926
Bus 12-Bus 3	9.617743	9.602648	8.771477
Bus 13-Bus 14	0.218467	0.218459	0.199262
Bus 13-Bus 15	22.91058	22.91058	20.89692
Bus 15-Bus 16	0.756704	0.756699	0.690169
Bus 15-Bus 18	23.24322	23.24322	23.32506
Bus 16-Bus 17	50.22326	50.22326	50.2223
Bus 16-Bus 15	50.22326	50.22326	50.2223

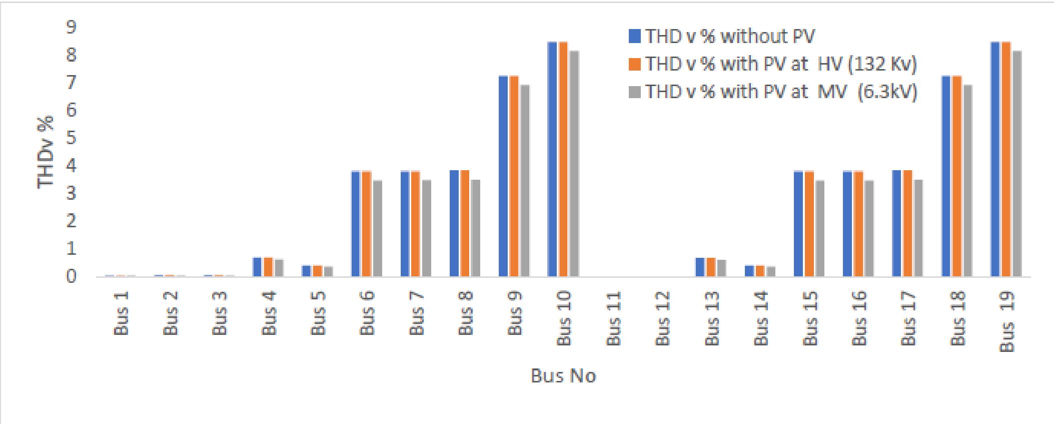

Fig. 16. THDv in MV and HV sides with different PV connection

IV. CONCLUSION

The objective of this paper is to investigate the harmonic contents according to loading conditions as well as solar PV integration in MV grid and HV grid. From these cases, the followings are investigated:

1- The voltage/current harmonic distortions at various buses/branches in MV and HV grids without PV integration.

2- Effect of PV integration in both LV, MV and HV sides on THDv and THDi. 3- Effect of PV penetration on THDv and THDi.

4- Effect of different PV converter harmonic models on THDv and THDi. From these studies, the followings can be concluded:

1- THDi is inversely proportional with loading conditions. 2- THDV is nearly constant with loading conditions

3- Integration of solar PV increases the harmonic contents in the system beyond the prescribed limit and have higher effect on MV side than HV side.

4- THDi depends on the point of common coupling (PCC) between the grid and PV system. 5- THDi increases with number of PV.

6- PV integration at HV side produces less harmonic distortion compared with integration at MV side. 7- PV converter harmonic model affect THDi level

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