HARMONICS ISSUES THAT LIMIT SOLAR PHOTOVOLTAIC GENERATION ON DISTRIBUTION CIRCUITS

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ABSTRACT

This paper describes the authors' analysis of harmonics issues that limit the amount of solar photovoltaic (PV) generation in a 12.47 kV distribution circuit with major capacitors installed at the substation. The capacitors introduce resonant frequencies in the circuit which may be excited by harmonic currents from inverter based PV units on the same circuit. This leads to potential voltage or current distortions beyond the criteria specified in the IEEE-519 or IEEE-1547 standards, thereby limiting the amount of PV penetration on the circuit. To allow more PV penetration, countermeasures such as installing harmonic filters and repurposing capacitors may be applied. In addition, the authors identify appropriate ways to interpret the standards, model the study circuit for simulation and develop assumptions for analysis. The paper concludes with recommendations on best practices to model and identify harmonic constraints in a distribution circuit with both capacitors and PV inverters, and on the application of mitigation solutions that lead to more PV penetration without sacrificing the safety and reliability of the distribution system.

1. INTRODUCTION

Harmonics of a waveform are components whose frequencies are multiple integers of a 60 Hz or 50 Hz fundamental wave. For example, 120 Hz, 180 Hz, 240 Hz, and 300 Hz are the 2nd, 3rd, 4th and 5th harmonic components of a 60 Hz fundamental waveform. Harmonic distortion is usually caused by non-linear devices in electric power systems [1]. Harmonics pose a risk to power systems in terms of overheating of transformers, motors, lines, and cables which can lead to shortened life, interference with communication systems (generally for services on the same electric pole such as cable TV and phone) and with the operation of sensitive loads, and outages associated with blown fuses and failed equipment. Power electronic converters, which are widely used in modern power systems, are some of the major sources of harmonics. Solar photovoltaic generation depend extensively upon power electronic converters to produce alternating current output for interconnection purposes. Therefore, the harmonic issue is one the most important aspects affecting the integration of renewable energies.

IEEE Standard 519-1992 [2] is the standard that specifies limits on the amount of harmonics allowed in the grid. On the other hand, IEEE Standard 1547-2003 [3] focuses on the interconnection requirements of renewable resources. These two standards inform the model development and simulation methods used in this paper. A case study described in this paper illustrates how PV penetration on a 12.47 kV distribution circuit may be limited by harmonic issues.

2. SIMULATION SETUP

2.1 Modeling of the Study 12.47 kV circuit

The study in this paper is based on a 12.47 kV distribution circuit supplied from a 10 MVA 69/12.47 kV substation transformer as illustrated in Fig. 1. There are two feeders connected to the 12.47 kV bus. One feeder is a 10-mile overhead line with a 3 MVA lumped load at a power factor (p.f.) of 0.9 lagging under peak load connected at the end of the feeder. This represents a distribution feeder in a rural area where customer load may be served over a long distance. The other feeder is composed of a 2-mile 500 MCM underground cable with a total load of 3 MVA (0.9 p.f.) lagging at peak load. The load is represented by 4 lumped equivalents at locations Load#1 ~ 4. This feeder is connected to the 12.47 kV bus through utility transformers (Utility TSF#1 ~ 4). Four 3-phase PV units rated at 500 kW each are also connected to these utility transformers. Four additional 3-phase PV unit#1 ~ 4 are also connected along the 2-mile feeder to test PV penetration limits. The minimum load is assumed to be 50% of the peak load. The utility short circuit contribution at peak load condition is 597.5 MVA for a 3-phase fault and 250 MVA for a line-ground fault. The utility short circuit contribution at minimum load is assumed to be 50% of the peak load contribution.

Capacitors are sometimes installed at a main substation for voltage control of distribution circuits. In this study, there is a 3-stage 4 Mvar capacitor bank connected at the 12.47 kV bus, as shown in Fig. 1, which can operate at 1, 2, or 4 Mvar.

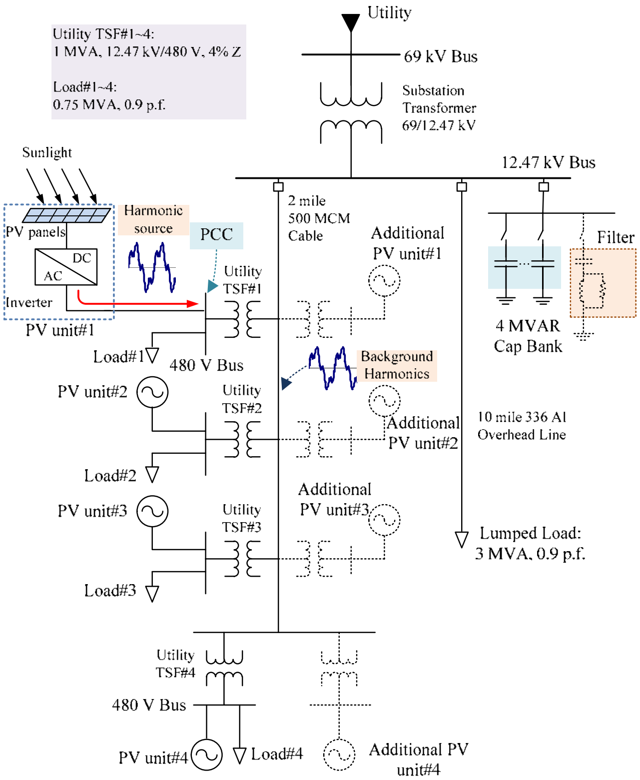

Fig. 1: An Illustration of the Study 12.47 kV Distribution Circuit

2.2 Harmonic Sources

A PV unit is comprised of the PV panels that generate DC, and the inverter, which converts DC to AC, as illustrated in Fig. 1 (PV unit#1). Inverters are power electronic devices that are major sources of harmonics. The harmonic current is injected from the inverters to the distribution circuit potentially affecting customers connected to the same circuit.

The profile of harmonic content can vary significantly among the many commercially available UL listed PV inverters. Two examples, both taken from actual measurements, are shown in Fig. 2. In the first example, identified as Type-1, the inverter produces a total harmonic distortion (THD) of current slightly less than 3% ($I_{THD} < 3\%$). For this PV inverter, the AC output waveform visually shows some distortion but remains close to a sine wave. In the second example, identified as Type-II, I_{THD} is higher than 5%. For this second PV inverter, the AC output waveform clearly shows more distortion of the sine wave. For analysis purposes, particularly where the harmonic spectrum of a specific PV unit is not available, the Type-II may be used to represent a worst case model. In the study reported in this paper, both Type-I and Type-II inverters are applied in the analysis.

Type-1 (Ithd<3%)		Type 2 (Ithd>5%)	
Harmonic Order	Magnitude (pu)	Harmonic Order	Magnitude (pu)
1	1	1	1
2	0.0188	2	0.01124
3	0.01041	3	0.03255
4	0.0078	4	0.00261
5	0.0166	5	0.03466
6	0.0016	6	0.00124
7	0.0052	7	0.01118
8	0.0016	8	0.00815
9	0.0004	9	0.00484
10	0.0016	10	0.00838
11	0.0018	11	0.00669
12	0.0004	12	0.00793
13	0.0024	13	0.00454
14	0.0006	14	0.01057
15	0.0004	15	0.00303
16	0.0012	16	0.005
17	0.0006	17	0.01474
18	0.0004	18	0.00584
19	0.0012	19	0.01132
20	0.0008	20	0.00709
21	0.0004	21	0.00496
22	0.0018	22	0.00396
23	0.0026	23	0.00208
24	0.001	24	0.00352
25	0.005	25	0.01328
26	0.002	26	0.00192
27	0.0004	27	0.00608
28	0.001	28	0.01194
29	0.0006	29	0.00893
30	0.0002	30	0.00671
%THD	2.98%	%THD	6.27%

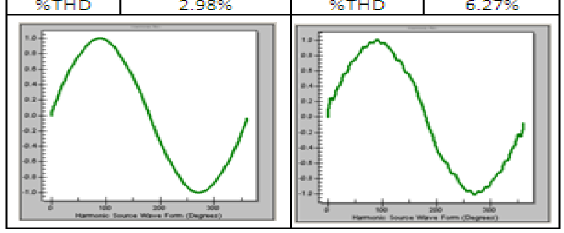

Fig. 2: Type-I and Type-II Current Harmonics of PV Units (Type-II adapted from [4])

In addition, there is also a certain amount of background harmonics in the distribution circuit coming from customer load and utility equipment. For purposes of analysis, the background harmonic current is assumed to be 2% of the total load current on the 2-mile long feeder, with the contribution from TV and computers, fluorescent lamps and compact fluorescent evenly divided. The typical harmonic content of different types of consumer devices is listed in Table 1.

TABLE 1: TYPICAL HARMONIC CONTENT OF RESIDENTIAL AND COMMERCIAL LOADS

Harmonic Order	Harmonic Sources (p.u.)		
	TV, Computer	Fluorescent Lamp	Compact Fluorescent
1	1	1	1
3	0.81	0.09	0.82
5	0.60	0.01	0.68
7	0.37	0.02	0.45
9	0.16		0.25
11	0.03		0.14
13	0.05		0.14
15	0.07		0.13
17	0.04		0.10

3. STUDY APPROACH

3.1 Study Cases

Considering the circuit load, operation of the capacitor bank as well as the output of PV units, there are mainly 4 different cases as summarized in Fig. 3 and Table 2.

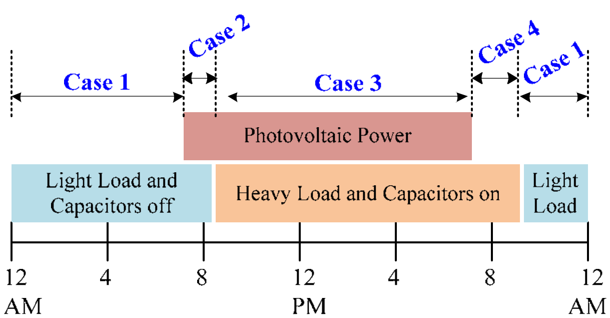

Fig. 3: System Loading Time Profile

TABLE 2: SIMULATION CASES TO DETERMINE HARMONIC IMPACT ON DISTRIBUTION CIRCUIT

Case	Loading	Capacitor Bank	PV	Simulated
Case 1	Light	off	off	No
Case 2	Light	off	on	No
Case 3	Peak	on	on	Yes
Case 4	Peak	on	off	Yes

Case 1 and Case 2 apply to overnight hours from 9 pm to 8 am characterized by light loading. During this period, the capacitors are out of service and the output of PV units is zero or very low. Therefore, harmonic issues are not likely to be a concern for these cases and Case 1 and Case 2 are not studied.

Case 3 and Case 4, on the other hand, represent the situation when the capacitor banks are likely to be in use and introducing resonant frequencies on the circuit. The staging of the capacitor banks are such that there are three potential configurations for capacitor size: 1, 2 and 4 Mvar. Furthermore, during the time range of Case 3 and Case 4, solar insolation can result in any number of PV units being online. For purposes of analysis, the maximum amount of PV considered for the study circuit is 2 MW, which is the total output of the four PV units of 500 kW each, with the potential to add four more additional 750 kW PV units. The PV inverters' harmonics in combination with background harmonics could excite the resonant frequency or frequencies of the circuit with capacitor banks in service leading to harmonic content that violates standards. To compare impacts at the point of common coupling (PCC), the analysis further tests inverters as being either Type-I or Type-II.

3.2 Criteria

Table 3 shows the limit for voltage THD and the individual voltage harmonics specified in IEEE Standard 519-1992 for electrical circuits rated 2.3 kV and higher. For the 12.47 kV bus of the study circuit, the voltage THD is limited to 5% and individual harmonic content should not exceed 3%. IEEE Std-1547 states that before a distributed resource is added to the system, the voltage distortion on the system should be lower than 2.5%. However, IEEE Std-1547 does not provide the voltage distortion limit after the distributed resource is added to the system. Thus, the study reported in this paper uses the IEEE Std-519 limits (given in Table 10.3 of the standard) to determine the allowable PV penetration level.

Table 4 lists the maximum harmonic current distortion in percentage as specified in IEEE Std-519 in the voltage range of 0.12 - 69 kV. IEEE Std-1547 adopts the A1 criteria in IEEE Std-519 ($I_{SC}/I_L < 20$, $I_{THD} = 5\%$) as in Table 4, which is more restrictive than IEEE Std-519 when I_{SC}/I_L is larger. The authors note that IEEE Std-519 has a very strict limit on even harmonics, which is 25% of the preceding odd harmonic. When IEEE Std-519 was first introduced, most of the harmonic sources were 3-phase drives and other large equipment that had little even harmonics. Ostensibly, a value for the even harmonics of 25% of the odd harmonics was arbitrarily assigned since it was not then a controlling factor. As seen by the harmonic content of the PV inverters in Fig. 2, there are even harmonics whose magnitudes are comparable to the odd harmonics. Technically there is no reason why the old harmonics are more detrimental to the system than the even harmonics. It is the authors' opinion that the even harmonics should have the same criteria as the odd harmonics. Therefore, for the study system, modified criteria are applied, where the maximum harmonic distortions of the even harmonics are the same as the preceding odd harmonics. Furthermore, this paper uses a modified IEEE Std-1547 as well as the modified IEEE Std-519to find the maximum PV penetration.

TABLE 3: HARMONIC VOLTAGE DISTORTION LIMITS FOR NON-LINEAR LOADS AT THE POINT OF COMMON COUPLING (PCC) (ADAPTED FROM IEEE-519 1992)

Harmonic Voltage Distortion in % at PCC			
	2.3 - 69 kV	69 - 161 kV	> 161 kV
Maximum for Individual Harmonic	3.0	1.5	1.0
Total Harmonic Distortion (THD)	5.0	2.5	1.5

TABLE 4: MAXIMUM HARMONIC CURRENT DISTORTION IN % OF LOAD DEMAND CURRENT (ADAPTED FROM IEEE STD 519 1992 TABLE 10.3)

ID	**Maximum Harmonic Current Distortion in % of Load Demand Current Voltages 0.12-69-kV based on Table 10.3 IEEE Std 519 1992**						
	I_{SC}/I_L	**Harmonic Order (Odd Harmonics)**					THD
		<11	11<h<17	17<h<23	23<h<35	35<h	
A1	<20*	4	2	1.5	0.6	0.3	5
A2	20<50	7	3.5	2.5	1	0.5	8
A3	50<100	10	4.5	4	1.5	0.7	12
A4	100<1000	12	5.5	5	2	1	15
A5	>1000	15	7	6	2.5	1.4	20

Even harmonics are limited to 25% of the odd harmonic limits above.

* All power generation equipment is limited to these values of Current distortion, regardless of actual I_{SC}/I_L.

where: I_{SC} = Maximum short-circuit current at PCC

and I_L = Maximum load demand current (fundamental frequency) at PCC

3.3 Point of Common Coupling

In the circuit model, as there are loads connected to the secondary side of the utility transformers, where the PV units are also connected, the point of common coupling (PCC) are the 480 V buses, as illustrated in Fig. 1.It is possible that the cumulative effects of a number of harmonic sources can result in violation of the harmonic limits on the utility side, even when the harmonic distortion from each individual PV unit is within criteria [5]. The 12.47 kV bus, therefore, is also monitored to determine if there is harmonic impact on the distribution circuit.

4. ANALYSIS, RESULTS AND DISCUSSIONS

The following are the steps taken in conducting the analysis of harmonic impacts. First, the impedance scan is performed at the PCC as well as at the 12.47 kV bus, assuming different operating conditions to find the resonance points. Second, Type-I and Type-II harmonics are injected from each PV unit to evaluate the voltage and current THD. The results are compares to the limits specified in IEEE Std-519. The critical penetration level is identified at the PCC and at the 12.47 kV bus.

4.1 Capacitors and Resonance Points

It is essential to know the operating mode of the capacitor bank. The capacitor bank introduces parallel resonance due to interaction between the capacitive reactance and circuit inductive reactance. If the parallel resonance occurs at a frequency near a major PV harmonic current contribution, the harmonic current is excited and amplified and can lead to large oscillating currents, and, consequently, high harmonic voltages. The impedance scans in Fig. 4 show that the resonant frequency for the case without the capacitor occurs around the 35th harmonic order, where the harmonic contribution from PV units is negligible. The background harmonics whose major components are no higher than the 17th order harmonics, as shown in Table 1, do not introduce a harmonic issue either. With the capacitor bank in service, however, the resonant frequencies are shifted to a much lower frequency between the 5th and the 10th harmonic orders. Both the background harmonic and the harmonic contribution from the PV units have a considerable amount of contribution around the 5th order, and therefore could lead to serious voltage or current distortions. The worst case occurs during noon time when there is heavy loading, the capacitor bank is in service at the maximum of 4 Mvar and PV units produce their maximum output, as in Case 3 in Table 2 and Fig. 3.

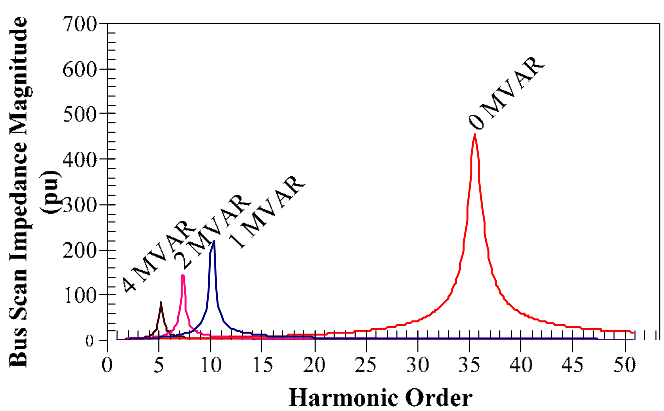

Fig. 4: Impedance Scan at the 12.47 kV Bus

4.2 Penetration Levels

To provide a baseline for determining maximum penetration levels, the first simulation case assumes that the capacitor bank is operated at 4 Mvar and the PV units introduce Type-I harmonics. Background harmonics are not included in this case. Fig. 5 and Fig. 6 show, respectively, the voltage distortion percentage at the 12.47 kV bus and the current distortion percentage at the secondary side of the utility transformer where PV units are connected. Fig. 5 indicates that up to 5 MW of PV has no violation of the IEEE Std-519 on individual voltage distortion (3%) and the V_{THD} (5%). Fig. 6 shows also that no violation of the current harmonics criteria for penetration levels of up to 5 MW occurs for the Type-I inverters. Fig. 6 includes three criteria for current harmonics: IEEE Std-519, modified IEEE Std-519 and modified IEEE Std-1547. The modified criteria use the same limit for the even harmonics as the preceding odd harmonics.

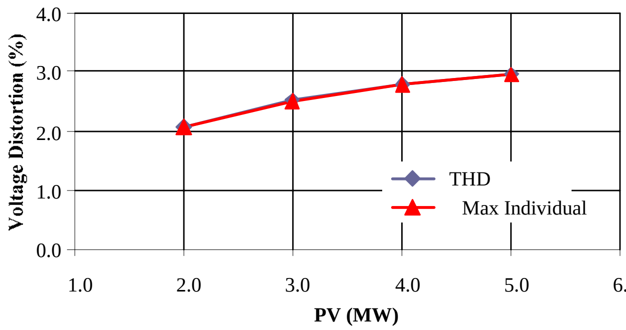

Fig. 5: Voltage Distortion Percentage at 12.47 kV Bus with 4 Mvar Capacitor in Service and Type-I Harmonics Injection

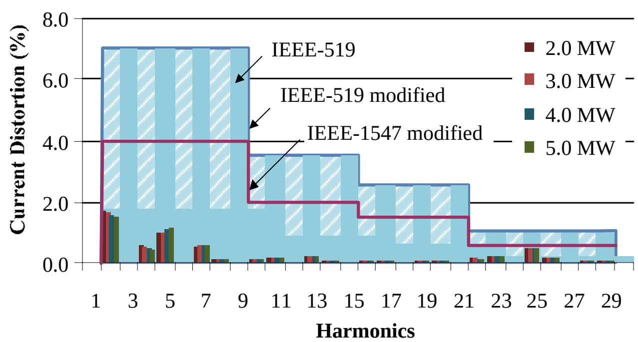

Fig. 6: Current Distortion Percentage at 480 V Cable with 4 Mvar Capacitor in Service and Type-I Harmonics Injection

Next, the tests simulate use of PV units with Type-II harmonics. As the penetration of PV increases to 1.2 MW, the 5th voltage harmonic content at the 12.47 kV bus violates the limit of 3% distortion, as shown in Fig. 7. There is no violation of the voltage THD for up to 2.0 MW PV on the circuit. For current distortion, violation of the modified IEEE Std-519 occurs at the 25th harmonic order as the amount of PV penetration reaches 1.6 MW. When the PV penetration increases further to 2.0 MW, a second violation occurs at the 27th harmonic order. Using the modified IEEE Std-1547 criteria, the PV penetration limit occurs at 1.0 MW. Furthermore, using an unmodified IEEE Std-1547, where the limits for even harmonics are unchanged, the PV penetration limit is at 0.8 MW for a violation at the 28th harmonic order.

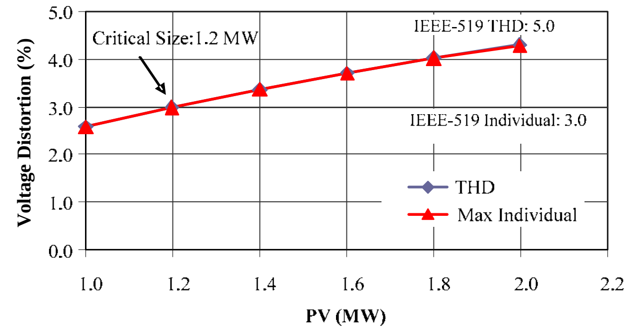

Fig. 7: Voltage Distortion Percentage at 12.47 kV Bus with 4 Mvar Capacitor in Service and Type-II Harmonics Injection

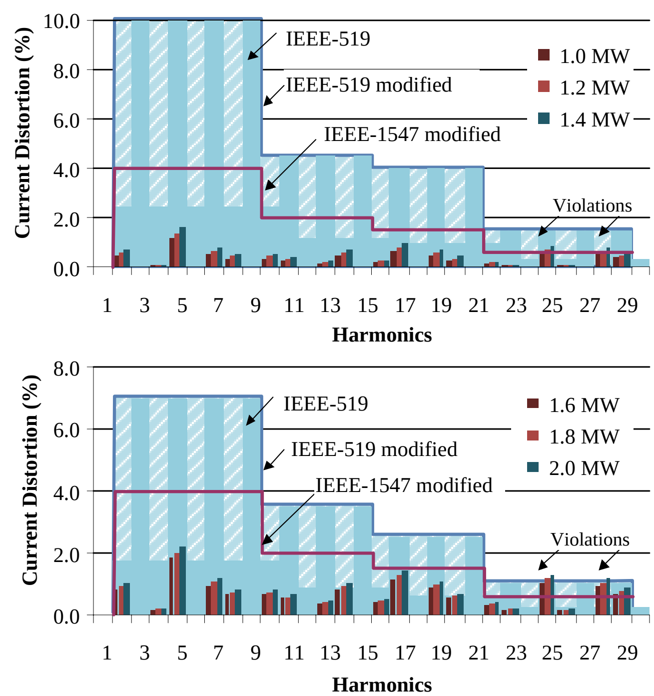

Fig. 8: Current Distortion Percentage at 480 V Cable with 4 Mvar Capacitor in Service and Type-II Harmonics Injection

Compared to use of PV units with Type-I injection characteristics, the drop in penetration limit from greater than 5.0 MW to 1.2 MW for the Type-II units is substantial. This indicates that PV units that individually introduce more harmonics result in overall larger distortions and contribute to the worst case scenario.

The inclusion of background harmonics will further restrict the allowable PV penetration levels. The background harmonics itself will cause a voltage THD of about 2.0% prior to the installation of the PV units, as illustrated in Fig. 9. This is within the 2.5% voltage THD specified in IEEE Std-1547. With Type-II harmonics injection in combination of background harmonics, the maximum PV penetration level is reduced to 0.8 MW as shown in Fig. 9. Table 5 summarizes the PV penetration limit with and without background harmonics. The penetration limits for PV taking into account background harmonics, is 0.8 MW when using inverters with Type-II harmonic injection and 3.0 MW when using Type-I inverters.

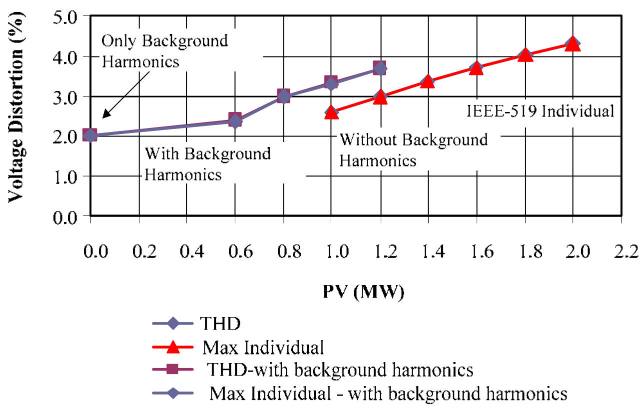

Fig. 9: Comparison on the Voltage Distortion Percentage at the 12.47 kV Bus with and without Inclusion of Background Harmonics for Type-II Harmonics Injection, 4 Mvar Capacitor in Service

TABLE 5: PV PENETRATION LIMIT COMPARISON WITHOUT AND WITH BACKGROUND HARMONICS

		Type-I Harmonics		Type-II Harmonics	
		w/o background harmonics	w/ background harmonics	w/o background harmonics	w/ background harmonics
12.47 kV Bus		5 MW	3.0 MW	1.2 MW	0.8 MW
480 V Cable (*)	**IEEE Std- 519**	> 5 MW	> 5 MW	0.6 MW	0.6 MW
	IEEE Std-519 modified	> 5 MW	> 5 MW	1.6 MW	> 2.MW
	IEEE Std-1547 modified	> 5 MW	> 5 MW	1.0 MW	1.0 MW

* Further check may be required for all PCC

4.3 Mitigation Options

To further increase the PV penetration levels, certain mitigation options may be applied. Harmonic filters tuned for specific excitation frequencies are typically the most cost-effective solution. The filters may be applied in conjunction with the available power factor capacitors on the circuit, an approach termed as "repurposing" the existing capacitors. In some situations, the existing capacitors may not qualify to be converted to harmonic filters due to their voltage margin. Hence, stand alone filters may be specified, typically comprising of a high-pass filter and a notch filter that are paralleled with the existing capacitors to reduce both current and voltage harmonic distortions. This solution results in a smaller harmonic filter that operates independently of the existing capacitors, and is relatively more cost-effective compared to repurposing the existing capacitors to harmonic filters. Note that, in this case, using only a notch filter (single tune filter only or without combination with high pass filter) in parallel with capacitor banks not only is ineffective in reducing harmonic resonance magnitudes but can create new parallel resonance(s) that lead to further criteria violations. Fig. 10 shows the impedance scan at the 12.47 kV bus without filters and with filters with the 4 Mvar capacitor bank in service. With the notch filter tuning at the 5th order harmonics and the high-pass filter tuning at the 7th order harmonics, the resonance at the 5th order harmonics due to the 4 Mvar capacitor bank is depressed. A penetration level larger than 5 MW with Type-II harmonics injection is possible with the combination of the two filters in service. This design illustrates the possibility of improving PV penetration level, but the authors are not suggesting this is an optimized design.

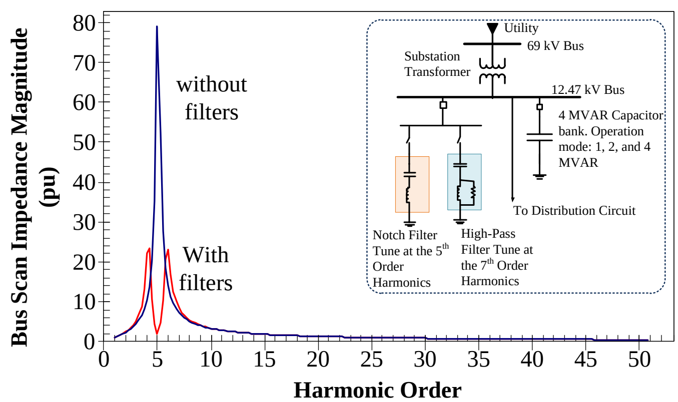

Fig. 10: Filters and Their Depression of the Resonance with 4 Mvar of Bus Capacitors

Another option to mitigate the impacts of harmonics from PV units and allow for increase penetration is to implement a harmonic meter/relay with output contacts that will trip the capacitor on high current distortion. If equipment solutions are not feasible, the PV units on the circuit may be subject to curtailment.

5. CONCLUSIONS

This paper presents the criteria, assumptions, and mitigation options that relate to determining maximum solar PV penetration that could be connected to a distribution circuit from the perspective of harmonic impact. The concepts are illustrated using a study circuit with a relatively large capacitor bank (4 Mvar). The paper concludes that the maximum PV penetration can be significantly influenced by the acceptable criteria adopted by utility, assumptions used for capacitor operating modes as well as the assumption used for harmonic injection spectrum of future PV units. If the PV units have a harmonic injection with < 3% I_{THD}, a penetration level larger than 100% of the peak load could be achieved without violating the harmonic criteria. This assumes that issues other than harmonic impact do not limit PV penetration at a lower level.

If the harmonic distortion issue becomes the bottle neck for PV penetration, passive harmonic filter can be applied to increase PV penetration. By adding a combination of a high-pass filter and a notch filter in parallel with the existing capacitor, both current and voltage harmonic distortions can be reduced. This solution generally offers a more cost effective means of using smaller harmonic filter design that operate independently of the existing capacitors compared to repurpose existing capacitors to harmonic filter.

6. ACKNOWLEDGMENTS

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