Locating Major Harmonic Current Contributors by Layered Knowledge Discovery in Database

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***Abstract*–Harmonic monitoring becomes increasingly important in harmonic management of building low voltage power distribution system (LVPDS). Excessive harmonic currents result in decreasing energy efficiency. It is also harmful to the sensitive devices and can even lead to the failure of devices. As a result, power quality monitoring system (PQMS) has been widely installed in a facility management to monitor building LVPDS. This paper presents a diagnosis approach for the PQMS to locate major harmonic currents contributors based on a knowledge discovery in database (KDD) procedure. The key data used for the analysis includes the normalized values of instant power consumption and total harmonic distortion of current (THDI). The diagnosis is illustrated with a case study for which a PQMS is installed in an education institute. The results obtained from the PQMS are also useful for demand-side management and demand dispatch in future microgrid system.**

***Index Terms*— Harmonic monitoring, knowledge discovery in database, low voltage electric power system, major harmonic currents contributors, total harmonic distortion of current.**

I. Introduction

THERE has been a rapid increase in using power electronic devices and non-linear loads in low voltage power distributed system (LVPDS) and subsequently changes its operational environment. These devices have non-linear voltage-current characteristics and emit harmonic currents to the system they are connected. These devices thus inject excessive harmonic currents into the system and consequently distort the supply voltage [1]. With the distorted supply voltage, most of the non-linear and power electronic devices produce more harmonic currents [2]. BS EN61000-3-14 [3] provides guidance to system operators for engineering practices, which will facilitate the provision of adequate service quality for all connected customer installations. It also suggests the allocation of the capacity of the system to absorb disturbances such as harmonics, interharmonics, rapid voltage changes and unbalance. As a result, introducing a power quality monitoring system (PQMS) into LVPDS by facility management operators becomes a general practice in large scale complex building for recording data for further analysis. The system is consisted of metering devices, communication networks and storage devices. The basic system is used to monitor voltages, currents, power consumption, total harmonic distortion of voltage and current, power factor and so on. The PQMS is also important for demand side management and demand dispatch for the building integrated microgrid system.

Since the total harmonic distortion of current (THDI) and power consumption (kW) are primary information to indicate the healthiness of the system, they have been chosen as the key data for the analysis. According to the CoP for Energy Efficiency of Electrical Installations [4], the suggested Maximum THDI for any circuit should not exceed the limits shown in Table I. Also, the power supply utility may disconnect the supply to any installation, which by reason of unsteady or fluctuating demand or by injection of undesirable waveforms into the Company's system, adversely affects the Company's system or the electricity supply to other customers. THDI for the electrical system is one of the requirements of the power supply utility.

TABLE I
Maximum THD of current in percentage of fundamental

Circuit Current at Rated Load Condition (I) at 380V/220V	Maximum Total Harmonic Distortion of Current
I < 40A	20.0%
40A ≤ I <400A	15.0%
400A ≤ I < 800A	12.0%
800A ≤ I < 2000A	8.0%
I ≥ 2000A	5.0%

Most of the power electronic devices and non-linear loads inject current harmonics into the LVPDS. Therefore, locating the equipment that produce the most harmonic current becomes important. Given the huge amount of data recorded by the PQMS, a more sophisticated analysis method is necessary for analyzing the recorded data. A knowledge discovery in database (KDD) process is hence introduced to extract the useful information from the PQMS data.

KDD refers to the overall process of discovering useful knowledge from data [5]. It includes data selection, data cleaning, data preprocessing, incorporating appropriate prior knowledge and proper interpretation of the results. In this

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process, the nodes having high power consumption and high THDI in the system are located by the sum of normalized values of power consumption and THDI of each node.

A PQMS has been installed in an education institute and the data collected forms a database. The education institute provides tertiary education for a wide range of disciplines. The total installed supply capacity of the education institute is 25.5MVA, supplied through 17 nos. 11kV/380V 1500kVA transformers. The LVPDS is arranged in a radial topology, consisting basically three layers, and three different grades of meter are installed at different layers throughout the system. Data over a year was recorded and is available for analysis. As a case study, the diagnosis approach is demonstrated by using this database.. The threshold of THDI is calculated according to CoP for Energy Efficiency of Electrical Installations [4] as shown in Table 1 and is compared with data recorded by PQMS. After that the major harmonic currents contributors are located so that mitigation measures would be conducted readily.

This paper is organized as follows: Section II describes the detail of the PQMS; Section III presents procedures of the KDD process; Section IV presents a case study of the LVPDS to illustrate the KDD based diagnosis approach; and Section V contains the conclusions.

II. Power Quality Monitoring System (PQMS)

A PQMS is implemented for a LVPDS. The system consists of three components: power quality (PQ) meters, a communication network and storage devices. The system architecture is shown in Fig. 1.

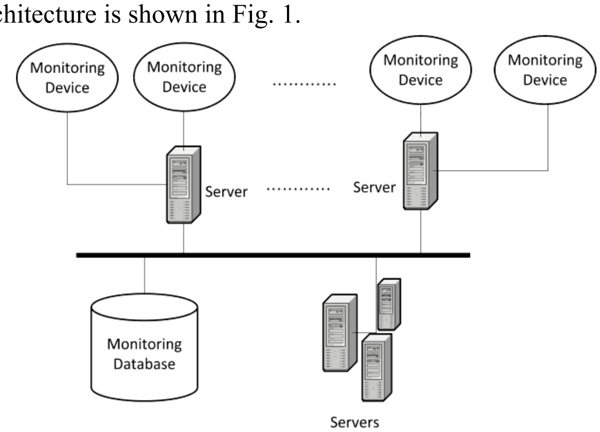

Fig. 1 Power Quality Monitoring System (PQMS) configuration

The LVPDS is generally divided into three layers and three different grades of PQ meters are installed. PQ meters are installed at LV sides of each 11kV/380V transformer, at each rising mains and at the tee-off nodes of each floor. The PQ meters used are Schneider made PowerLogic™ ION7550, PowerLogic™ 820 and PowerLogic™ 710; their features are shown in Table II. These devices provide real time and event information to help diagnose and mitigate power problems; and to improve power system reliability. They also help to reduce electricity charges and increase equipment utilization by optimizing equipment deployment.

At layer I, the PQ meters are installed at LV side of the 11kV/380V step-down transformers. It monitors incoming supply from the power supply utility. Class A to IEC61000-4-30 device that is the most powerful monitoring device out of the three was installed at this layer. This monitoring device is able to monitor individual voltage and current harmonics up to the 63rd with sampling frequency of 12.8kHz. Facility managers would like to know as much as information about this node for ensuring that the building operation meets the requirements of the power supply utility. At the same time facility managers are conscious about the electricity charges.

TABLE II
Features of PQ meters

Devices	Types	Features
PowerLogic ION 7550	A	Three phases measurement of voltage, current, active power, reactive power, apparent power, power factor, frequency, phase reversal, individual harmonics, true rms up to the 63rd, total even harmonics, total odd harmonic, total harmonic distortion, K-factor and crest factor, 256 samples per cycle
PowerLogic 820	B	Three phases measurement of voltage, current, active power, power factor, frequency, individual harmonics, true rms up to the 31st, total harmonic distortion, 128 samples per cycle
PowerLogic 710	C	Three phases measurement of voltage, current, active power, power factor, frequency, individual harmonics, true rms up to the 15th, total harmonic distortion, 32 samples per cycle

In layer II, the PQ meters are installed at each rising mains. PowerLogic 820 PQ meter is installed at this layer to monitor the rising mains. The main features of monitoring device are shown in Table II. It is deemed that 31 orders of harmonics are sufficient information in this layer.

In layer III, the PQ meters are installed on the node on each floor. PowerLogic 710 PQ meter is installed at this layer to monitor supply to end-users on each floor. The main features of this device are shown in Table II.

For the communication system, the monitoring system offers instantaneous readings directly from the PQ meters using the web browser via Ethernet. The communication system consists of Ethernet network and servers. PQ meters used in the PQMS offer a number of standard interfaces such as RS-232, RS-485 and Ethernet for transferring recorded data for storage. Intermediate servers are used to collect the data from PQ meters and then transfer to monitoring database for storage. However, the communication system is one of the factors for determining the interval of data recording and dispatching synchronization signals to all PQ meters for ensuring that the data recorded are time-stamped. After considering the size and actual needs of the data, the data was recorded in 15 minutes interval.

For storage device, a reliable database system is used.

III. Knowledge discovery in database (KDD)

The PQ meters are able to record lots of information from the LVPDS such as current usage, voltage, THD and individual harmonic contents of voltages and current, etc.. All these information are saved in database. It is not an easy task to extract useful information from the data. Hence, KDD is introduced to extract useful knowledge from the data [5]. Fig. 2 shows a flowchart of the KDD process. KDD refers to the overall process of discovering useful knowledge from data. It includes data selection, data cleaning, data preprocessing, incorporating appropriate prior knowledge and proper interpretation of the results.

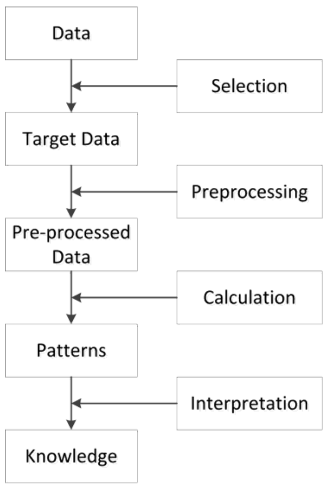

Fig. 2 Flowchart of the KDD process

The major steps of KDD are described as follows.

1) Data Selection: Data captured by PQ meters are stored in the database. The first step is to select appropriate data for further analysis. In this case, power consumption and THDI are selected for processing since these two data are deemed to indicate the healthiness of the node effectively. The CoP [4] states that the percentage THDI allowed is dependent on circuit ratings. Therefore one should assess THDI with regard to the circuit ratings and actual power consumptions.
2) Data Cleaning and Preprocessing: In this stage, the inconsistencies on the data and outliers are detected and replaced based on the information of similar days. In the preprocessing stage, missing values are detected and replaced by regression techniques. Linear regression is used to estimate numerical attributes like missing data in the measurements [6].
3) Data Processing: The sum of normalized value of THDI and instant power consumption is used to determine the nodes worthy of in-depth analysis by comparing with the value of THDI threshold. THDI threshold is calculated from the limits of THDI for various circuit ratings as stipulated in CoP for Energy Efficiency of Electrical Installations [4].
4) Interpretation of the discovered knowledge: Based on the sum of normalized values and the THDI thresholds, a group of nodes that inject excessive harmonic currents to the LVPDS can be located. The daily profile of power consumption and THDI of these nodes are created for further study. The data of daily profile is represented by vector P = $\{P_1, P_2, \ldots, P_n\}$ where P_n is the average value of the instant power consumption over a specific period, ranging from a month to a year, and n = 1, 2, …, 96, represents the measurement data collected over a 15-min interval in a day. The daily profile is then plotted by the vector P versus time which starts from 00:00 to 23:59 with a 15-min interval. The daily profile illustrates the pattern of the power consumption and THDI of the node in the LVPDS. After determining the nodes and the time at which excessive amount of current harmonics was injected into the LVPDS, improvement works can be carried out accordingly.

IV. Case Study

A case study concerning the diagnosis of a LVPDS is presented in this section. The LVPDS under study is installed in an education institute providing multi-disciplinary tertiary education. The LVPDS consists of 17 nos. 11kV/380V 1500kVA transformers with an installed capacity of 25.5MVA. It is becoming a general practice that a PQMS is installed in such a large scale LVPDS for assessing the compliance of the building operation to CoP for Energy Efficiency of Electrical Installations [4] and the supply rules of electricity supply utility. The PQMS is consisted of 17 nos. Type A meters at Layer I, 61 nos. Type B meters at Layer II, and 211 nos. Type C meters at Layer III. Data over a year were recorded and is available for analysis. The distribution of PQ meters in the LVPDS is illustrated in Fig. 3.

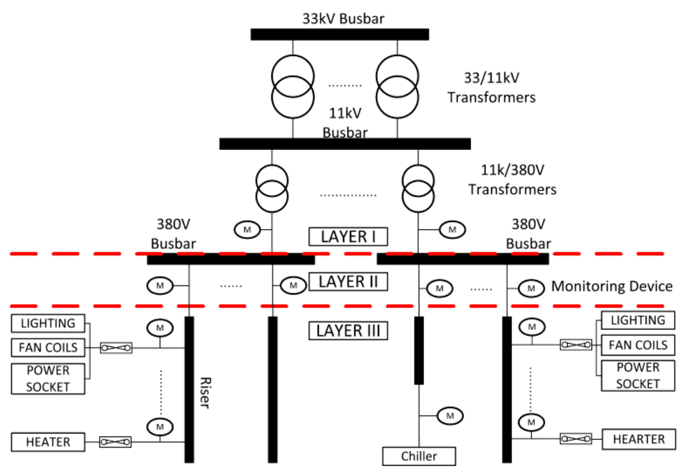

Fig. 3 Distribution of PQ meters in electrical power system

Diagnosis on the data from the PQMS is done layer by layer by the KDD process. Firstly, Layer I data representing the data recorded at the utility entry point via low-voltage side of the transformers is extracted from database. The average values of THDI and the instant power consumption of all transformers are shown in Table III. In any case the THDI must not exceed the value stipulated in Table IV. Table IV is derived from Table I, with current rating replaced by power rating.

TABLE III
The average values of THDI and instant power consumption of transformers

Transformer	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
THDI (%)	3.4	2.4	5.1	3.8	6.2	2.7	10.2	9.9	7.0
Power (kW)	240	399	376	215	484	246	112	348	350
Transformer	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	
THDI (%)	5.3	11.0	6.3	9.9	8.0	23.4	9.2	2.4	
Power (kW)	371	453	637	576	502	391	209	293	

TABLE IV
Threshold of THDI for 380V -phase circuits

Power Rated Load Condition	Threshold of THDI
P < 26.3kW	20 %
26.3 ≤ P < 263 kW	15 %
263 ≤ P < 527 kW	12 %
527 ≤ P < 1316 kW	8 %
P ≥ 1316 kW	5 %

Comparing Tables III and IV, it is found that the THDI of transformer no. 13 and 15 exceeds the recommended THDI limits. Fig. 4 and Fig. 5 show the daily profile of the instant power consumption and THDI respectively of these transformers. The sum of normalized value of instant power consumption and THDI are calculated and shown in Table V. It is used to determine the condition of nodes which inject excessive harmonic currents into the LVPDS. The transformer with the highest sum of normalized value needs immediate attention for further analysis, i.e. Transformer no. 15 as shown in Table V.

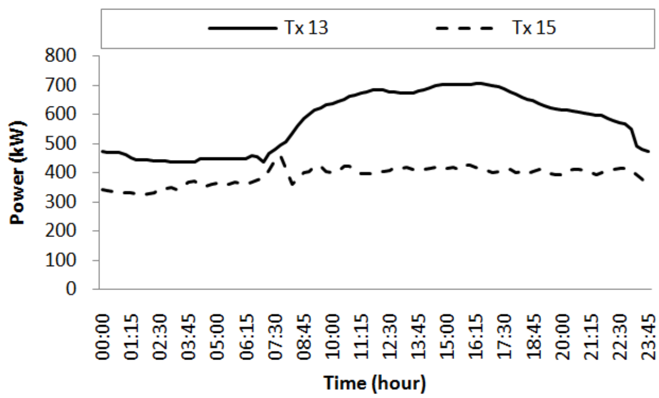

Fig. 4 Daily profile of power consumption for Transformer no. 13 and 15

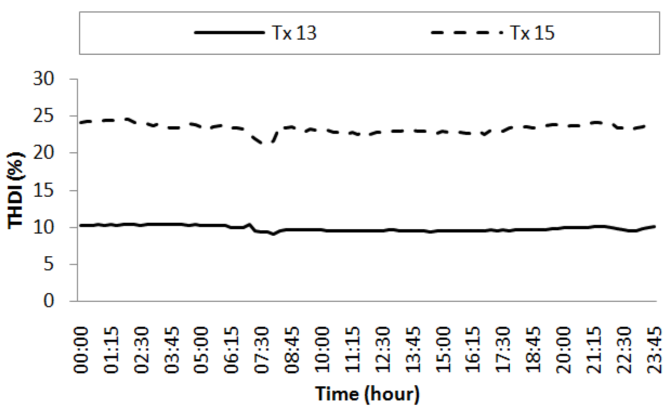

Fig. 5 Daily profile of THDI for Transformer no. 13 and 15

TABLE V
Sum of normalized value of power consumption and THDI on particular transformers

Transformer	13	15
THDI (%)	9.9	23.4
Instant Power Consumption (kW)	576	391
Normalized THDI	0.42	1
Normalized Instant Power Consumption	1	0.68
Sum of normalized value	1.42	1.68

Layer II analysis is then focused on outgoing circuits connected to Transformer no. 15. The diagnosis approach in Layer I is repeated in Layer II, using data collected for Layer II nodes. The data of layer II for Transformer no. 15 are extracted from database and then processed by the KDD process. There are four nodes in transformer no. 15: node 1 supplies to an air conditioning system; node 2 supplies to water heaters, lighting system, wall mounted sockets, fans and compressors; node 3 supplies to external lighting system; and node 4 supplies to flat roof green house. The normalized values of THDI and instant power consumption of all nodes of Transformer no. 15 are shown in Table VI. Fig. 6 and Fig. 7 show the daily profile of instant power consumption and THDI respectively for the four nodes. It is observed that node 1 has the highest value of sum of normalized value of THDI and instant power consumption, and clearly violates the stipulated limits in Table IV. Further analysis will be performed at this node.

TABLE VI
Sum of normalized value of instant power consumption and THDI on Transformer no. 15

Node	1	2	3	4
THDI (%)	26.8	13.5	11.9	12.8
Instant Power Consumption (kW)	324	55	0.4	10
Normalized THDI	1	0.50	0.44	0.48
Normalized Instant Power Consumption	1	0.17	0.00	0.03
Sum of normalized value	2	0.67	0.44	0.51

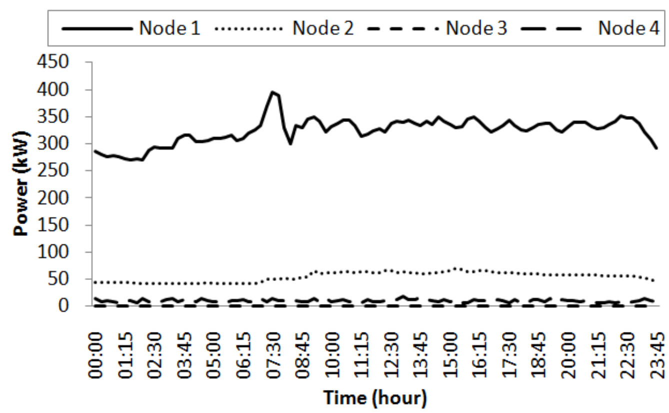

Fig. 6 Daily profile of instant power consumption for all nodes in Layer II of Transformer no. 15

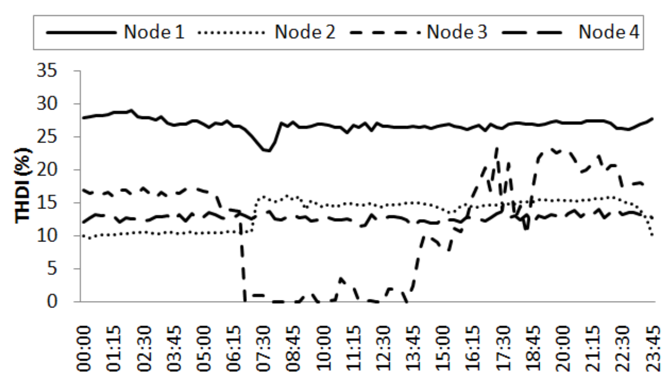

Fig. 7 Daily profile of THDI for all four nodes in Layer II of Transformer no. 15

Similarly, the diagnosis approach in layer III repeats the steps of diagnosis used in layer II, with data collected in Layer III. Data in Layer III of node 1 in Layer II are extracted from the database and then processed by KDD process. It is found that the only load that is connected to node 1 in Layer II is a chiller plant of the central air-conditioning system. A chiller plant consumes substantial power and so is a common practice to supply it through a dedicated rising main circuit. Therefore this is no Layer III data available for this circuit and the diagnosis process stops here.

As a result, the diagnosis process reveals that node 1 in Layer II of Transformer no. 15 is the major harmonic current contributor in this LVPDS and improvement measures should be implemented at this node.

V. Conclusions

Data of power consumption and THDI from a PQMS in a typical LVPDS has been analyzed using layered diagnosis approach. This approach allows facility managers to locate major current harmonic contributors at each layer of the entire LVPDS. A KDD process based on sum of normalized values of THDI and instant power consumption has been shown to be able to locate the major current harmonic contributor from the recorded data of a PQMS. The major advantage of this approach is that it can quickly locate the major current harmonic contributors and then the harmonic reduction devices or other mitigation measures can be implemented. The major difficulty of this approach is to handle huge amount of data and convert them into useful information. Further work will be conducted on studying the significance of voltage and current harmonics in the diagnosis process. It is worthwhile to point out that the PQMS and the diagnosis process presented in this paper are very useful for building integrated microgrid system as it can help in demand side management and demand dispatch.

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VII. Biographies

M. K. So received his BEng degree in Computer Engineering in 2009 and currently he is pursuing his PhD study in City University of Hong Kong. His research is focusing on Low-voltage electrical distribution system, power quality and harmonic studies.

Wing-Hong Lau (M’88–SM’06) received the B.Sc. and Ph.D. degrees in electrical and electronic engineering from the University of Portsmouth, Portsmouth, U.K., in 1985 and 1989, respectively. In 1990, he joined the City University of Hong Kong, Kowloon HongKong, where he is currently an Associate Professor in the Department of Electronic Engineering. His current research interests include the area of digital signal processing, digital audio engineering, and PWM spectrum analysis. Dr. Lau was a recipient of the IEEE Third Millennium Medal. He was the Chairman of the IEEE Hong Kong Section in 2005, Chairman of the IEEE Hong Kong Joint Chapter on Circuits and Systems/Communications for 1997 and 1998.

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