Some Findings on Harmonic Measurement in Macao

Sio-Un Tai*, Man-Chung Wong*, Ming-Chui Dong*, Ying-Duo Han**
* Faculty of Science and Technology, University of Macau, Macau, SAR, P.R. China
** Department of Electrical Engineering, Tsinghua University, Beijing, P.R. China

Abstract—**This paper reports some findings on harmonic measurement at several buildings of Macao. The findings are current harmonic, harmonic current is caused by variable refrigerant volume (VRV) air-conditioning system, harmonic effect on capacitor, even order current harmonic and neutral current harmonic, they are for reference for Macao to set up the harmonic standard limits in the future.**

Index Terms—**power quality, current harmonic.**

I. Introduction

Power quality has become an increasing concern for utilities and their electrical customers, in recent years; there has been proliferation of modern electronics such as computer loads, variable speed drives and industrial logic controllers. While such devices are sensitive to the variation of the supply voltage, they are also the source for power quality disturbances. Due to their nonlinear nature, these loads inject harmonic current into the power system and cause voltage harmonic distortion. There is a need to understand how the disturbances will affect sensitive loads and develop appropriate specifications, or install appropriate power conditioning systems. Harmonics can result in equipment heating, communication interface and control malfunctions. Voltage sags of only few cycles can cause loss of computer data or errors. The increased concern for power quality has resulted in significant advances in monitoring equipment that can be used to characterize disturbances and power quality variations [1].

Macao is a part of China's territory. It is located on the Southeast coast of China to the west of the Pearl River Delta. Moreover, there are not any formal regulations for harmonics, imbalance and flicker in Macao. Therefore, a power quality study is recommended to perform at different types of buildings in Macao, they are: Industrial type: a special facility building (Fac), Public type: three public administrative buildings (Pub A, B & C), Residential type: five residential buildings (Res A, B, C, D & E), Other type: a commercial building (Com), a hotel (Hot), a middle school (Sch) and an indoor sport center (Cen). The measurement period for each location is one week (seven days) for achieving the whole pattern, the measurement point is main power distribution panel of building and the measurement equipment is power quality analyzer ACE-4000.

This work was supported by the Research Committee of University of Macau.

This paper introduces the results of harmonic monitoring and then reports the findings on current harmonic, harmonic current is caused by variable refrigerant volume (VRV) air-conditioning system, harmonic effect on capacitor, even order current harmonic and neutral current harmonic.

This paper is divided into four sections, the first section is introduction, the second section is results of harmonic monitoring, the third section is findings on harmonic measurement, and the final section is conclusions.

II. Results of Harmonic Monitoring

This section reports an estimation of harmonic in Macao which is based on the monitoring results in the above several locations of Macao is as below [2]:

- High voltage harmonic (THD_V%) may be caused by the local power network;
- Order 3, 5 & 7 are main voltage harmonic components;
- Somewhere background voltage harmonic is found;
- High phase current harmonic (TDD_I%) may be caused by the large power capacity equipments inside buildings;
- Order 3, 5 & 7 are main phase current harmonic components;
- Some neutral current exceed 20% of phase current and harmonic is main component.

III. Findings on Harmonic Measurement

This section reports some findings on harmonic measurement which are worth to concern and analysis, they are: current harmonic (THD_I%) vs. current harmonic (TDD_I%), more harmonic current is caused by VRV centralized air-conditioning system, harmonic effect on capacitor bank, even order current harmonic and neutral current harmonic. The findings may let the end-users to pay more attentions or more researches on these power quality terms in the near future.

A. Current Harmonic (THD_I%) vs. Current Harmonic (TDD_I%)

In this section it reports the finding on current harmonic (THD_I%) vs. current harmonic (TDD_I%) by using the measured current harmonic results in Macao.

Current harmonic distortion levels can be characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component [3]. It is also common to use a single quantity,

the Total Current Harmonic Distortion (THD_I%) or Total Current Demand Distortion (TDD_I%) to evaluate the harmonic levels. IEEE 519-1992 recommends to use current harmonic (TDD_I%) but other areas such as Hong Kong recommends to use current harmonic (THD_I%) to evaluate the current harmonic levels. Table 1 shows the current harmonic standard limits from IEEE 519-1992 and Hong Kong (ESMD). The main differences of the two ways are: current harmonic (TDD_I%) value must be referred to a constant base (e.g. the rated load current or demand current), current harmonic (THD_I%) value must be referred to the fundamental current base which can vary over a wide range.

According to the power quality measurement, in general the buildings are equipped with centralized air-conditioning system (chiller unit), its current harmonic (THD_I%) is low during office hours but high during non-office hours since the injected harmonic current from the chiller unit generally is little, and the fundamental current of the chiller unit exceeds 40% of the total fundamental current of the building. Moreover, the increasing of harmonic current due to nonlinear load such as computer equipment is less than the increasing of fundamental current of chiller unit. As a result, the base current is increased too much but the harmonic current is increased little during office hours but it is opposite during non-office hours.

Fig. 1 shows the measured total current harmonic distortion (THD_I%) figure of the public administrative building C which is equipped with chiller unit, its harmonic (THD_I%) value is around 5% and 20% during office hours and non-office hours respectively, the difference is 15%. In other words, the values during office hours are within the limits (<5%) which mentioned in Table 2 but during non-office hours exceeds the limits. Moreover, the results seem is not reasonable and even it is wrong if only using the total current harmonic distortion (THD_I%) limits to evaluate the harmonic level of the building since in fact the injected harmonic current during non-office hours is lower than the injected harmonic current during office hours. On the other hand, the main concept of the current harmonic standards are to limit individual power consumers inject harmonic current for assuring that voltage distortion (THD_V%) at the PCC does not exceed 5%. Fig. 2 shows the measured total current harmonic distortion (THD_Irms) figure of the public administrative building C, its harmonic (THD_Irms) value is around 35A and 15A during office hours and non-office hours respectively, the difference is 20A. Moreover, when comparison between the trend of harmonic distortion (THD_I%) and the trend of harmonic distortion (THD_Irms), it finds that generally current harmonic distortion (THD_Irms) is opposite to current harmonic distortion (THD_I%). The above assumes the chiller unit is switched-on during office hours and is switched-off during non-office hours.

On the other hand, for other types of buildings such as residential building, the difference of current harmonic (THD_I%) between office hours and non-office hours is not as large as the difference in the building which is equipped with chiller unit. Fig. 3 shows the measured current harmonic (THD_I%) figure of the residential building B which harmonic (THD_I%) is around between 15% and 25%, the difference is 10%.

As a conclusion, for all types of buildings using current harmonic (THD_I%) to evaluate the current harmonic level seems is not reasonable. Current harmonic (THD_I%) seems is more suitable to use for evaluating the harmonic level of an equipment since the base fundamental current of an equipment would not vary over a wide range.

From the above, it seems that using total current demand distortion (TDD_I%) is a reasonable way to estimate current harmonic level since it could reflect the actual harmonic current level, but the calculation of current harmonic (TDD_I%) needs to get I_{SC} and I_L first, different selection of I_{SC} and I_L will affect the results. In general the end-users may not easy to get a correct I_{SC} and I_L. Therefore, the selected I_{SC} and I_L may not be corrected and would evaluate the harmonic level incorrectly, or choosing different values under different persons. One of the good harmonic indices is characterized by the following: Harmonic indices should be simple and practical so that they can be widely used with ease. Thus it is recommended the local power supply company could acknowledge the end-users about their I_{SC} and I_L at interval.

Finally, Table 2 & 3 show the measured current harmonic (THD_I%) and calculated current harmonic (TDD_I%) from the power quality measurement in several buildings of Macao, it shows that generally harmonic (THD_I%) exceeds the limits but harmonic (TDD_I%) is within the limits.

Table 1
Current harmonic standard limits

Standard Limits		From
I_{SC}/I_L *		IEEE 519-1992
<20,	TDD_I%<5%	
20<50,	TDD_I%<8%	
50<100,	TDD_I%<12%	
100<1000,	TDD_I%<15%	
>1000,	TDD_I%<20%	
I<40A,	THD_I%<20% **	Hong Kong (ESMD)
40A≦I<400A,	THD_I%<15%	
400A≦I<800A,	THD_I%<12%	
800A≦I<2000A,	THD_I%<8%	
I≧2000A,	THD_I%<5%	

* I_{SC}=maximum short-circuit current at PCC
I_L=maximum demand load current at PCC
** I=rated current of building

Table 2
Current harmonic (THD_I%) limits and measured current harmonic (THD_I%)

Location	THD_I% Limit	Phase A THD_I% (Max.)	Phase B THD_I% (Max.)	Phase C THD_I% (Max.)
Fac	5%	55.30%	42.57%	29.21%
Pub A	12%	28.09%	50.75%	47.65%
Pub B	5%	19.27%	20.06%	27.12%
Pub C	5%	25.61%	28.84%	27.01%
Res A	12%	27.74%	34.43%	29%
Res B	12%	28.44%	34.64%	29.01%
Res C	12%	21.4%	26.91%	18.82%
Res D	12%	21.79%	17.89%	14.64%
Res E	12%	26.48%	32.3%	29.26%
Com	5%	37.04%	39.96%	45.41%
Hot	5%	33.21%	30.8%	28.66%
Sch	12%	46.83%	64.13%	63.73%
Cen	15%	120.1%	16.17K%	16.14K%

Table 3
Current harmonic (TDD_I%) limits and calculated current harmonic (TDD_I%) from measured current harmonic (THD_Irms)

Location	TDD_I% Limit	Phase A TDD_I%	Phase B TDD_I%	Phase C TDD_I%
Fac	5%	69.70%	68.20%	12.73%
Pub A	12%	3.58%	2.99%	4.67%
Pub B	8%	4.56%	4.60%	6.78%
Pub C	8%	4.74%	4.73%	5.81%
Res A	12%	5.52%	5.81%	5.18%
Res B	12%	4.74%	4.81%	5.03%
Res C	12%	5.85%	6.64%	6.60%
Res D	12%	5.78%	6.77%	5.47%
Res E	12%	4.45%	4.42%	4.68%
Com	5%	2.64%	2.65%	2.56%
Hot	8%	4.83%	4.95%	3.86%
Sch	15%	9.30%	9.04%	9.70%
Cen	15%	8.04%	6.81%	13.24%

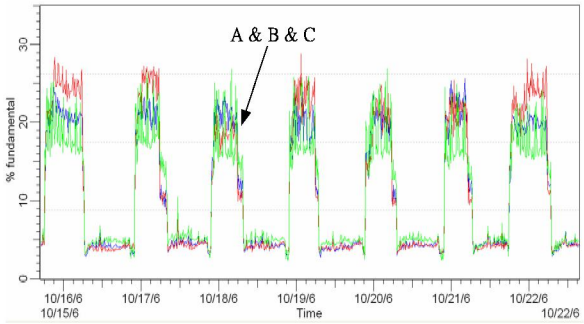

Fig. 1 Current harmonic (THD_I%) versus time in the public administrative building C

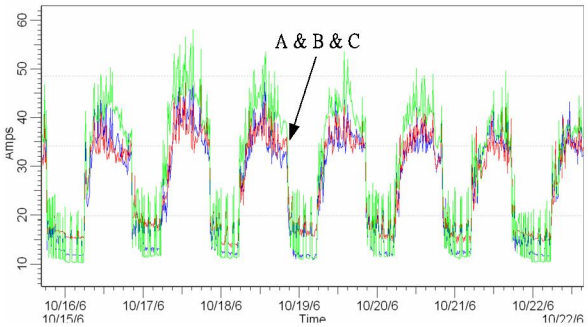

Fig. 2 Current harmonic (THD_Irms) versus time in the public administrative building C

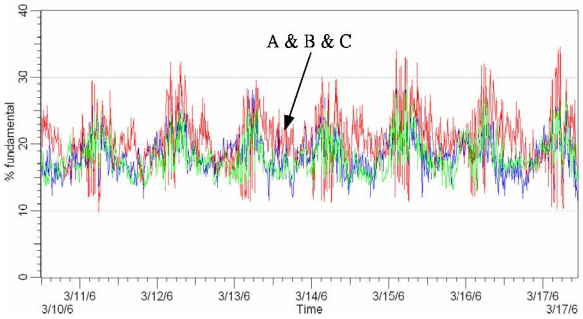

Fig. 3 Current harmonic (THD_I%) versus time in the residential building B

B. More Harmonic Current is caused by Variable Refrigerant Volume (VRV) Centralized Air-conditioning System

In this research, besides taking the measurement in the main power distribution panels of several buildings of Macao, it has also measured three types of popular centralized air-conditioning systems in Macao since most industrial, public and commercial type buildings in Macao are using the air-conditioning systems, and the operation current of the air-conditioning systems generally exceed 40% of the total operation current of the building, the power quality level of air-conditioning system for building is very important. The three types of systems are: Variable Refrigerant Volume (VRV) Air-Conditioning System, Air-Cooled Chiller Unit and Water-Cooled Chiller Unit. VRV system is a new and advanced air-conditioning system, it mainly uses variable speed drive technology, and the other two types of chiller units are traditional centralized air-conditioning systems. In this section it reports the measured current harmonic results in Macao from three types of centralized air-conditioning systems.

Table 4 shows a comparison table of the harmonic level among VRV system, air-cooled chiller unit and water-cooled chiller unit which are based on the measurement results. The results show that the current harmonic distortion (THD_I%) of VRV system is 38.5%, it exceeds the standard limits, but the harmonic distortion of air-cooled chiller unit and water-cooled chiller unit are 7.2% and 3.1% respectively, they are less than VRV system 31.3% and 35.4% respectively, they are within the standard limits. In other words, more harmonic current is caused by the VRV air-conditioning system.

Fig. 4 ~ 6 show the measured voltage waveform and current waveform of VRV system, air-cooled chiller unit and water-cooled chiller unit respectively. The figures show that the current harmonic distortion of VRV system is much larger than the current harmonic distortion of the two chiller units.

In the future, for the purpose of energy saving and more flexible use, more variable speed drive technology will be applied to different equipments such as lifts, air-conditioning systems and motors in Macao and other areas. At that time more harmonic current would be produced and injected into the power system to affect the operation of equipments. Therefore, it is recommended

that the current harmonic of all variable speed drive products should be limited.

Table 4
Comparison of current harmonic among VRV system, air-cooled chiller unit and water-cooled chiller unit

Air-conditioning system	Operation current RMS	Harmonic current RMS	THD_I%
VRV system	16.3A	6.2A	38.5%
Air-cooled chiller unit	205A	14.7A	7.2%
Water-cooled chiller unit	143A	4.45A	3.1%

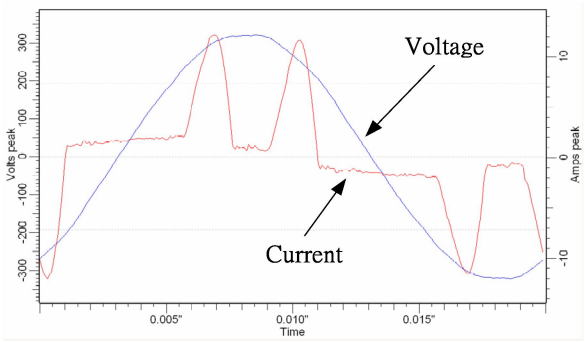

Fig. 4 Voltage and current waveform of VRV air-conditioning system

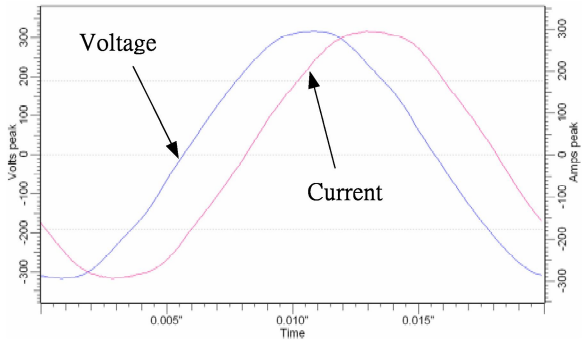

Fig. 5 Voltage and current waveform of air-cooled chiller unit

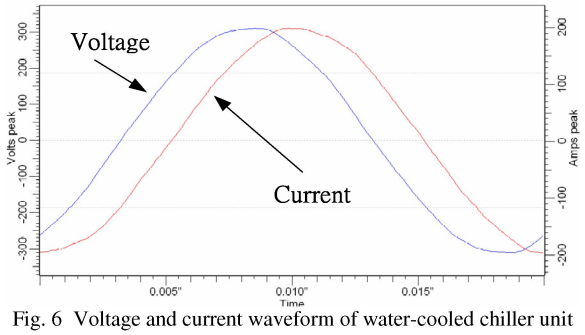

Fig. 6 Voltage and current waveform of water-cooled chiller unit

C. Harmonic Effect on Capacitor Bank

The use of capacitor is to improve power factor and voltage also has a significant influence on harmonic levels. Capacitor does not generate harmonics, but provide network loops for possible resonant conditions. If the addition of capacitor tunes the system to resonate near a harmonic frequency present in the load current or system voltage, large currents or voltage at that frequency will be produced.

According to the power quality measurement in several buildings of Macao, it seems that there is not any harmonic is amplified, one of the reasons is only 1 of 13 measured locations has installed capacitors due to nowadays there are not any formal regulations and standard limits for controlling the harmonics and instructing the installation of capacitor in Macao. Based on the measurement in Macao, it knows that order 3, 5 & 7 are main current harmonic components in Macao. Therefore, the end-users should note the harmonics before installing any capacitor. Moreover, the understanding of harmonic levels in Macao is not much until to the present, so it is also recommended the end-users should measure their individual order harmonic level once they need to install capacitor banks to increase the power factor or reduce the energy losses in the future.

D. Even Order Current Harmonic

In general the even order current harmonic level is less than the odd order current harmonic level. Therefore, many power quality compensators focus on how to reduce the odd order current harmonic but not focus to reduce the even order harmonic. In this research it reports the measured odd and even order current harmonic results, and uses the limits shows in Table 5 from IEEE 519-1992 to evaluate individual order harmonic status.

Table 6 and 7 show the maximum odd order current harmonic and even order current harmonic results in percent of I_L respectively from the power quality measurement in several buildings of Macao. It finds that some even order current harmonic results in the special facility building, the public administrative building C and the middle school exceed the limits. Therefore, it should start to care the even order current harmonic. Besides, the maximum even order current harmonic is near the maximum odd order current harmonic in the special facility building, the public administrative building A, the public administrative building C and the middle school, it shows that the even order harmonic also is a main component of harmonic.

Table 5
Individual order harmonic standard limits

Maximum Harmonic Current Distortion in Percent of I_L					
Individual Harmonic Order (Odd Harmonics)					
I_{SC}/I_L *	<11	11≦h<17	17≦h<23	23≦h<35	35≦h
<20	4.0	2.0	1.5	0.6	0.3
20<50	7.0	3.5	2.5	1.0	0.5
50<100	10.0	4.5	4.0	1.5	0.7
100<1000	12.0	5.5	5.0	2.0	1.0
>1000	15.0	7.0	6.0	2.5	1.4
Even harmonics are limited to 25% of the odd harmonic limits above.					

* I_{SC}=maximum short-circuit current at PCC
I_L=maximum demand load current at PCC

Table 6
Measured maximum odd order current harmonic in percent of I_L

Location	Order Limit	Order	Phase A (Max.)	Phase B (Max.)	Phase C (Max.)
Fac	4%	3	27.96%	24.72%	7.47%
Pub A	10%	3	2.58%	2.13%	3.35%
Pub B	7%	3	4.15%	4.26%	6.43%
Pub C	7%	5	3.71%	3.41%	4.30%
Res A	10%	5	4.05%	4.18%	3.86%
Res B	10%	5	4.01%	4.14%	3.88%
Res C	10%	3	4.47%	5.01%	5.41%
Res D	10%	3	4.61%	5.01%	3.74%
Res E	10%	3	3.21%	3.01%	3.76%
Com	4%	5	2.27%	2.23%	2.20%
Hot	7%	5	3.97%	4.11%	3.06%
Sch	12%	3	7.18%	7.00%	7.25%
Cen	12%	3	7.37%	5.81%	9.37%

Table 7
Measured maximum even order current harmonic in percent of I_L

Location	Order Limit	Order	Phase A (Max.)	Phase B (Max.)	Phase C (Max.)
Fac	1%	2	28.62%	22.42%	4.75%
Pub A	2.5%	2	2.31%	2.26%	1.92%
Pub B	1.75%	2	1.20%	1.08%	1.06%
Pub C	1.75%	2	3.03%	2.86%	3.11%
Res A	2.5%	2	0.91%	1.49%	1.97%
Res B	2.5%	2	1.63%	0.56%	1.32%
Res C	2.5%	2	1.29%	1.30%	0.98%
Res D	2.5%	2	0.81%	0.90%	1.07%
Res E	2.5%	2	1.76%	1.60%	0.73%
Com	1%	2	0.54%	0.53%	0.63%
Hot	1.75%	2	0.73%	0.69%	0.66%
Sch	3%	2	5.67%	5.56%	6.14%
Cen	3%	10	0.46%	0.46%	1.53%

E. Neutral Current Harmonic

High neutral current can cause overload power feeder, distribution transformer and voltage distortion [4]. Table 8 shows the measured neutral current RMS is between 7.9% and 91.6% of the phase current RMS, most exceed the limits (< 20% of phase current) [5]. On the other hand, the harmonic components on neutral line play a larger role than the linear load unbalances since generally the neutral current harmonic (THD_I%) is more than 100%.

Nowadays, usually it is focus on how to limit the phase current harmonic but not focus on limit the neutral current harmonic. Table 9 shows the neutral current harmonic (THD_Irms), neutral current harmonic (THD_I%), neutral current harmonic (TDD_I%) and phase A current harmonic (THD_Irms) results from the power quality measurement in several buildings of Macao. The table shows some neutral harmonic current (THD_Irms) is higher than phase harmonic current (THD_Irms), and some neutral current harmonic (TDD_I%) values exceed the limits in the public administrative building C, the residential building C, the middle school and the indoor sport center even their phase current harmonic (TDD_I%) are within the limits. The neutral harmonic current is mainly due to the triplen harmonic currents which add in the neutral conductor. Therefore, it should start to limit the neutral current harmonic. Besides, all neutral current harmonic (THD_I%) exceeds the limits too much.

Fig. 7 shows the measured current harmonic (THD_Irms) of the public administrative building C, its neutral current harmonic is higher than the phase current harmonic.

Finally, due to the possibility of large triplen harmonic currents existing in the neutral conductor for building loads with a large proportion of non-linear equipment, it is not recommended to use neutral conductors with a cross-sectional area less than that of phase conductors in the main circuit.

Table 8
Measured phase and neutral current RMS

Location	Phase A (Max.)	Phase B (Max.)	Phase C (Max.)	Neutral (Max.) (% of phase current)
Fac	1797A	1801A	1373A	121.3A (8.8%)
Pub A	305.1A	304.9A	308.5A	44.9A (14.7%)
Pub B	1.629KA	1.637KA	1.639KA	130.2A (7.9%)
Pub C	966.8A	985.6A	960.0A	101.2A (10.5%)
Res A	198.4A	154.5A	153.7A	106.5A (69.2%)
Res B	163.5A	120.8A	171.2A	94.2A (78.0%)
Res C	245.3A	241.9A	307.2A	112.7A (46.5%)
Res D	243.9A	263.5A	253.9A	99.0A (40.6%)
Res E	142.9A	147.8A	156.9A	67.1A (46.9%)
Com	454.0A	448.0A	419.7A	82.7A (19.7%)
Hot	310.6A	337.6A	261.9A	89.2A (34.2%)
Sch	227.6A	243.9A	254.5A	68.5A (30.1%)
Cen	52.0A	32.5A	31.6A	29.0A (91.6%)

Table 9
Measured current harmonic

Location	TDD_I % Limit	Phase A THD_Irms (Max.)	Neutral THD_Irms (Max)	Neutral THD_I% (Max)	Neutral TDD_I% (Max)
Fac	5%	1.394KA	45.88A	18K%	2.29%
Pub A	12%	17.89A	36.81A	92.71K%	7.36%
Pub B	8%	72.92A	126.9A	485.9K%	7.93%
Pub C	8%	47.35A	91.02A	165.4K%	9.1%
Res A	12%	33.13A	58.95A	106.2K%	9.83%
Res B	12%	28.43A	57.09A	162.2K%	9.52%
Res C	12%	35.09A	82.82A	541.6K%	13.8%
Res D	12%	34.68A	66.06A	665.1K%	11.0%
Res E	12%	26.7A	53.58A	181.9K%	8.9%
Com	5%	52.76A	60.47A	712.9%	3.0%
Hot	8%	77.24A	46.88A	76.21K%	2.9%
Sch	15%	27.91A	62.55A	14.65K%	20.8%
Cen	15%	6.434A	18.55A	2.964K%	23.1%

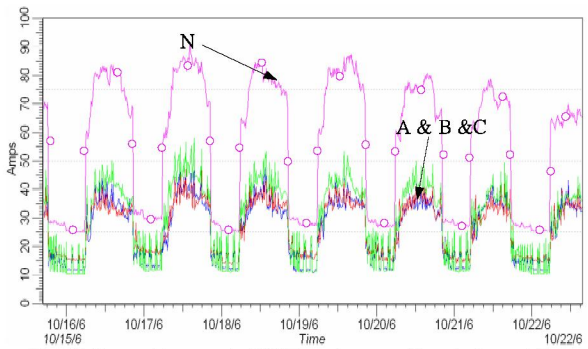

Fig. 7 Current harmonic (THD_Irms) versus time in the public administrative building C

IV. Conclusions

Five point's findings on harmonic measurement in Macao have been reported and it could be concluded as below:

- It should note the differences between current harmonic THD_I% and TDD_I%, TDD_I% is more suitable to estimate the current harmonic level than THD_I% for building.

- More harmonic current is caused by variable refrigerant volume (VRV) air-conditioning system than traditional air-cooled chiller unit and water-cooled chiller unit.

- The end-users should measure their individual order harmonic level once they need to install capacitor banks to improve the power factor.

- Some even order current harmonics exceed the limits, thus it should start to care the even order current harmonic.

- Harmonic is a main factor on neutral current and some neutral current harmonic (THD_Irms) is more than phase current harmonic (THD_Irms).

ACKNOWLEDGEMENT

The authors would like to thank the Research Committee of University of Macau for their supports, and also thank the persons of the buildings for their support and helpful for this power quality monitoring.

REFERENCES

[1] Eloi Ngandui, and Cedric Meignant, "Power quality monitoring and analysis of a university distribution system," *IEEE CCECE,* vol. 2, pp. 863-867, May 2001.

[2] Sio-Un Tai, Man-Chung Wong, Ming-chui Dong, Ying-Duo Han, "Power quality study in Macao," *Proc. of 7th Int. Conf. on Power Electronics and Drive Systems (PEDS 2007)*, Bangkok (Thailand), Nov. 2007. (Accepted)

[3] Vannoy, D.B., McGranaghan, M.F., Halpin, S.M., Moncrief, W.A., Sabin, D.D. "Roadmap for power quality standards development," *Petroleum and Chemical Industry Conference, Industry Applications Society 52nd Annual,* pp. 267-276, Sept. 2005.

[4] T.M. Gruzs., "A survey of the neutral current in three-phase computer power systems," *IEEE Trans. on industry applications,* vol. 26, pp. 719-725, July-August 1990.

[5] A. C. Liew, "Excessive neutral currents in three-phase fluorescent lighting circuits," *IEEE Trans. on industry applications,* vol. 25, no. 4, pp. 776-782, July/August 1989.