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Impact of Harmonic Resonance and V-THD in Sohar Industrial Port–C Substation

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Abstract**—**This paper presents an analysis study on the impacts of the changes of the capacitor banks, the loss of a transformer, and the installation of distributed generation on the voltage total harmonic distortion and harmonic resonance. The study is applied in a real system in Oman, Sohar Industrial Port–C Substation Network. Frequency scan method and Fourier series analysis method are used with the help of EDSA software. Moreover, the results are compared with limits specified by national Oman distribution code.

Keywords**—**Power quality, capacitor bank, voltage total harmonics distortion, harmonic resonance, frequency scan.

I.INTRODUCTION

THE demand of electrical energy is increasing in Oman, especially in areas experiencing industrial and commercial developments such as Sohar. One of the important issues related to these developments is power quality and harmonic distortion level. Levels of harmonic distortions are tending to increase due to increase in the number of industrial and commercial loads that are connected to the electric power grid.

The harmonics produced by some non-linear loads in the distribution system impacts negatively customer equipment as well as network components. This impact appears as a reduction in the efficiency of network components, and malfunction of the network devices. As a result, this issue can cause significant economic losses for both utilities and customers.

The main objectives of this paper are as follows. Firstly, investigate the effect of capacitors on harmonic resonance and determine the Total Harmonic Distortion (THD) of voltages at each bus. Secondly, investigate the effect of absence of one of transformers on the harmonic resonance and determine the V-THD at each bus. Thirdly, study the effect of presence of a distributed generator (DG) on the harmonic resonance and again determine V-THD at each bus. Frequency scan and Fourier series methods are used to achieve this analysis using EDSA software. The rest of this paper is arranged as follows: Section II introduces harmonics, Section III presents harmonic resonance, Section IV describes Sohar industrial port C substation network, and Section V presents simulation results Section VI provides a conclusion.

II.HARMONICS

An ideal distribution system delivers a pure sinusoid voltages and currents. However, in the practical situation, there are many forms of distortions that distort the power quality, which classified in: transient, voltage imbalance, waveform distortion, voltage fluctuation and power frequency variation. In fact, the most significant power quality problem is lying under the waveform distortion category which is harmonics. In addition, harmonics is defined as integer multiples of the fundamental frequency which increases closer to the load. Significant power system distortion occurs when the capacitance of the systems results in what is called resonance at a critical frequency of the harmonics [1].

Harmonic distortion is usually caused by non-linear loads such as battery chargers, uninterruptable power supplies (UPSs) and other variable frequency devices. The distorted waveform actually can be expressed as a sum of sinusoids in which the frequency of each sinusoid is the integer multiple of the fundamental frequency. In order to analyze the distorted waveform, Fourier series is used to decompose the waveform. It allows analyzing each harmonic individually [2]. If the positive and the negative half cycle of the waveform have identical shapes, Fourier series contains only odd harmonics. However, the presence of even harmonics means that there is something wrong either in the load equipment or in the transducers which are used in measurements [3].

A. Harmonic Indices

Harmonic measurement describes effective values of the harmonic. There are two harmonic Indices[1]:

- Total Harmonic Distortions (THD).
- Total Demand Distortions (TDD).

1. Total Harmonic Distortions

Total Harmonic Distortion (THD) is the potential heating value of the harmonics related to the fundamental. THD can be calculated by:

$$THD = \frac{\sqrt{\sum_{h>1}^{hmax} {M_h}^2}}{M_1} \qquad (1)$$

where $\mathrm{M_h}$ is the rms value of $\mathrm{h^{th}}$ harmonic component $\mathrm{M_1}$ is the rms value the fundamental. THD is a practical way of quantifying harmonic distortion. However, it is not good indicator of the voltage stress within a capacitor because that the latter is related to the peak value of the waveform [1].

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2. Total Demand Distortions

Total Demand Distortion (TDD) refers to fundamental of the peak demand load current rather than the fundamental of the present sample. It is defined as:

$$TDD = \frac{\sqrt{\sum_{h=1}^{hmax} I_h{}^2}}{I_L} \tag{2}$$

where I_L is the peak fundamental load current for a period of time. For a new facility, I_L has to be estimated based on the predicted load profiles [1].

B. Harmonic Standards

In order to achieve the agreements between the distribution systems and the loads in the existence of harmonics, there are some standards that have been set by national and international organizations. It includes maximum allowable voltages and currents distortions.

1. Omani Standards

To organize the electricity distribution in Oman, the grid code and the distribution code has been set by authorized companies, which contains maximum allowable voltage distortion levels.

a) The Grid Code

The grid code has been set by Oman Electricity Transmission Company (SAOC) and approved by Grid Code Review Panel (GCRP). It states that ″ The maximum total levels of harmonic distortion on the Transmission System at 220kV and 132kV, from all sources under both normal, Planned Outage and Forced Outage conditions, (unless abnormal conditions prevail) shall not exceed a total harmonic distortion of 2.0% with no individual harmonic greater than 1.5 %″ [4].

b) The Distribution Code

According to the distribution code, ″The maximum total levels of harmonic distortion on the Distribution System at 66kV, 33kV and 11kV, from all sources under both normal, planned outage and fault outage conditions, shall not exceed a total harmonic distortion of 2.0% with no individual harmonic greater than 1.5% unless abnormal conditions prevail. At LV the maximum total levels of harmonic distortion from all sources shall not exceed a total harmonic distortion of 2.5%″ [5].

2. International Electrotechnical Commission Standards (IEC)

According to International Electrotechnical Commission (IEC), IEC 61000 4-7 standard describes allowable percentages of the voltage distortion of different orders as shown in Table I [6].

3. Institute of Electrical and Electronics Engineer Standards (IEEE)

Institute of Electrical and Electronics Engineer Standards specify the total voltage distortion limits as shown in Table II.

TABLE I
IEC LIMITS ACCORDING TO IEC 61000 4-7 [4]

Odd Harmonics Non Multiple of Three			**Odd Harmonics Multiple of Three**			**Even Harmonics**		
Harmonic Order h	Harmonic Voltage %		**Harmonic Order h**	Harmonic Voltage %		**Harmonic Order h**	Harmonic Voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	**3**	4	2	**2**	1.8	1.4
7	4	2	**9**	1.2	1	**4**	1	0.8
11	3	1.5	**15**	0.3	0.3	**6**	0.5	0.4
13	2.5	1.5	**21**	0.2	0.2	**8**	0.5	0.4
17<=h<=49	1.9*17/h-0.2	1.2*17/h	**21<h<=45**	0.2	0.2	**10<=h<=50**	0.25*10/h+0.22	0.19*10/h+0.16

TABLE II
TOTAL CURRENT DISTORTION LIMITS ACCORDING TO IEEE 519-1992 [7]

% voltage						**Voltage (kV)**
Isc/I(load)	<11	11<=h<17	17<=h<35	35>=h	TDD	**120-69**
<20	4	2	1.5	0.6	5	
20-50	7	3.5	2.5	1	8	
50-100	10	4.5	4	1.5	12	
100-1000	12	5.5	5	2	15	
>1000	15	7	6	2.5	20	
Isc/I(load)	<11	11<=h<17	17<=h<35	35>=h	TDD	**69-161**
<20	2	1	0.75	0.3	2.5	
20-50	3.5	1.75	1.25	0.5	4	
50-100	5	2.25	2	0.75	6	
100-1000	6	2.75	2.5	1	7.5	
>1000	7.5	3.5	3	1.25	10	
Isc/I(load)	<11	11<=h<17	17<=h<35	35>=h	TDD	**>161**
<50	2	1	0.75	0.3	2.5	
>=50	3	1.5	1.15	0.45	3.75	

4. View on Standards

It is noticed that Oman grid code is more influenced by the IEC standards than the IEEE standards. IEC standards emphasis only the allowable voltage distortion percentage. Whereas, IEEE standards concentrates on both voltage level and short-circuit current. It also noticed that Omani standard is stricter than others.

III.HARMONIC RESONANCE

Harmonic resonance is a phenomenon which can occur in a power system when the inductive reactance X_L and the capacitive reactance X_C of the power system become equal. That condition – X_L and X_C are equal – is causing the electrical energy to oscillate between the magnetic field of the inductor and the electric field of the capacitor and therefore the resonance is occurring. It can cause damage to electrical components such as capacitors and transformers [8].

At the resonance:

$$X_L = \omega_r L = X_C = \frac{1}{\omega_r C} \qquad (3)$$

$$\xrightarrow{yields} \omega_r = \frac{1}{\sqrt{LC}}\, rad/sec \qquad (4)$$

That is, the frequency at resonance:

$$f_r = \frac{1}{2\pi\sqrt{LC}}\, Hz \qquad (5)$$

The resonance can be of a series or a parallel type, depending on the way that the reactive elements are arranged throughout the system.

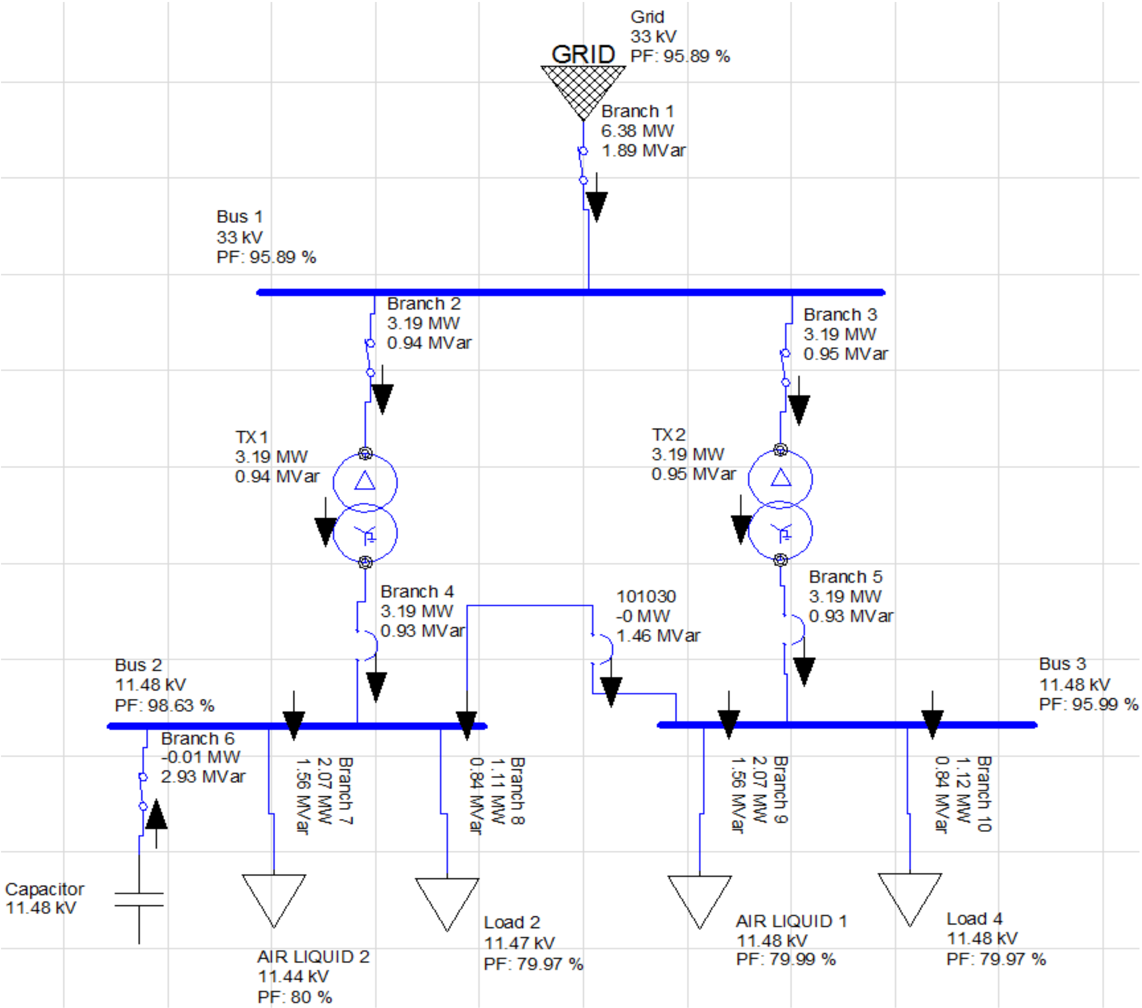

Fig. 1 System under study

A. Series Resonance

Series resonance circuits are one of the most important circuits used in various electrical and electronic circuits. For example, they can be found in AC mains filters, noise filters and also in radio and television tuning as they only function on resonant frequency [9].

At resonance, the two reactants (X_L and X_C) cancel each other out which makes a series LC combination act as a short circuit. So the total impedance of the circuit becomes just the value of the resistance. Therefore in series resonance, a small exciting voltage can develop high current since the total impedance is low [9]. At resonance, the current – which is produced by the source – will flow through this low impedance path causing interference in communication circuits and excessive voltage distortion at the capacitor [6].

B. Parallel Resonance

The parallel resonance circuit is almost the same as the series resonance circuit. Both types have a frequency point where their two reactive components cancel each other.

At resonance, the parallel combination acts like an open circuit. So the total impedance of a parallel resonance circuit at resonance becomes also just the value of the resistance of the circuit and it is at maximum value. Therefore in parallel resonance, a small exciting current can develop large voltage which can cause damage to capacitors and other electric equipment [9].

C. Resonance Analysis Techniques

Resonance can be analyzed by using different types of signal processing instruments. Nowadays, analog and digital methods are available. There is also another method used for analyzing the resonance which is known as frequency scan [6]. Frequency scan technique is basically the determination of the driving point impedance over the defined frequency range of interest as viewed from the neutral bus of the generator under study [10]. In this method, a 1 A constant current at harmonic source is injected into the system and swept over the harmonic frequencies [11]. If any impedance resonant frequency in the system is equal – or close – to a harmonic frequency, there will be a high harmonic distortion at that impedance.

IV. SOHAR INDUSTRIAL PORT–C SUBSTATION NETWORK

The system network shown in Fig. 1 is Sohar Industrial Port–C Substation (SIP-C S/S) which is supplied by Majan Electricity Company (MJEC). The system network is supplied from a 33kV substation. Bus 2 is fed by a 20MVA transformer (Tx1) which steps the voltage down to 11.5kV, and supplies power to two loads, AIR LIQID 2 and Load 2 (130A & 70A respectively) and a 5MVAR power factor correction capacitor bank. Bus 3 is fed by a 20MVA transformer (Tx2) which steps the voltage down to 11.5kV, and supplies power to two loads, AIR LIQID 1 and Load 4 (130 A & 70 A respectively).

SIP-C S/S network is analyzed by conducting three case studies. The studies are described as follows:

Case 1. Vary the capacitor values from 1MVA to 5 MVA and Conduct Frequency Scan & Harmonic Analysis.
Case 2. Vary the capacitor values from 1MVA to 5 MVA and Conduct Frequency Scan & Harmonic Analysis when one of the transformers is out of service.
Case 3. Integrate a distributed generation unit (synchronous generator) and then repeat case 1.

In all cases a 6-pulse Harmonic Current Source (4MVA) was inserted at the third bus of the SIP-C S/S network to model the presence a harmonic distortion source.

V. SIMULATION RESULTS

A. Case 1

In this case the capacitor size was varied from 1MVA to 5 MVA and Frequency Scan & Harmonic Analysis were conducted.

1. Results of System Resonance

The parallel and series resonance for the five different rated values of the capacitor are summarized in Table III.

2. Results of Voltage Harmonic Distortion

The voltage THD at each bus with five different rated values of the capacitor bank was determined as shown in Table IV.

B. Case 2

In this study, SIP-C S/S network was analyzed when the second transformer (Tx2) is out of service. The frequency scan was carried out for five different rated values of the capacitor when the second transformer (Tx2) is out of service.

TABLE III
PARALLEL AND SERIES RESONANCE FOR THE FIVE DIFFERENT RATED VALUES OF THE CAPACITOR

		Parallel Resonance	**Series Resonance**
5 MVAR Capacitor	**Bus 1**	522 Hz	876 Hz
	Bus 2 & 3	522 Hz	-
4 MVAR Capacitor	**Bus 1**	581 Hz	994 Hz
	Bus 2 & 3	581 Hz	-
3 MVAR Capacitor	**Bus 1**	640 Hz	1171 Hz
	Bus 2 & 3	640 Hz	-
2 MVAR Capacitor	**Bus 1**	817 Hz	1407 Hz
	Bus 2 & 3	817 Hz	-
1 MVAR Capacitor	**Bus 1**	1112 Hz	1997 Hz
	Bus 2 & 3	1112 Hz	-

TABLE IV
THD VOLTAGE AT EACH BUS WITH FIVE DIFFERENT RATED VALUES OF CAPACITOR

		1 MVAR Capacitor	**2 MVAR Capacitor**	**3 MVAR Capacitor**	**4 MVAR Capacitor**	**5 MVAR Capacitor**
THD Voltage	**First Bus**	2.25%	3.05%	4.22%	2.68%	2.54%
	Second Bus	2.95%	3.95%	5.53%	3.53%	3.35%
	Third Bus	2.95%	3.95%	5.53%	3.53%	3.35%

TABLE V
THE SERIES AND PARALLEL RESONANCE WITHOUT TX2 AT DIFFERENT VALUES OF CAPACITORS

		Parallel Resonance	Series Resonance
5 MVAR Capacitor	**Bus 1**	422 Hz	645Hz
	Bus 2 & 3	450 Hz	-
4 MVAR Capacitor	**Bus 1**	489 Hz	722 Hz
	Bus 2 & 3	488 Hz	-
3 MVAR Capacitor	**Bus 1**	567 Hz	822 Hz
	Bus 2 & 3	560 Hz	-
2 MVAR Capacitor	**Bus 1**	734 Hz	1000 HZ
	Bus 2 & 3	734 Hz	-
1 MVAR Capacitor	**Bus 1**	933 Hz	1134 Hz
	Bus 2 & 3	1000 Hz	-

1. Results of System Resonance

The parallel and series resonance at each bus are summarized in Table V.

2. Results of Voltage Harmonic Distortion

The voltage THD at each bus with for five different rated values of the capacitor when one of the transformers is out of service was determined as shown in Table VI.

C. Case 3

A preset model of a distributed generator (synchronous generator) in EDSA was connected to the SIP-C S/S network at the third bus. The network will be analyzed in presence of the distributed generator while its size is varied from 2 MVA to 5 MVA.

TABLE VI
THD VOLTAGE AT EACH BUS WHEN TX2 IS OUT OF SERVICE

		1 MVAR Capacitor	2 MVAR Capacitor	3 MVAR Capacitor	4 MVAR Capacitor	5 MVAR Capacitor
THD Voltage	**First Bus**	2.29%	3.54%	2.86%	2.52%	2.84%
	Second Bus	3.72%	5.67%	4.62%	4.15%	4.77%
	Third Bus	3.72%	5.67%	4.62%	4.15%	4.77%

1. Results of System Resonance

The parallel and series resonance for the five different rated values of the DG are summarized in Table VI.

2. Results of Voltage Harmonic Distortion

The voltage THD at each bus in presence of a DG (for four different rated values) was determined as shown in Table VII.

TABLE VI
PARALLEL AND SERIES RESONANCE FOR THE FIVE DIFFERENT RATED OF DG GENERATORS

		Parallel Resonance	Series Resonance
2 MVA	**Bus 1**	640 Hz	1171 Hz
	Bus 2 & 3	640 Hz	-
3 MVA	**Bus 1**	640 Hz	1171 Hz
	Bus 2 & 3	640 Hz	-
4 MVA	**Bus 1**	699 Hz	1171 Hz
	Bus 2 & 3	699 Hz	-
5 MVA	**Bus 1**	699 Hz	1171 Hz
	Bus 2 & 3	699 Hz	-

TABLE VII
THD VOLTAGE AT EACH BUS IN PRESENCE OF DG

		2 MVA DG	3 MVA DG	4 MVA DG	5 MVA DG
THD Voltage	**First Bus**	4.4%	4.4%	4.34%	4.12%
	Second Bus	5.72%	5.72%	5.63%	5.34%
	Third Bus	5.72%	5.72%	5.63%	5.34%

VI. DISCUSSION OF RESULTS

Case 1. The harmonic resonance appeared at each bus due to presence of the capacitor bank in the network. However, the harmonic resonance is occurred at higher frequency as the rated of capacitor bank is decreased as shown in Table III. On the other hand, Table IV shows that THD voltage exceeds the limit (2.5% according to the Oman distribution code). It can be noticed that, the worst THD voltage was when the rated of the capacitor bank was 3 MVA, because the frequency at that rating is close to the 11th harmonic which is the same harmonic as the harmonic source produced.

Case 2. From Table V, the harmonic resonance is occurring at higher frequency as the size of capacitor bank is decreasing. On the other hand, Table VI shows that THD voltage exceeds the limit (2.5% according to the distribution code). It can be noticed that, worst THD voltage was when the size of the capacitor bank was 2 MVA.

Case 3. The harmonic resonance appeared at each bus in presence of a DG. Table VII shows that the harmonic resonance is occurred at same frequencies in case of 2 MVA and 3 MVA DG. Also the harmonic resonance is occurred at same frequencies in case of 4 MVA and 5 MVA DG due to specifications of the chosen DGs from the library of EDSA software. Therefore, the harmonic resonance is occurring at higher frequency as the rated of DG is increased due to decrease in the total impedance of the network as the equation ($f=1/(2\pi\sqrt{LC})$). On the other hand, Table VIII shows that THD voltage exceeds the limit (2.5% according to the distribution code). It can be noticed that as the rating of the DG increases the THD voltage decreased. It was obvious that the severest THD voltage was when the rated of the DG was 3 MVA (same for 2 MVA) because the frequency at that rating is close to the 11th harmonic which is the same harmonic as the harmonic source.

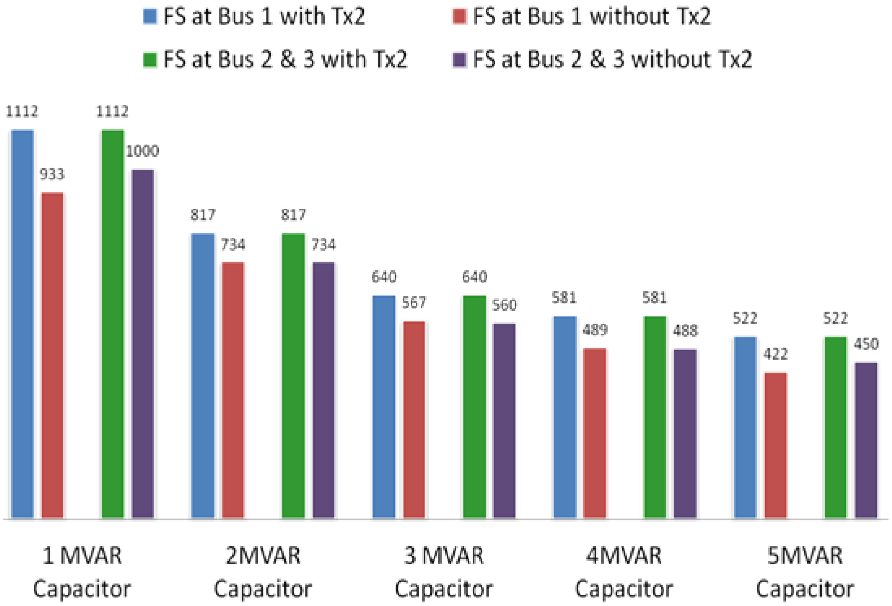

Fig. 2 Comparison between the frequency scan at each bus for study 1 and study 2

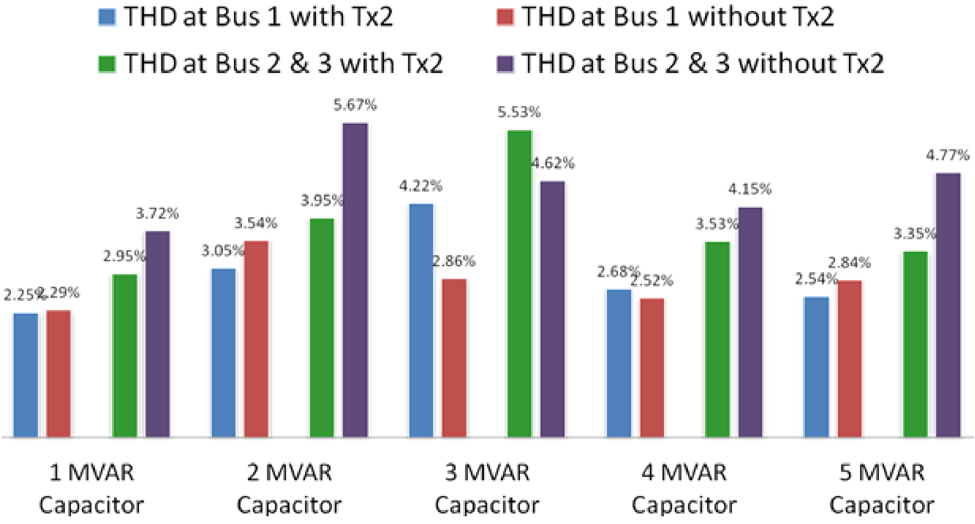

Fig. 3 Comparison between the THD voltage at each bus for study 1 and study 2

A. Comparison between Case 1 and 2

Fig. 2 shows a comparison between case 1 and case 2 in order to see the effect on the harmonic resonance when one of the transformers is out of service. It is obvious from the figure that, the harmonic resonance occurred at lower frequency in case of one of the transformers is out of service. That is because the total impedance of the network will increase. Also, it's noticed that the harmonic resonance is occurred at higher frequency as the rated of capacitor bank is decreased.On the other hand, Fig. 3 shows a comparison between the THD voltage at each bus for study 1 and study 2. It is obvious from the figure that, the THD voltage is higher when Tx2 is out of service than the case with Tx2 is online due to the increase in the total impedance of the network.

B. Comparison between Study 1 and Study 3

Fig. 4 shows a comparison between the frequency scan at each bus for study 1 and study 3 when the rated of the capacitor bank is 3 MVA. It is obvious from the figure that, the harmonic resonance occurred at same frequency for both studies when the rated of the DG are 2 MVA and 3 MVA because the presence of DG didn't affect the impedance of the network that much in these cases. However, the harmonic resonance occurred at higher frequency when the rated of the DG are 4 MVA and 5 MVA compared with study 1. On the other hand, Fig. 5 shows a comparison between the THD voltage at each bus for study 1 and study 3. It was noticed that the THD voltage will decrease as the rating of DG increase.

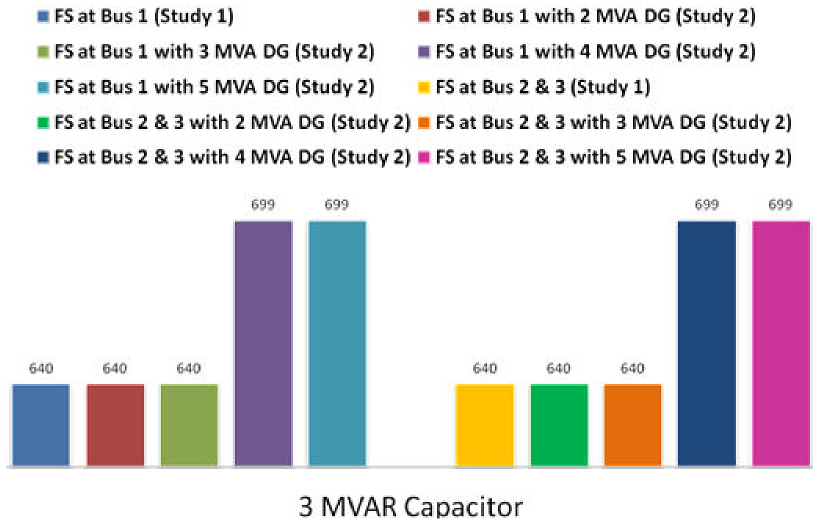

Fig. 4 Comparison between the frequency scan at each bus for study 1 and study 3

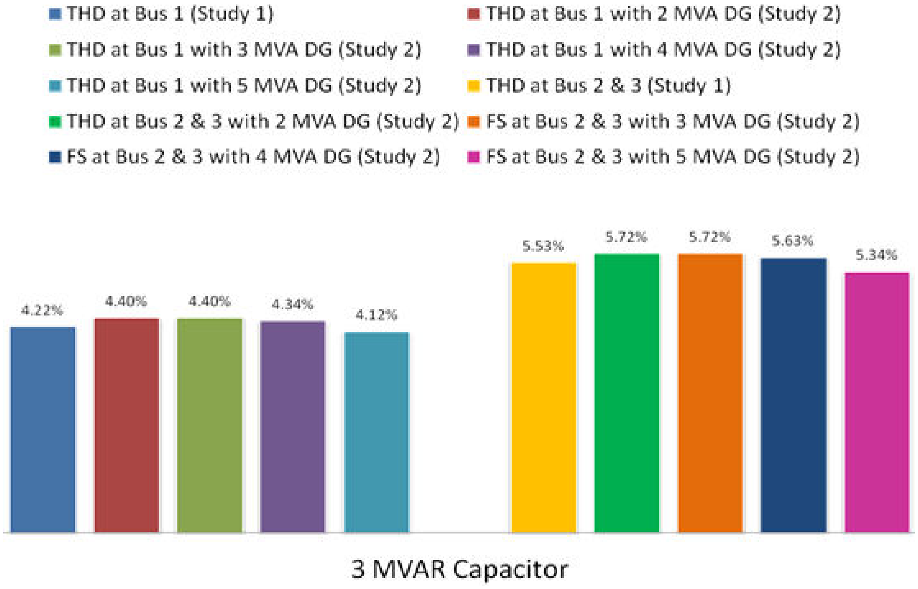

Fig. 5 Comparison between the THD voltage at each bus for study 1 and study 3

VII. CONCLUSION

This study analyzed the voltage THD and harmonic resonance in a real industrial power system in Oman. The system consists of two 20MVA transformers that steps the voltage down from 33kV to 11.5kV and a 5MVAR power factor correction capacitor bank. The study considered the implications of different scenarios: changing the capacitor size, the loss of one transformer, and the installation of distributed generation. It was demonstrated that the harmonic resonance is shifting to higher frequencies as the rating of capacitor bank is decreasing. In addition, it was shown that the harmonic resonance is shifting to higher frequency with larger sizes of distributed generators. In addition, it is worth mentioning that voltage THD is higher when one transformer is out of service.

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