Investigation of Power Quality at a Distribution Network in Brunei Darussalam

Hjh Zuriayati, S.P. Ang, M.A. Salam, Pg Jamra Weira

***Abstract*-- As more industries and residential development are rapidly increasing in the state, PQ monitoring needs more attention by the industry. The IEEE 519-1997 standards are currently used to maintain the PQ level within Brunei Darussalam's network. This paper presents an investigation on the PQ related issue of a particular 11kV distribution network. The aim is to look into the impacts of PQ issues in particular the presence of harmonics on the 11 kV network. The study is carried out by modeling the network using power simulation software, ERACS.**

***Keywords*: Distribution network, harmonics, triplen, Dy11, Dyn11, neutral current, square waveform harmonics, total harmonic distortion**

I. INTRODUCTION

POWER Quality (PQ) problems or issues arise when the sinusoidal waveform of both voltage and current is distorted in any way from a pure sine wave in terms of magnitude, frequency or purity [1]. Power Quality is becoming increasingly important due to the increasing use of power electronic devices, coupled with the increasing penetration of loads, which are sensitive to voltage disturbances [2]. The increased number of PQ-related problems in recent years had led to several studies and research in this subject area. This concern is because of the influence of two simultaneous trends: the first is the increasing use of power electronic controllers that usually draw current which is not sinusoidal. The increasing use of loads such as personal computers, industrial controllers, microprocessor-based controllers and power electronic devices is the second trend that are sensitive to voltage disturbances. With more large nonlinear power electronic converters being utilized, power system waveform distortion has called for the development of stringent harmonic distortion control limits by several agencies around the world. Philip P. Barker et al. [3] have discussed several major points which a utility should keep in mind when assessing their networks power quality. The study concluded the cause(s) of poor power quality can only be identified by simultaneous recording of both primary and secondary disturbances. Jan J.M. Desmet et al. [7] experimentally concluded that an asymmetry up to 10 or an unbalance of 10% in the power supply has only a minor effect on the r.m.s value of the neutral conductor current. An unbalance in load conditions increases the neutral conductor current. Harmonics in the power supply voltage highly affects the r.m.s value of the neutral conductor current.

In this paper, the PQ related issues of a particular 11 kV distribution network are evaluated with the aim to determine the maximum fundamental current value which place the total harmonic distortion (THD) % limits for current and voltage within the IEEE 519-1992 standard and how the harmonics would impact the network by connecting a non-linear load with this fundamental value at the 415 V busbar. A worst case scenario is illustrated by injecting a square waveform in the network. Different load scenarios are considered at the 415 V busbar and analysis is carried out by ERACS software.

II. SINGLE LINE DIAGRAM OF 11 KV DISTRIBUTION SYSTEM

A particular 11 kV Distribution network is considered from the Department of Electrical Services network as shown in Fig. 1. This network is used to supply power to a light industrial area, which mostly consists of workshops, packing and crystal ornament manufacturing factories.

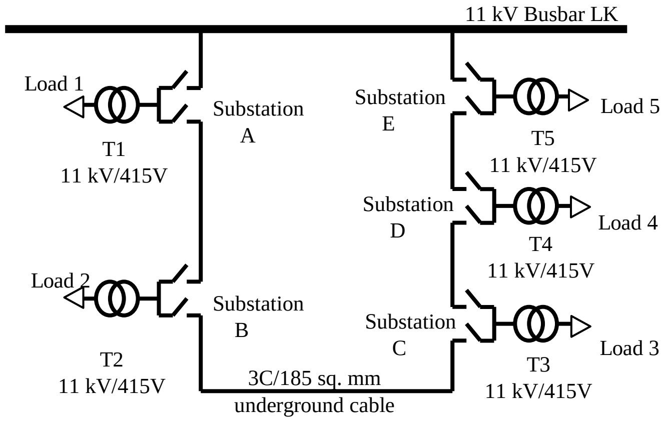

Fig. 1. Single-line diagram of the 11 kV distribution system.

The network consists of the following data: There are five units transformers each of rating of 1 MVA, 11 kV/415 V connected to the respective busbars as shown in Table 1.

The loads connected at the secondary substations are actual loads that are connected as shown in Table 2.

The secondary substations are connected by 3C/185 sq.mm cable with parameters shown in Tables 3 and 4.

Hjh Zuriayati Hj Md Zainal is with Institute Technology Brunei, Brunei Darussalam (e-mail:hzuriayati@gmail.com)

S.P. Ang is with Institute Technology Brunei, Brunei Darussalam (e-mail: ang.swee.peng@itb.edu.bn).

M.A.Salam is with Institute Technology Brunei, Brunei Darussalam (e-mail: abdus.salam@itb.edu.bn).

Pg Jamra Weira Pg Hj Petra is with Department of Electrical Services, Brunei Darussalam (email: jamraweira@yahoo.com)

Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada July 18-20, 2013.

Table 1.
Substation Transformer Ratings

Transformer Name	Type	Voltage Ratio	Rating (kVA)	Impedance (%)
T 1	Dyn11	11 kV/433 V	1000	4.920
T 2	Dyn11	11 kV/433 V	1000	4.640
T 3	Dyn11	11 kV/433 V	1000	4.640
T4	Dyn11	11 kV/433 V	1000	4.640
T5	Dyn11	11 kV/433 V	1000	4.920

Table 2.
Connected loads

Load	Real Power (MW)	Apparent Power (MVAr)
Load 1	0.252	0.189
Load 2	0.275	0.207
Load 3	0.040	0.030
Load 4	0.244	0.183
Load 5	0.393	0.294

Table 3.
Cable parameters

Type of Cable	Resistance	Reactance	Capacitance
3C/185 sq.mm	0.128 Ω/km	0.097 Ω/km	0.370 µF/km

Table 4.
Cable length

Busbar	Length (km)
Busbar LK– Subs.A	0.600
Subs. A – Subs.B	0.450
Subs. B – Subs.C	0.250
Subs. C– Subs.D	0.100
Subs.D – Subs.E	0.400
Subs.E – busbar LK	0.700

III. Description of 11kV model

Fig. 2 shows the single-line diagram of the 11 kV network modeled in ERACS simulation software. All the components in the single-line diagram are modeled in ERACS. The normal open point in this network is at busbar 2’ as per actual normal operating configuration.

A. 11 kV busbar model

The 11 kV busbar is modeled with a default setting of three phase fault rating of 500 MVA and single phase fault rating of 700 MVA. The 11 kV busbar illustrates the switchgear busbars.

B. 415 V busbar model

The 415 V busbar is modeled with a default setting of three phase fault rating of 31 MVA and single phase fault rating of 45 MVA.

C. Grid Infeed model

The grid infeed is modeled with a three-phase fault level of 123 MVA and single-phase fault level of 106 MVA connected.

D. Transformer model

All the transformers employed in the network are modeled based on 1 MVA, 11 kV/433 V, ONAN delta-wye neutral connected (Dyn11) transformer. The parameters used to model the transformer are shown in Table 1.

E. Load model

The load model employed at all the 415 V busbars are power shunts with fixed real power (P) and apparent power (Q) parameters as in Table 2.

F. Cable model

The cable is represented based on 3C/185 sq.mm XLPE cable. The parameters used to model are resistance, inductance, capacitance and length of cable as in Tables 3 and 4 respectively.

G. Switch/ Circuit breaker model

The switch or circuit breaker is modeled with default settings taken from adjacent busbar.

IV. Load Flow Study

The simulation model of the 11 kV network is validated by carrying out load flow study and comparing it with another software, IPSA. The results are shown in Tables 5, 6 and 7 respectively.

In Brunei the specified acceptable limit for voltage tolerance is ± 5% (0.95 – 1.05 p.u) of one per unit. It is found that the power flow data are within the acceptable limit.

Table 5.
Comparison of branch in load flow study between ERACS and IPSA

Bus-bar	ERACS		IPSA		% Deviation	
	Real Power (MW)	Reactive Power (MVAr)	Real Power (MW)	Reactive Power (MVAr)	Real Power	Reac-tive Power
6 - 1’	0.53	0.40	0.53	0.41	0.00	-2.5
1’- 1	0.25	0.19	0.25	0.19	0.00	0.00
1’- 2’	0.28	0.21	0.28	0.21	0.00	0.00
2’- 2	0.28	0.21	0.28	0.21	0.36	0.00
2’- 3’	0.00	0.00	0.00	0.00	0.00	0.00
3’- 3	0.04	0.03	0.04	0.03	0.00	0.00
3’- 4’	0.04	0.03	0.04	0.03	0.00	0.00
4’- 4	0.24	0.19	0.24	0.19	0.00	0.00
4’- 5’	0.29	0.21	0.28	0.22	3.45	-4.76
5’- 5	0.39	0.31	0.39	0.31	0.00	0.00
6 – 5’	0.68	0.50	0.68	0.52	0.00	-4.00

Table 6.
Comparison of Grid infeed in loadflow study between ERACS and IPSA

	ERACS		IPSA		% Deviation	
	Real Power (MW)	Reactive Power (MVar)	Real Power (MW)	Reactive Power (MVar)	Real Power	Reac-tive Power
Grid Infeed	1.21	0.90	1.20	0.93	0.83	-3.33

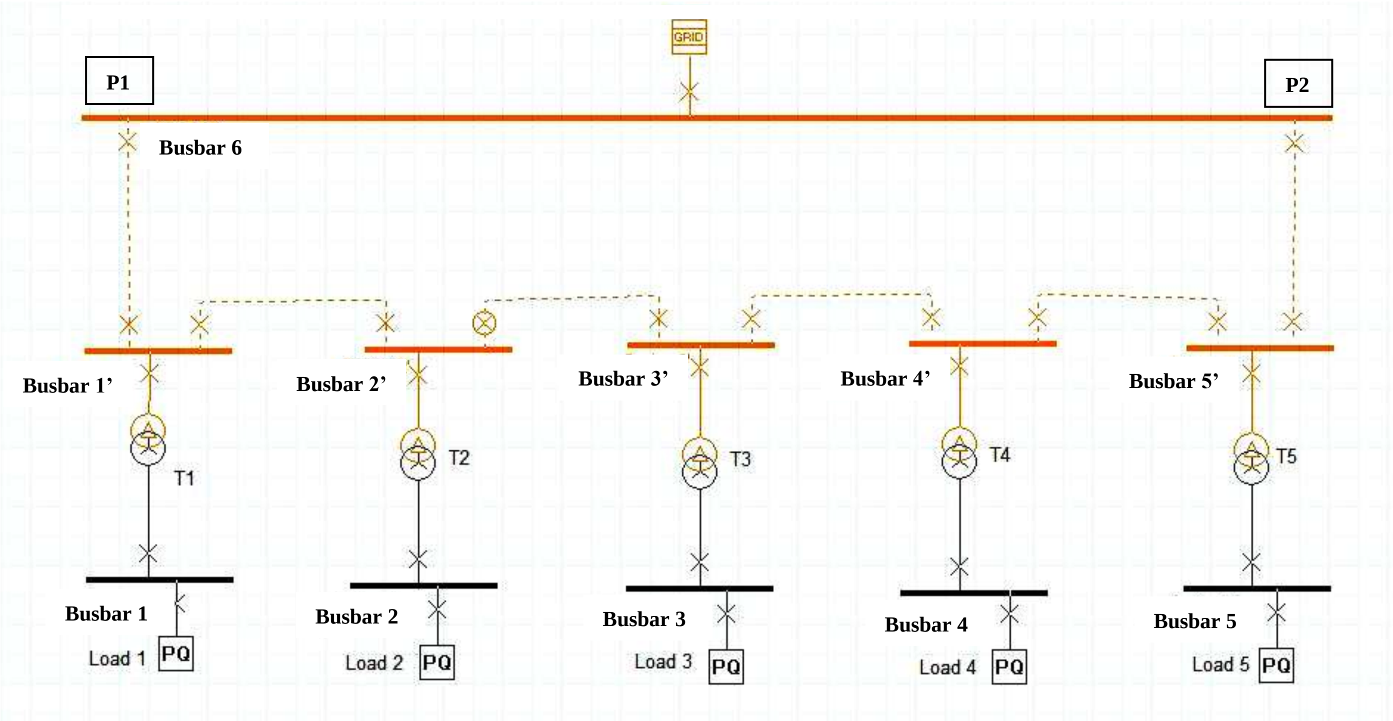

Fig. 2. 11 kV network model in ERACS

TABLE 7.
COMPARISON OF BUSBAR VOLTAGE IN LOADFLOW STUDY BETWEEN ERACS AND IPSA

Bus-bar	ERACS		IPSA		% Deviation	
	Voltage (p.u)	Angle (°)	Voltage (p.u)	Angle (°)	Voltage	Angle
6	1.00	0.00	1.00	0.00	0.00	0.00
1’	0.99	0.00	0.99	0.00	0.00	0.00
1	1.03	-0.66	0.99	-0.70	3.88	6.10
2’	0.99	0.00	0.99	0.00	0.00	0.00
2	1.03	-0.67	0.99	-0.70	3.88	4.50
3’	0.99	0.00	0.99	0.00	0.00	0.00
3	1.04	-0.10	0.99	-0.10	4.04	0.00
4’	0.99	0.00	0.99	0.00	0.00	0.00
4	1.03	-0.60	0.99	-0.70	3.88	17.0
5’	0.99	0.00	0.99	0.00	0.00	0.00
5	1.02	-1.03	0.98	-1.10	3.92	6.79

V. HARMONICS SIMULATION STUDY

For the purpose of this study, a current harmonic source is used as the current distortion which is constant and independent of any distortion in the supply system for many nonlinear devices. The harmonic content derived from the Fourier series of the square waveform is use to represent a typical nonlinear load. The square waveform is also the foundation of many nonlinear devices [1], [4].

Initially, two sensitivity studies on the impact of square waveform on busbars 1, 1’ and 6 in Fig. 2.with different values of fundamental current were carried out. Each study is carried out with different vector type of transformer namely the Dy11 and Dyn11 to study the effect of the grounded neutral. These initial studies were done to acquire the maximum fundamental current to produce both current and voltage Total Harmonic Distortion (THD) within the IEEE 519-1992 standard range at the secondary winding of the transformers. The recommended IEEE 519-1992 standard limits for current harmonics is 8% while for voltage harmonics is 5%.

In the first study using the Dy11 transformers, it was found that at fundamental current 5.94 A, the voltage THD (%) had reached 9999 %. Table 8 shows the comparison of voltage and current THD at busbar 1, 1’ and 6 for both sensitivity studies at this point. It is observed that voltage THD (%) is very much higher in busbar 1 for Dy11 than Dyn11. It is also observed that the current THD (%) at busbar 1, 1’ and 6 from both studies are the same. This indicates that in the Dyn11, the triplen harmonics add in the neutral at the wye side. The ampere-turn balance in the delta allows the ‘triplens’ to flow but remains trapped in the delta. When the load is balanced, the ‘triplens’ behave as zero sequence components therefore does not show up in the line currents at the delta side [1].

Fig. 3(a) shows that the maximum fundamental current for the second study within the IEEE 519-1992 standard voltage THD (%) limit of 5% is 2556 A. At this point, the current THD (%) is above the IEEE 519-1992 standard current THD limit at approximately 173.9 %.

Fig. 3(b) shows that the maximum fundamental current for the second study which will be within the IEEE 519-1992 standard current THD (%) limit of 8% is 117.7 A. At this fundamental current, the voltage THD (%) at busbar 1 and busbar 1’ is 1.82 and 0.23 respectively.

For the voltage THD (%) and current THD (%) at busbar 1’ to be within the recommended IEEE 519-1992 standard limits for current and voltage harmonics, the fundamental current used in this subsequent simulation is 117.7 A. The vector group for the transformers used is Dyn11. A square current waveform with this maximum fundamental value is then injected into loads 1, 2, 3, 4 and 5 in turns to look into how the characteristics of the nonlinear loads impact different parts of the network.

From this study, it was observed that the THD (%) for current harmonic is higher than the IEEE 519-1992 standard at the path where the harmonic source is injected as shown in Table 9. This is because the current harmonics usually flows back into the power system through the shortest path of low impedance [5]. It was observed in Table 10, the voltage THD (%) at each point of injection is within 5% range of the voltage THD (%) in the sensitivity study.

TABLE 8
COMPARISON OF CURRENT AND VOLTAGE THD AT BUSBAR 1 USING Dy11 AND Dyn11 TRANSFORMERS AT 5.94 A

	Busbar	**Dy11**	**Dyn11**
Simulated current THD (%)	1	0.65	0.65
	1’	0.40	0.40
	6	0.20	0.20
Simulated voltage THD (%)	1	9999	0.09
	1’	0.01	0.01
	6	0.01	0.01

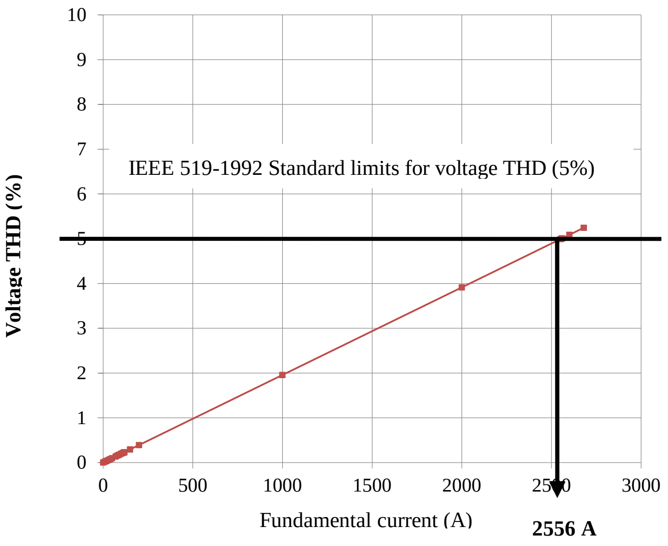

Fig. 3(a). Result curve of voltage THD (%) at busbar 1’.

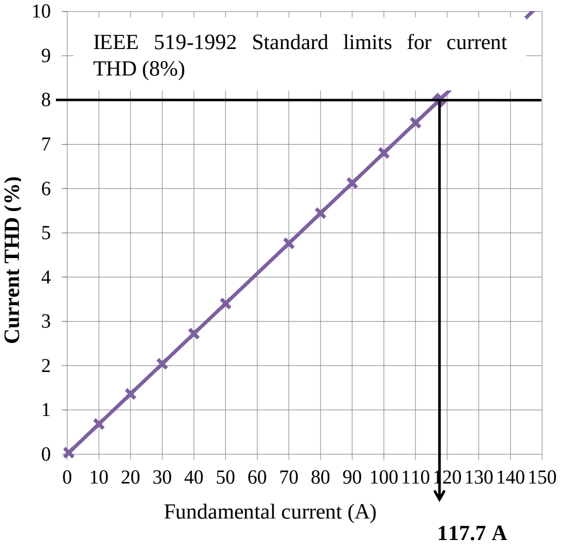

Fig. 3(b). Result current of current THD (%) at busbar 1’.

TABLE 9
CURRENT THD (%) AT VARIOUS BUSBAR

Injected point at nonlinear Load	**Current THD(%) at busbar**										
	1	**1’**	**2**	**2’**	**3**	**3’**	**4**	**4’**	**5**	**5’**	**6**
Load 1	**12.85**	**8.01**	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	1.72
Load 2	0.04	0.04	**11.76**	**7.33**	0.03	0.03	0.03	0.03	0.03	0.03	1.72
Load 3	0.03	0.03	0.03	0.03	**81.67**	**50.90**	0.04	0.04	0.04	0.04	1.72
Load 4	0.03	0.03	0.03	0.03	0.04	0.04	**13.28**	**8.28**	0.04	0.04	1.72
Load 5	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	**8.19**	**5.11**	1.73

TABLE 10
VOLTAGE THD (%) AT VARIOUS BUSBAR

Injected point at nonlinear Load	**Voltage THD(%) at busbar**										
	1	**1’**	**2**	**2’**	**3**	**3’**	**4**	**4’**	**5**	**5’**	**6**
Load 1	**1.82**	0.23	0.23	0.23	0.22	0.22	0.22	0.22	0.21	0.22	0.22
Load 2	0.23	0.23	**1.75**	0.24	0.22	0.22	0.22	0.22	0.21	0.22	0.22
Load 3	0.21	0.22	0.21	0.22	**1.73**	0.24	0.22	0.23	0.22	0.22	0.22
Load 4	0.22	0.22	0.22	0.22	0.23	0.23	**1.75**	0.23	0.22	0.22	0.22
Load 5	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	**1.83**	0.22	0.22

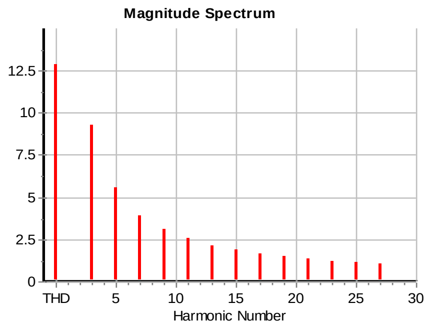

Fig. 4(a) Current harmonics spectrum at the point of injection at busbar 1

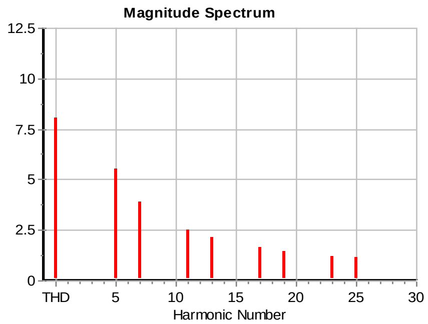

Fig. 4(b) Current harmonics spectrum waveform at busbar 1’

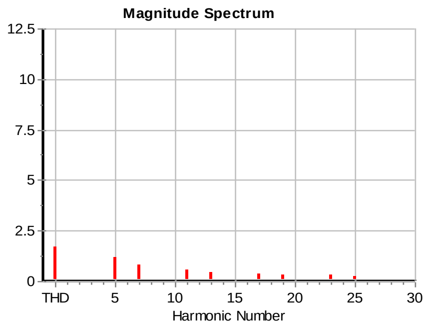

Fig. 4(c) Current harmonics spectrum at busbar 6

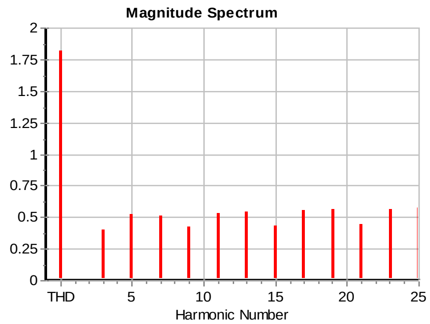

Fig. 5(a) Voltage harmonics spectrum at the point of injection at busbar 1

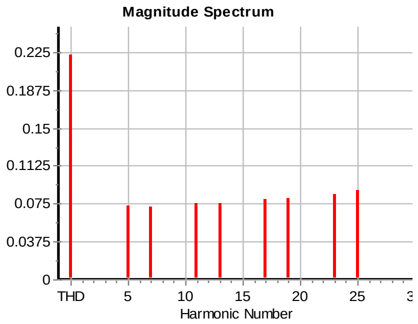

Fig. 5(b) Voltage harmonics spectrum at busbar 1’

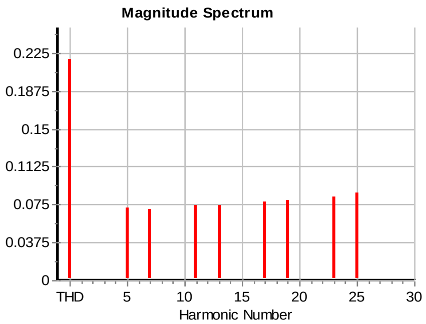

Fig. 5(c).Voltage harmonics spectrum at busbar 6

The harmonics i.e 5th, 7th, 9th orders, caused by nonlinear loads usually cancel each other out with the exception of the “triplen”. These “triplen” are additive in the neutral wire. The consequence of these harmonic currents may cause two major problems i.e. (i) increase the I^2R losses and (ii) reduced system capacity in the system [6]. It was also observed that the current and voltage THD (%) at the 11 kV busbar 1’, busbar 2’, busbar 3’, busbar 4’ and busbar 5’ have decreased as the harmonics passed through the transformers as shown in Tables 9 and 10.

It can be noted that the current THD (%) is higher when the load is lighter at Load 3 and lower current THD (%) at heavier load at Load 5. This confirms that at a lighter load, the transformer magnetizing current in the core will often raise the current harmonics to their maximum levels [10].

It was also observed that the “triplen” or harmonics divisible by three had been filtered out as shown in Figs. 4(a) the current spectrum at busbar 1, 4(b) the current spectrum at busbar 1’ after passing through the transformer, 4(c) the current spectrum at busbar 6 at the main 11 kV busbar, 5(a) the voltage spectrum at busbar 1, 5(b) the voltage spectrum at busbar 1’ after passing through the transformer and 5(c) the voltage spectrum at busbar 6 at the main 11 kV busbar respectively. This is due to the characteristics of the three phase delta-wye transformer. The delta winding provides a path for the harmonics to flow thereby reducing the third harmonics [1], [8]. This reduction will only be effective if the voltages are balanced [10].

It can also be observed that in Fig. 4(a), only the current THD (%) is reduced from 12.89% at busbar 1 to 8.03% at busbar 1’ as shown in Fig. 4(b). The magnitude of the current spectrum in Fig. 4(a) and 4(b) remains the same. At busbar 6, both the magnitude of the current spectrum and the current THD (%) is reduced further as shown in Fig. 4(c).

When the harmonic square wave was injected at load 3, it was also observed that at the cable point connecting busbar 3’ from busbar 2’, even though there is no current passing through from busbar 2’ to busbar 3’, there is a current THD (%) of 4.18%. This is due to the fact that the fundamental component is very small at that point thereby increasing the THD (%) value. The current THD (%) is also due to induced current harmonics by the capacitive component in the cable. A simulation is done to verify this statement by changing the capacitance parameter at cable between busbar 2’ and busbar 3’ to zero. The result is as expected, the current THD (%) drops down to zero.

Using oversized and special transformers to accommodate 3rd harmonic currents will avoid harmonic overloads in the system but will waste energy. The only harmonic mitigating method to save energy and reduce facility operating costs is by actually eliminating the 3rd harmonic current flow.

A K-rated zig-zag transformer or a three winding transformer can be placed near the load to cancel the harmonic currents especially the ‘triplen” in the transformer secondary winding. This transformer acts as a filter by having a low impedance neutral connection.The transformer will also reduce transformer heating [1], [6]. It is also essential to make sure that the voltages are balanced [10].

The effects of current harmonics on cables will overload both phase and neutral conductors. Usually, the neutral conductor cross-sectional area is sized smaller or equal to the phase conductors and the neutral to be shared among the lines.

Due to the electromagnetic effects which occurred in the non-linear loads and real current flowing through the neutral, the cross-sectional area should be larger or equal to the phase conductors. Separate neutral conductor for each line should also be considered [7].

VI. CONCLUSIONS

From this study, the voltage and current harmonics from the loads did not exceed the limits at busbar 6 due to the filtering in the Dyn11 transformers. The current harmonics is also very dependent on the size of the nonlinear loads. At lighter loads, the transformer core magnetising current will increase the current harmonics to its maximum level. The neutral cable sizing of the transformer is also important as most of the harmonics flows out of the system through the neutral as can be seen from the sensitivity studies.

With the rise of more and more heavy industries and residential areas in Brunei, reinforcement on power quality standards and policies for distribution network have to be strengthen, complying the international standards IEEE 519-1992 so as to protect the network's reliability and assets. The use of special transformers such as K-rated zig-zag at strategic locations where harmonics are detected would be more economical and practical in reducing the current harmonics.

The investigation done in this paper is by no means final, further research and onsite PQ monitoring will be carried out at different distribution sites and sector to determine the trends and other power quality phenomena experienced in Brunei Darussalam's distribution network to further ensure the quality and reliability of the network.

VII. ACKNOWLEDGMENT

The authors would like to gratefully acknowledge the Department of Electrical Services, Offices of Minister of Energy, Brunei Darussalam for their technical support.

VIII. REFERENCES

[1] Roger C. Dugan,Mark F.McGranaghan, Surya Santoso, H.Wayne Beaty, *Electrical Power Systems Quality Second Edition*, Tata McGraw-Hill, 2008, pp. 6, 179, 241.

[2] E.C. Bentley, G.A. Putrus, S. McDonald, P. Minns, "Power quality disturbance source identification using self-organising maps", *IET Gener. Transm. Distrib*., Vol. 4, No. 10, pp. 1188–1196, 2010.

[3] Philip P. Barker, James J. Burke, Thomas A. Short, Cheryl A. Warren, Clayton W. Bums, Jerome J. Siewierski, "Power Quality Monitoring Of A Distribution System", *IEEE Transactions on Power Delivery*. Vol. 9, No. 2, pp.1136-1142, April 1994.

[4] Angelo Baggini, *Handbook of Power Quality*, John Wiley & Sons Limited, 2008, p. 188.

[5] Surya Santoso, *Fundamentals of Electric Power Quality*, University of Texas at Austin, Winter 2010 Edition, p. 200

[6] Michael Z. Lowenstein, "Eliminating Harmonic Neutral Current Problems", 2008, Transmission and Distribution Conference and Exposition, pp. 1-4.

[7] Prof Jan Desmet, Hogeschool West-Vlaanderen, Prof Angelo Baggini, "Harmonics - Neutral sizing in harmonic rich installations", Leonardo Power Quality Initiative (LPQI), June 2003.

[8] Martin J. Heathcote, *J & P Transformer Book – Twelfth Edition*, Newnes, 1998, p.18.

[9] Oscar Armando Maldonado Astorga, José Luz Silveira, Julio Carlos Damato, "The influence of harmonics from non-linear loads in the measuring transformers of electrical substations", 2006, International Conference of Renewable Energy and Power Quality, Paper ID:411

[10] Jos Arrillaga and Neville R. Watson, *Power System Harmonics – 2nd Edition*, John Wiley & Sons Limited, 2003, p. 63-64