The Study of Distribution Voltage Drop and Neutral-to-Ground Voltage of A Healthcare Facility Using MATLAB-Simulink

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Abstract—**This paper presents the impact of increasing harmonic current on voltage drop and neutral-to-ground voltage (VNG). The study started with identifying problem related to power quality (PQ) at Clinical Training Centre (CTC), UiTM Sg. Buloh where there were severe equipment malfunctions reported. It is decided to log power monitoring device to assess the facility's power quality. Based on the facility's single line diagram and measurement data, a selected feeder was simulated using MATLAB-Simulink, where the original recorded harmonic current percentage were increased percentage by percentages to predict the limit before violating the standard voltage drop and neutral-to-ground (VNG) outlined by the utility provider. The results showed that the magnitude of harmonic current that can be borne by each phase cable are different. The finding of this study may help the facility in planning future load installation by phases as well as considering the VNG.**

Keywords—Power Quality, MATLAB-Simulink, neutral-to-ground voltage, harmonics, current harmonics, voltage drop

I. INTRODUCTION

Power Quality issues becomes a growing concern primarily among large scale consumers due to their financial impact. It is stated in [4] that roughly 30 to 40 percent of all business downtime is related to power quality problems while the total cost of power quality disturbance suffered by European Economy exceeds 150 billion €. In US alone, the losses are to the extend of 188 billion USD.

The advancement in power electronics has dramatically changed the healthcare industry. Magnetic resonance imaging (MRI), digital syringe pump and radiology equipment are common equipment in any hospital nowadays. Such loads have the potential to create a host of disturbances for the utility and the other equipment sharing the same feeder line. The main problem stems from the flow of non-active energy caused by harmonic currents and voltages [5]. The harmonic currents passing through the impedance of the system cause a voltage drop for each harmonic. This results in voltage harmonics appearing at the load bus. Surveys [6,7] reported that the 95% probability level for the 5th harmonic voltage sustained a steady increase from 3% to 5% i.e. 1.67% per 10 years.

Harmonic distortions and unbalances in real electrical power system affect not only phase components but also neutral voltages and currents. Information regarding neutral harmonic component is very important since it augments system losses, reduce the sensitivity of ground–fault relays and causes interruption to communication systems and electronics devices [9]. The significant increse of neutral harmonic components in today network is a consequence of unbalances in distribution system, non-linear loads as well as switching (time-varying) devices [10]. Therefore, computer based techniques to analyze four-wire three phase harmonic generation and penetration are very important for the study of electrical networks [9].

Power system study has gone through a long journey. There are IEEE Test Feeders have been developed to assist the validation of power system analysis program. There are also individual contributions such as neutral-to-earth voltage (NEV) single feeder case program developed by W.H. Kersting which was successfully simulated at 60Hz using two methods. One of which was Current Injection Method and another test was Alternative Transient Program (ATP) [11]. Other works using this test system is also been stated in [12] where Four-Wire Three-Phase Harmonic Current Injection Metthod (FHCIM) had been applied including the presence of 3rd harmonic load. While [9] applied FHCIM with 3rd harmonic loads and a SVC to represent nonlinear loads.

The main objective of the work is to investigate how far the existing electrical system cable of the facility can operate before it violates the permissible voltage drop and NG voltage during symmetrical and unbalanced load condition based on the standard voltage drop outlined by TNB which allows a drop of not more than 10% of nominal voltage of 230V and NG voltage of not more than 5V. This paper serves as a preliminary study as the scope is limited to one feeder only. This information can be used for better planning when installing sensitive equipment in future. Meanwhile, this paper also highlights the impact of power quality disturbance in term of financial, what equipment involves which open to further research in the future and exoposure to power monitor device i.e. Fluke 1750.

II. METHODOLOGY

The flowchart of the work done is presented in Fig. 1. The data of equipment malfunction disclosed by the facility was being inspected. The equipment involved were of highly sensitive power electronics equipment, thus, harmonics was believed to be the cause of the problem. Accordingly, it was decided to log power monitoring device, Fluke 1750 at affected feeders. In order to build the simulation, some data from the measurement and single line diagram were retrieved. There were data that needed calculation to obtain desired parameters to be incorporated into the simulation. Simulation using MATLAB-Simulink function was performed by increasing the magnitude of harmonic current of nonlinear loads injected into the circuit.

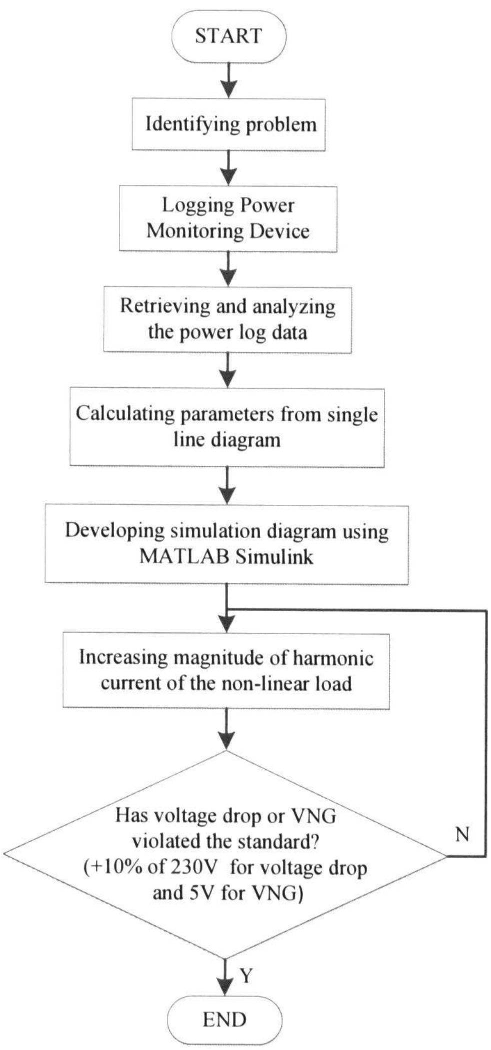

Fig. 1. Flowchart of the work

A. *Identifying Problem*

The problem of power quality disturbance was being identified through the data of equipment malfunction disclosed by the facility, only part of them are presented in this paper and is shown in Table I. Based on the price of the equipment themselves, it can be known that they are of high-tech medical equipment and the price of their maintenance are also high. There were case repetition on the same equipment such as patient monitor which had twice main board replacement, monitoring software reinstallation and calibration within the two year period at fatal cost. Overall, the total cost of loss borne by this facility was RM 298 389 which was severe.

TABLE I. CLAIMED WORK ORDER CAUSED BY ELECTRICITY PROBLEM AT CTC BUILDING (MAC 2013-APRIL 2015)

Equipment	Price (RM)	Dept.	Remark	Price (RM)
OT light ceiling	181, 521	OT	To replace faulty transformer	14,150
Central monitoring system/ Central monitor	134, 766	CCU	Replace faulty display monitor, desktop	550 550 595
	134, 766	CICU	To replace central monitoring, central processing unit and reinstall monitoring software inclusive calibration	9,250
Echocardio -gram	1,020, 000	NICL	To replace faulty echocardiogram LCD screen	22,950
Ultrasound	462, 000		To replace faulty LCD screen assembly	18,880
	1,020, 000	NICL	To replace monitor	26,500
Patient monitor	18, 466	CCU	To replace faulty main board, to reinstall monitoring software and calibration	12,625 12,625
	5,656		To replace faulty display board	1,700
Ventilator	40,461	ICU	Change board	13,850

There are also free work order caused by electricity problems such as fuse problem, fuse faulty, fuse blow, no power as well as problems with plug cable, 3-pin plug, and plug top. Besides, there were also problems with cable and power cable, power supply adapter and socket (equipment: ultrasound) as well as problems involving highly sensitive electronics equipment like echocardiography system, central monitor and de souter, etc. such as no input, no display on screen, monitor faulty, CPU processor faulty, and transistor faulty. Though those were considered free work order, it is the number of occurrence that intense which deteriorated the efficiency of the healthcare service provision.

B. *Logging of Power Monitoring Device*

In order to obtain a reliable power log data, it is advised to log the monitoring device for a shift. A shift is a complete cycle of consumer's electrical activity depending on the type of facility [14]. As for this facility, the logging work started with Phase 1 where the monitoring devices were logged at the main feeders for seven days. This is an important measure to decide whether the problem comes from the utility provider or the consumer as it is the interface between the two or also known as point of common coupling (PCC). The CTC building's power system is divided into two types which are normal (N) and essential (E) supply. Each type is further divided into two parts resulting four main feeders labelled as Main Switch Boards (MSB) of N1, N2, E1 and E2.

The recorded data from Phase 1 were then analyzed. Interruption occurred in every feeders, however interruption is a common phenomenon that it can be neglected. It was found that only N2 and E2 feeder inhibited PQ event which was voltage swell of VNG. Example of voltage swell event is shown in Fig. 2 which showed a rise to averaged 110 V_{RMS} (48% of nominal voltage) from a normal VNG of 3 to 4 V_{RMS}. Events triggered at VNG shows that the problem source came from the local power system and not from the utility. The work was continued by logging Fluke at feeders of distribution boards (DBs) which demonstrated severe equipment malfunction as claimed in the list of equipment malfunction in Table I and other electricity problems aforementioned.

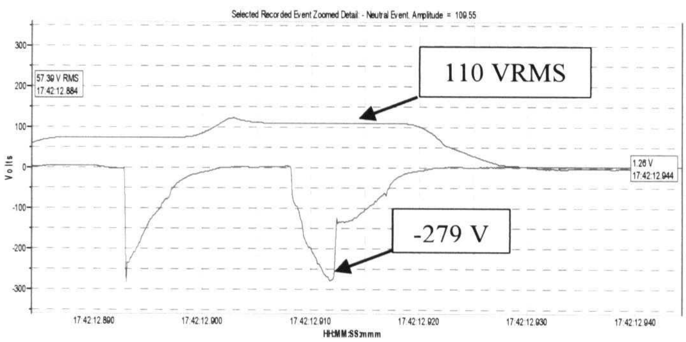

Fig. 2. Voltage swell triggered at VNG of MSB E2 (Snapshot from Fluke Analyzer software)

After phase 1, since the source of PQ problem had been decided to be from the building's power system, the power monitoring work was continued down the single line diagram. NICL, CCU, OT and CATHLAB were among most critical areas where problems occurred. Hence Phase 2 logging were done on feeders linked to those areas. One of the feeder was E2-4 from main feeder E2, being ICU/CCU/CCL room as one of the load it served. The other three were feeders M2-4, M2-7 and M2-8 from main feeder N2 which also feeds ICU/CCU/CCL room and CATHLAB as well as others.

The analysis of data from Phase 2 showed 88 voltage swell events triggered at VNG occurred at all feeders and 17 voltage dip/sag events triggered at phase A-to-neutral occurred at M2-4 and M2-8 feeders. From here, user can begin analyzing the data depends on the direction and depth of study. There are a lot of ways in term of the right location to log the device. For example, measuring THD value directly at specific machine i.e. CT scan as in [1].

C. *Data Retrieval and Analysis*

Fluke 1750 provides a complete power monitoring tool comprising parameters of RMS voltage/ampere during normal and distorted condition, automatic detection and classification of events either voltage or current event with ANSI, ITIC and CBEMA curve options, voltage/current harmonic and THD, flicker and power/energy comprising of active, reactive, and apparent power as well as pf value.

The recorded current harmonic data of E2-4 feeder is shown in Table II. The percentage of fundamental of phase current harmonics of 3rd, 5th and 9th harmonics of this feeder were considered of significant values. The fundamental (1st order harmonic) values are the average sinusoidal load currents of E2-4 feeder such that phase A: 180 A; phase B: 150 A and phase C: 115 A. Current THD is also presented in Table III.

TABLE II. AVERAGE CURRENT HARMONIC AMPLITUDE (%FUNDAMENTAL) OF E2-4 FEEDER

Harmonic Order	**Average Current Harmonic (% fundamental)**			
	A	***B***	***C***	***N***
Fund.	100	100	100	100
3rd	7.48	5.05	7.00	51.95
5th	6.89	4.78	4.45	14.19
7th	3.08	2.41	1.82	8.61
9th	4.85	2.87	2.92	30.14

TABLE III. APPROXIMATED CURRENT THD (% FUNDAMENTAL) OF E2-4 FEEDER

Phase	**A**	**B**	**C**	**N**
Min.	9.9	6	8.3	47.97
Avg.	11.95	8	10.05	83
Max.	14.00	10	11.8	118

The CBEMA-ITIC Power Acceptability curve provided in Fluke 1750 is an overview of voltage events occurring in the recorded system. Based on the magnitude (vertical axis) and the duration (horizontal axis) of the events, it defines:

i) An area in the center of the plot, where the equipment is expected to operate properly
ii) An area above the envelope where there is a risk of damage, overload and malfunction for the equipment.
iii) And an area below the envelope where the voltage are assumed to cause the load to drop out due to lack of energy

The CBEMA-ITIC curve for E2-4 contained 13 events plotted under the curve. Among them were 4 interruptions with duration within 1s to 1 day triggered at AN phase. The remaining 9 events were voltage swell event triggered at VNG with duration from 10ms to 40ms.The magnitude of swell ranged from 23V to 108V (10%-48% of nominal voltage).

The first case injected as nonlinear load into the system is calculated from the percentage from Table II out of their respective fundamental values. The values are stated in Table VI. Current harmonic injection only considers phase values since the neutral current harmonic is just the resultant of residual current from the phases hence neutral harmonic was not been simulated as nonlinear load component.

TABLE IV. MAGNITUDE OF CURRENT HARMONICS AT BASE CASE (A)

Harmonic Order	Magnitude of Current Harmonic Injection (A)		
	A	*B*	*C*
Fund.	180	150	115
3rd	13.464	7.575	8.05
5th	12.402	7.17	5.1175
7th	5.544	3.615	2.093
9th	8.73	4.305	3.358

D. Parameters Calculation

Before developing the Simulink model, there were some parameters that needed to be calculated in order to make sure that the simulation parameters syncs with the original system. The transformer rating is 11kV/400V. This value is in RMS. In simulation, it is easier to read maximum value of waveform. The RMS value was multiplied by $\sqrt{2}$, and additional division by $\sqrt{3}$ for star connection at secondary, the maximum primary and secondary voltages of the transformer became 15.56kV/ 326.6V. Understanding in differentiating between maximum value and RMS value is important in building simulation in order to get the desired parameters hence produces appropriate result.

From the single line diagram, the active power, P of the loads were known. While the reactive power, Q were unknown and been calculated using equation derived from power triangle $Q = P \tan \theta$ taking power factor, pf = 0.9 as averaged pf value recorded in Fluke.

The impedance value of the neutral and phase cables are obtained from Table 4B4E British Standard (BS 7671). For 240 mm sq. multicore armoured 90°c thermosetting insulated copper conductor cable, r = 0.175 mV/A/m, x = 0.125 mV/A/m. The cable resistance is simply calculated by multiplying r with cable length while the cable inductance is calculated by first converting x into inductance, L by dividing x by $2\pi.50$, then multiplied by the cable length. The length of the cable was assumed 400 meter. The length was adjusted up to 400 meters to achieve the desired VNG in the simulation to be nearly equal to the original Fluke data which is about 3 to 4.6 Vrms. The phase and neutral cable impedance are same since they are built in a single cable of 4 core (3 phase + 1 neutral) as stated in the single line diagram.

E. The MATLAB-Simulink model

MATLAB-Simulink method was chosen as it gives simple alternative way of simulation instead of other methods such as MATLAB's Power Systems Toolbox and hybrid simulation with PSIM and MATLAB [1].

For simulation purpose, is decided to develop only one feeder line which is E2-4 feeder for this preliminary study. E2-4 feeder is chosen as it feeds some critical areas mentioned earlier which are ICU/CCU/CCL and OT distribution boards.

The building consists of 5 floors and adopts TT grounding system such that the source and the end users' loads are connected directly to the earth. E2-4 feeder feeds one sub switch board per floor. In this simulation, load at floor 1 is replaced with non-linear load while the remaining loads are kept at their maximum demand (MD) values as in single line diagram.

As Fig. 3 shows, simulation parameters were as follow: the start-end time 0.0s-0.1s; solver is Ode23tb. The step length and the initial step is auto; the relative tolerance is 0.001, the absolute tolerance is auto. The source is three phase voltage source of 11 kV_{RMS}, 50 Hz. The source voltage is stepped down from 15.5 kV through a 225kVA transformer to 313V.

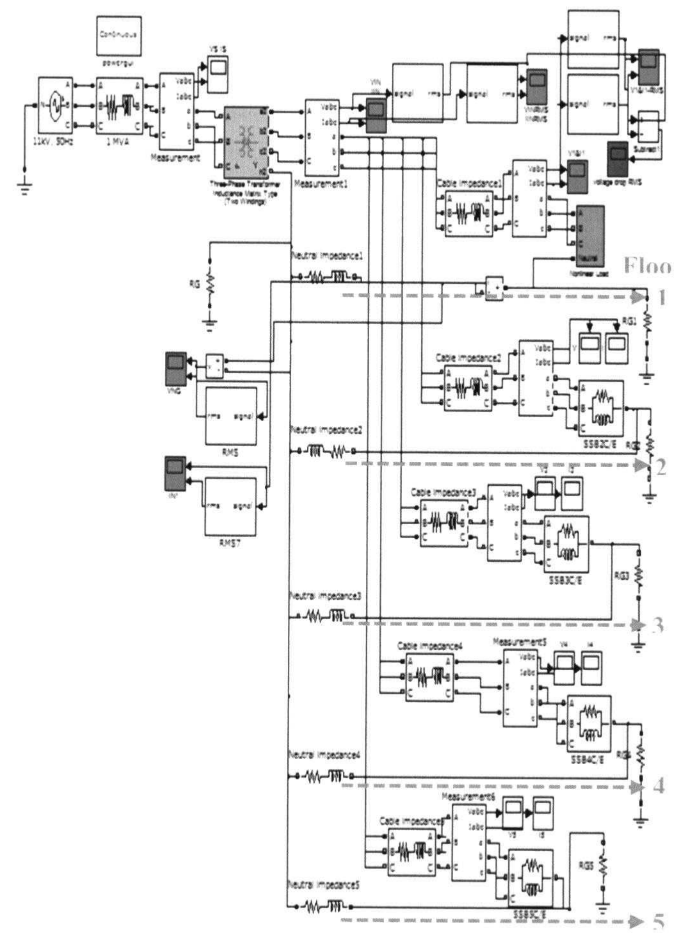

Fig. 3. The simulation model of E2-4 feeder

In the simulation diagram, the nonlinear load is simplified to subsystem. Subsystem is a function in this software to simplify complicated diagram. The hidden non-linear load diagram is as Fig. 4. Current source was used to represent current harmonic since nonlinear load injects current at multiple frequency of the fundamental frequency, 50Hz. 3rd harmonic is simply a triple of 50Hz hence the frequency becomes 150Hz. The same goes to further harmonic order resulting 250,350,450..Hz and these values were set as the respective frequencies of the harmonic components. The amplitude of current harmonic of each component were varied by increasing percentage of base case in Table IV. Example of percentage increment of base case is shown in Table V for 100% increment. While the phase (degree) of current were set such that; for phase A: 120^0; phase B: 0^0; phase C: 240^0. These values were adjusted so in order to make the current waveforms to closely follow the voltage waveform phases. Whereas, voltage drop is simply the subtraction of voltage at nonlinear load branch from the input voltage; the function was carried out using subtract block provided in Simulink.

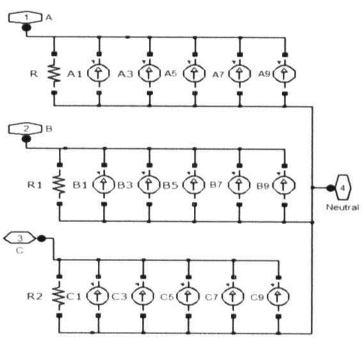

Fig. 4. Non-linear load model consisting of fundamental to 9th harmonic on each A, B and C phases

TABLE V. MAGNITUDE OF CURRENT HARMONIC INJECTION AT 100% INCREMENT FROM BASE CASE (A)

Harmonic Order	**Magnitude of Current Harmonic Injection (A)**		
	A	***B***	***C***
1	360	300	230
3	26.928	15.15	16.1
5	24.804	14.34	10.235
7	11.088	7.23	4.186
9	17.46	8.61	6.716

III. RESULTS AND DISCUSSIONS

A. Equipment Malfunction

High-tech medical equipment having integerated circuits built in them are sensitive to electrical and electromagnetic disturbances. In some cases, a temporary overvoltage can permanently damages power supply board of an equipment. From Table 1, there were numbers of LCD or display screen malfunction. Medical information displayed on cathode ray tubes (CRTs), liquid crystal displays (LCDs), films and printouts may be distorted by disrupted DC voltages powering the display, faulty data from memory, or a microprocessor failure. For instance, a waveform from an electrocardiograph printout may be disfigured, or film from an x-ray may have a white spot (a white area without any detail). Faulty data from memory or a microprocessor may also deteriorate the quality or resolution of an image captured by an imaging system.

However, the most common perpetrators that jeopardize microprocessor are power quality events such as voltage sags, voltage swells, voltage transients, and momentary power interruptions that cause switching of input and output of microprocessors from an on state to and off state. As one of undervoltage events triggered, DC voltage of an equipment decreases or one or more of the microprocessor inputs or outputs drop from an on state to an off state. Inversely, overvoltage events will cause opposite condition. In either case, data may be lost or disordered, or the microprocessor may lock up or otherwise misoperate. Additionally, such changes in logical states can alter stored data, such as the control parameters of a ventilator and imaging system. This might be the underlying power quality problem that had costed software reinstallation and recalibration as the final solution taken by the facility on such equipment.

B. Power Log Data Analysis

The analysis found that voltage harmonics and voltage THD were very low compared to standard limit of 3% and 5% respectively as stated in IEEE Std. 519 [14]. Hence this system is free from voltage harmonic problem. Meanwhile, individual current harmonics and current THD at phases were considered at a level that should be given attention. Meanwhile, individual current harmonics and THD at neutral was very high especially at 3rd and 9th harmonics averaging around 50% and 30% respectively. While current THD at neutral went from minimum 47% to 118% of fundamental. This result signifies a very high neutral current present in the neutral cable. Hence, it is crucial to study the effect of this current harmonic to phase and neutral cable.

The CBEMA-ITIC curve consisting 9 events under the curve indicated that the voltages are assumed to cause the load to drop out due to lack of energy. These events were voltage swell events. Accordingly, this enhance the investigation of the effect of aforementioned underlying current harmonic problem existed in the system to voltage drop in the phase cable.

C. Simulation Result

The result of the varied current harmonic percentage are shown below. The results in Table VI shows that, for this facility, the current harmonic percentage can penetrate up to approximately 120% of base value for phase A, approximately 160% for phase B and approximately 240% for phase C before the voltage drop limit of the phase cable are violated, the values are highlighted in the table. It can be said that the limits are far beyond excession especially for phase C hence it is estimated that the life of the cable will prolong for more years. Single phase C should be precedented as inlet point for medical electronics load especially the high-end one. While the neutral cable can withstand 30% of base case before the standard is violated. It was found that neutral current is 38 A_{rms} when the VNG is 3.8 V_{RMS}. Hence it is expected that neutral current reach 50 A_{RMS} at 30% increment case where VNG exceeds 4.96 V_{RMS}. High neutral current commonly related to the presence of third harmonic current where it is proven to be considerably high in the E2-4 feeder i.e. 7.48% (13.464 A) at phase A, 7% (8.05 A) at phase C and 5.05% (7.575 A) at phase B.

TABLE VI. VOLTAGE DROP AT PHASE CABLE A, B, C AND NEUTRAL-TO-GROUND VOLTAGE (VNG) AT NEUTRAL CABLE AS CURRENT HARMONIC PERCENTAGE IS INCREASED

Increment (%)	A(Y)	B(R)	C(B)	VNG
0	10.55	9.15	7.00	3.83
20	12.80	10.80	8.40	4.59
30	13.87	11.75	9.07	4.96
40	14.70	12.61	9.76	5.36
100	20.80	17.80	13.80	
120	22.75	19.5	15.10	
130	23.65	20.35	15.80	
150	25.50	22.00	17.25	
160	26.40	22.86	17.77	
180	28.20	24.50	19.00	
200	30.00	26.00	20.40	
230	32.53	28.60	22.33	
240	33.35	29.40	22.97	

Phase and neutral cables are important media in power distribution system. Phase conductor provides the required voltage to start, operate and turn off a device at end user's electrical outlet. Voltage drop higher than permissible limit will degrade the performance of the loads. While neutral cable serves as a path for return current from the load. Harmonic load injects current back to the power system through neutral cable, hence becomes neutral current. Neutral current higher than cable rating may damage the cable. In the simulation, it is found that as the neutral current increases, VNG increases as well as voltage drop. However, the factor of increment actually also depends on the magnitude of the cable impedance. In this simulation, the cable length was assumed 400 meters, eventhough it is not the precise cable length, the resulting VNG at base case approximates the measured data. A thorough and unambigous study of the building's power system must be done in the future to produce better results.

At present, cable rating calculation method take into account only the fundamental frequency current and the simplified method harmonic ccurrents in the phase conductors. In reality, the neutral cable can carry both fundamental frequency and harmonic currents (induced and unbalanced), leading to a further increase of cable temperature. In view of the increased harmonics and load imbalance in power distribution systems and the need to determine their impact on cables, this paper presents a method to estimate the maximum value of current harmonics that can be contained by the phases and neutral cables.

IV. CONCLUSION

This study provides prediction to control harmonic current instead of implementing harmonic mitigation in order to maintain the phase and neutral cable life and the performance of the electrical system from the impact of very high current pulled by nonlinear loads. The voltage drop at phase cables during nonlinear load loading had been presented in this paper as well as the affected VNG until their standard limits were exceeded. Since utility has no authority to control consumer load, as well as the facility management has no power to control loads that are coming into its system, the percentage increment as predicted in the paper are not impossible to be one day, amassed in the system with the fast changing technology era we are currently in. It is hoped that the method will contribute in a way for the facility to manage its load installation. However, the result would be useless without a tool to monitor the current harmonics accumulating in the feeder cables since the limit violation will go unnoticed without action be taken. Thus, further work is suggested to realize this idea into a working tool with suggested indicator lamps i.e red, yellow, green being employed as proposed in [4] for user-friendly feature. It is also recommended that the existing cable derating factor is revised so as to include unbalanced load and harmonics in determining the increase in cable loading.

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REFERENCES

[1] Adamu, S. S., Muhammad, H. S., & Shuaibu, D. S. (n.d.). Harmonics Assessment and Mitigation in Medical Diagnosis Equipment, 70–75.

[2] Ramirez-castro, D., Neill-camllo, E. O., & Santiago-p, J. (n.d.). Assessment of Harmonics at a Medical Facility, 619–624.

[3] Fayyaz Akram, M., & Mumtaz Bajwa, S. (2001). A sample power quality survey for emerging competitive electricity market in Pakistan. *IEEE International Multi Topic Conference*, 38–44.

[4] Ignatova, V., & Villard, D. (2015). Simple Indicators for an effective Power Quality Monitoring and Analysis.

[5] Orfanos, C. N., Topalis, F. V, & Ieee, M. (2000). Single-phase virtual power and energy analyzer in compliance with IEEE Std 1459-2000 for harmonic measurements on discharge lamps.

[6] H.J. Koster, F. Weinkel, "Voltage and current harmonics in low and medium voltage networks, Elektrizitatwirschaft". Vol. 88, pp. 759-764, 1989.

[7] I.M. Nejdawi, A.E. Emanuel, D.J. Pileggi, M.J. Corridori, R.D. Archambeault, Harmonics trend in NE USA:A preliminary survey. IEEE Trans. On Power Delivery, Vol. 14, No. 4, 1999, pp. 1488-1494.

[8] Daloub, L. M. (2011). Power Quality Optimization and Reactive Power Control by Modeling of SVC in Healthcare Centre, 1–5.

[9] Chen, T., & Yang, W. (2001). Analysis of Multi-Grounded Four-Wire Distribution Systems Considering the Neutral Grounding, *16*(4), 710–717.

[10] IEEE Working Group on Power System Harmonics, "Power System Harmonics: An Overview", *IEEE Trans. On Power Apparatus and Systems*, vol. pas-102, pp. 2455-2460, 1983

[11] Kersting, W.H. "A Three-Phase Unbalanced Line Model With Grounded Neutrals through a Resistance", Panel Discussion on Stray Voltage Analysis Techniques, *Proceedings of 2008 IEEE PES General Meeting*, Pittsburgh, PA. 2008.

[12] Sunderman, W.G., Dugan, R.C. and Dorr, D.S. "The Neutral-to-Earth Voltage (NEV) Test Case and Distribution System Analysis" in *Proceedings of 2008 IEEE PES General Meetting*, Pittsburgh, PA. 2008.

[13] IEEE 1159-1995 " Recommended Practice for Monitoring Electric Power Quality", IEEE Standards Coordinating Committee 22 on Power Quality, 1995.

[14] IEEE 519-2014 "Recommended Practice and Requirements for Harmonic Control in Electric Power Systems", IEEE Power and Energy Society, *2014*.