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Harmonic Analysis of a Third Rail Systems: A Case Study in Malaysia

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Abstract

Harmonic distortion is one of the most important power quality issues in third rail electrification systems. The use of rectifiers and inverters in the third rail system can inject a significant amount of harmonic distortion to the electrical network. This paper aims to investigate the harmonic distortions for a DC urban third rail system at various operating conditions. The electrical network of Mass Rapid Transit Line 2 (MRT 2) Malaysia is modelled using ETAP software. The model had considered the effect of the inter-phase transformer in the 12-pulse rectifier. The current injection method is used to measure harmonic distortion at Point of Common Coupling (PCC) at the 132 kV and 33 kV buses. A normal and degraded operating conditions of power supply are investigated. From the simulation results, it is found that the 11th and 13th order harmonics have exceeded the statutory limit at 33 kV network for the normal operating condition. For the degraded operating condition, only the 11th harmonic order has exceeded the statutory limit.

Keywords: Harmonic Distortion; DC Urban Rail; Various Operating Conditions

I. Introduction

Urban rail transit with DC electrification system is recognized as an eco-friendly transportation system because of its relatively low carbon dioxide emission. In Malaysia, the DC urban rail transit is known as the mass rapid transit (MRT) [1]. It was developed under the Great Kuala Lumpur (GKL) plan to mitigate the traffic congestion and reduce carbon footprint. The MRT Line 2 (MRT 2) is expected to provide a rail transit service in 2021 [2], [3].

The development of DC third rail in a metropolitan area can effectively mitigate traffic congestion and reduce carbon footprint. However, it may also cause power quality issues such as the harmonic distortions. In general, the DC electrification system uses rectifiers to convert the AC into DC to provide power to the trains. In most cases, rectifiers are considered to be the main cause of harmonics due to the non-linear relationship between the voltage and current across the switching device [4].

The MRT 2 adopts the third rail system and operates at the standard voltage of 750 V DC for its economic features such as operate at low voltage, have high passenger capacity, and low-speed locomotive [5]. The third rail system, normally, received its supply from a three-phase distribution network at medium-voltage or high-voltage and then being rectified into DC supply by means of rectifiers. In this study, the conversion group consists of rectifier transformers and 12-pulse diode-uncontrolled rectifiers [6].

The presence of harmonic current can give rise to a variety of problems which include the overheating of equipment, low power factor, de-rating of cables, flicker, resonance, malfunction of protective relays, and interference with communication devices [7], [8]. Besides, harmonic currents generated by power electronic loads will produce harmonic voltages and affect the measurement of the electric energy metering. Therefore, it is important to mitigate the harmonic distortions to improve the system reliability [9], [10].

Various solutions have thus been proposed to overcome the harmonic distortions problem. Different harmonic suppression methods have been compared and discussed in [7]. There are many harmonic mitigation techniques available nowadays. One of the commonly used techniques to reduce harmonics is using a multi-pulse rectifier. The harmonic currents can be reduced by increasing the number of pulses of the rectifier. However, the multi-pulse rectifier always accompanied by an increase in cost as well as size [11].

A modern DC traction rectifier system uses 12-pulse or 24-pulse rectifiers for the rectification. However, the cost of the 24-pulse rectifier is higher than that of 12-pulse rectifier. A cost deduction can be achieved by paralleling two 12-pulse rectifiers in which each rectifier is supplied by rectifier transformers that have a 30° phase shift. The performance of this approach is similar to that of 24-pulse rectifier system while both transformer rectifiers are sharing the loads equally [12], [13], [14], [15].

Typically, the 12-pulse rectifier with inter-phase transformer (IPT) is adopted because it can absorb the voltage variation which aids in the improvement of power quality [16], [17]. Phase-shifting transformers are important as it can provide a cancellation of harmonic orders [18]. The delta-wye configuration of the rectifier transformer is available with several vector groups including with and without its neutral windings. The neutral on the wye-connected side is not accessible as it is not connected to the load. Consequently, there are no triplen harmonics in the line current [19]. The same configuration can be applied to a zig-zag transformer [14], [20].

Another harmonic mitigation strategy is to install harmonic filters. Harmonic filters are connected either in series or shunt to reduce the harmonic currents. Both connections can provide power factor correction and suppression of harmonics. There are three categories of filter, namely the passive filter, active filter, and hybrid filter [21].

A passive filter is composed of fixed inductors and capacitors, in certain cases, with additional resistance or reactor. It is an economical harmonics suppression device [22]. The reactive power compensation and harmonic suppression that can be provided by the passive filter are limited to a certain range and may not be able to provide satisfactory compensation performance under the dynamic loads. Furthermore, the characteristics of the passive filter may change depending on the temperature, ageing, or variation of system impedance which gradually leads to a risk of resonance [23], [24].

Active filters perform better than passive filter as it can eliminate numerous harmonic orders produced by dynamic loads and prevent the resonance from happening. However, active filters are expensive and required additional control strategy to ensure a good performance [25]. Alternatively, hybrid filters that combine the active filter and a passive filter can meet the cost-effectiveness at the same time achieve the desired harmonic suppression. In [26], a comparative study for the harmonic reduction capability of active and passive filters had been carried out. It is necessary to select the most appropriate mitigation method according to the applications [27].

The authors in [28] stated that the measurement procedures of power quality in common power systems and railway electrification systems are different as the electrified train is considered as non-linear and time-varying loads. To evaluate the harmonic content of the voltage and current, the total harmonic distortion (THD) is introduced.

In this paper, the harmonic analysis is carried out to evaluate the individual harmonic distortion (IHD) and THD of MRT 2 at point-of-common-coupling (PCC). The measurements of IHD in this paper are calculated up to 50th orders and various operating conditions of MRT 2 are taken into accounts.

II. Methodology

A. Simulation Model

In this study, the Electrical Transient and Analysis Program (ETAP) is used as a comprehensive analysis tool to perform the harmonic analysis for various operating conditions of MRT 2. The operating length of MRT 2 is approximately 52.2 km, of which 13.5 km is underground. A total of 36 stations, of which 11 of them are underground stations. MRT 2 is also known as the SSP line because it runs Sungai Buloh-Serdang-Putrajaya (SSP) of the GKL. The terminal end of the SSP line is the termini Damansara Damai station and termini Putrajaya Sentral station.

MRT 2 is powered by three BSSs namely, the Jinjang BSS, Kuchai Lama BSS, and UPM BSS. The power is then fed to 25 TPSSs, 20 UBs, 4 intervention shafts, and a Depot. There are 36 MRT stations out of which 16 MRT stations and three intervention shafts are fed through TPSS and the remaining are fed through UB.

Due to the complexity of the actual electrical network of MRT 2, a simplified electrical network of MRT 2 is shown in Fig. 1 which comprises of one simplified Bulk Supply Substation (BSS), one simplified Traction Power Supply Substation (TPSS), and one Utility Building (UB). The traction loads are represented as the DC static loads and their value varies depending on the TPSS. The types of circuit breakers used are High Voltage Circuit Breaker (HVCB), Low Voltage Circuit Breaker (LVCB), and DC Circuit Breaker (DCCB).

Two transformers are installed at each BSS to step-down the supply voltage from 132 kV to 33 kV. The modelling of the 33 kV distribution network is in a form of a redundant ring. For instance, two circuits for each substation. This is to ensure the normal operating condition when one transformer is out of service. An earthing transformer is installed to provide earthing for each BSS transformer. Table I and Table II show the parameters of BSS transformer and earthing transformer respectively.

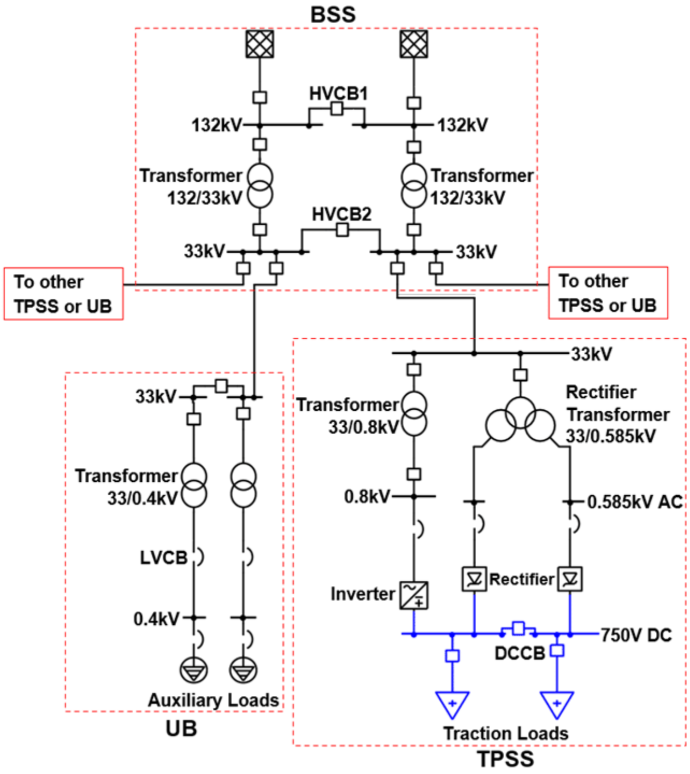

Figure 1: Simplified Electrical Network of MRT 2

TABLE I: PARAMETERS OF BSS TRANSFORMER

Parameters	Value
Rating (MVA)	50/ 40
Voltage level (kV)	132/33
X/R ratio	45
Impedance tolerance (%)	±7.5
Vector group	YNd1

TABLE II: PARAMETERS OF EARTHING TRANSFORMER

Parameters	Value
Rating (kVA)	160
Voltage level (kV)	33/0.4
X/R ratio	1.5
Impedance tolerance (%)	±10
Vector group	ZNyn11
Earth fault current limit (A)	900

The rectifier transformers in TPSS are designed to feed the rectifiers. Rectifier transformers are three-phase windings transformer with the phase shift of 30° are considered. The rectifier transformers step-down the voltage supply from 33 kV to 0.585 kV before it is fed into the rectifier for AC to DC conversion. Table III shows the parameters of the rectifier transformer. Vector group of various transformers are taken into considerations to mitigate the triplen harmonics.

TABLE III: PARAMETERS OF RECTIFIER TRANSFORMER

Parameters	Value
Rating (MVA)	2.3/ 3.5
Voltage level (kV)	33/0.585
X/R ratio	10
Impedance tolerance (%)	±10
Vector group	Dd0y11

The auxiliary service transformers are used to power the auxiliary loads and their ratings depend on the voltage requirement of the connected auxiliary loads. The parameters of the auxiliary service transformer are shown in Table IV.

TABLE IV: PARAMETERS OF THE AUXILIARY SERVICE TRANSFORMER

Parameters	Value				
Rating (MVA)	0.16/ 0.63	0.69	0.75/ 0.8/ 1/ 1.25	1.5/ 1.6/ 2/ 3/ 3.15	4
Voltage level (kV)	33/0.4	33/0.8	33/0.4	33/0.4	33/0.4
X/R ratio	1.5	3.5	3.5	6	8.5
Impedance tolerance	±10	±10	±10	±10	±10
Vector group	Dyn11	Dyn11	Dyn11	Dyn11	Dyn11

B. Harmonic Current Injection Method

Harmonic current injection method provided by ETAP is useful in the modelling of harmonic current sources. This method uses a mathematical approach of predicting the levels of harmonic distortion and the potential parallel resonance on an electrical network based on available system information. The parameters of harmonic current injection of the rectifier can be seen in Table V.

The harmonic analysis aims to identify the extent to which harmonics caused by rectifiers exist in the electrical network of MRT 2. The analysis includes the drawing of the electrical network of MRT 2, emphasizing the desired PCC, classification of harmonic current sources, modelling the components of MRT 2, measuring the IHD and THD at the PCC, and comparing the results obtained with the standards.

In this paper, two 12-pulse diode-uncontrolled rectifiers with the consideration of IPT are paralleled and connected to the 30° phase-shifted rectifier transformers to achieve an overall 24-pulse rectifier system. The 12-pulse diode-uncontrolled rectifiers are modelled to have a 0.96 lagging power factor and 98% efficiency. The IHD and THD are computed by ETAP at the PCC which are the 132 kV and 33 kV levels.

TABLE V: PARAMETERS OF HARMONIC CURRENT INJECTION OF RECTIFIER

Harmonic Order	Frequency (Hz)	Current Magnitude (%)
1	50	100
11	550	3.8
13	650	3.12
23	1150	1.18
25	1250	1.10
35	1750	0.59
37	1850	0.51
47	2350	0.25
49	2450	0.25

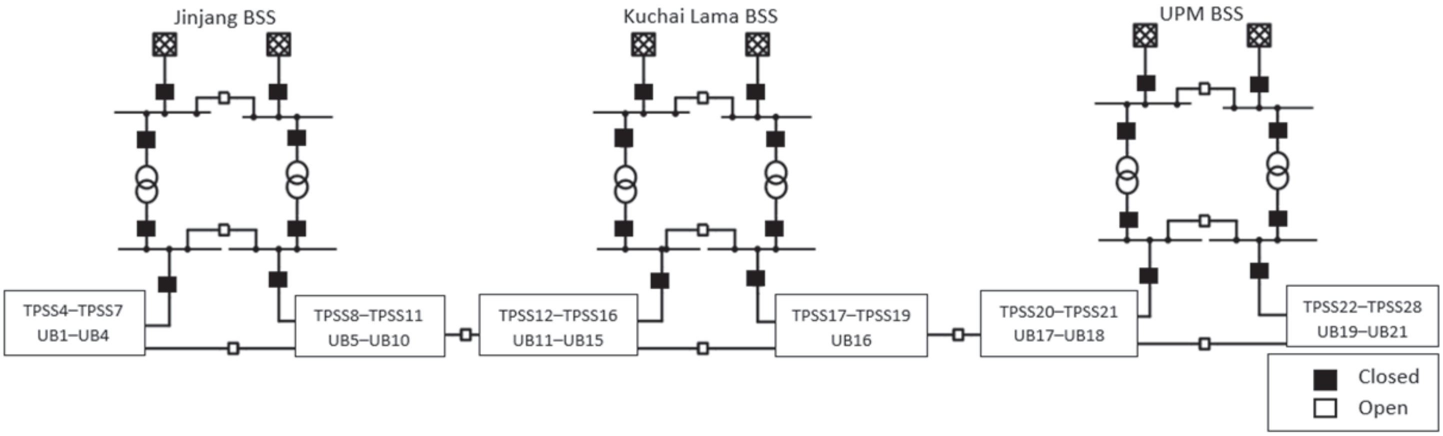

Figure 2: Normal Operation Condition of MRT 2

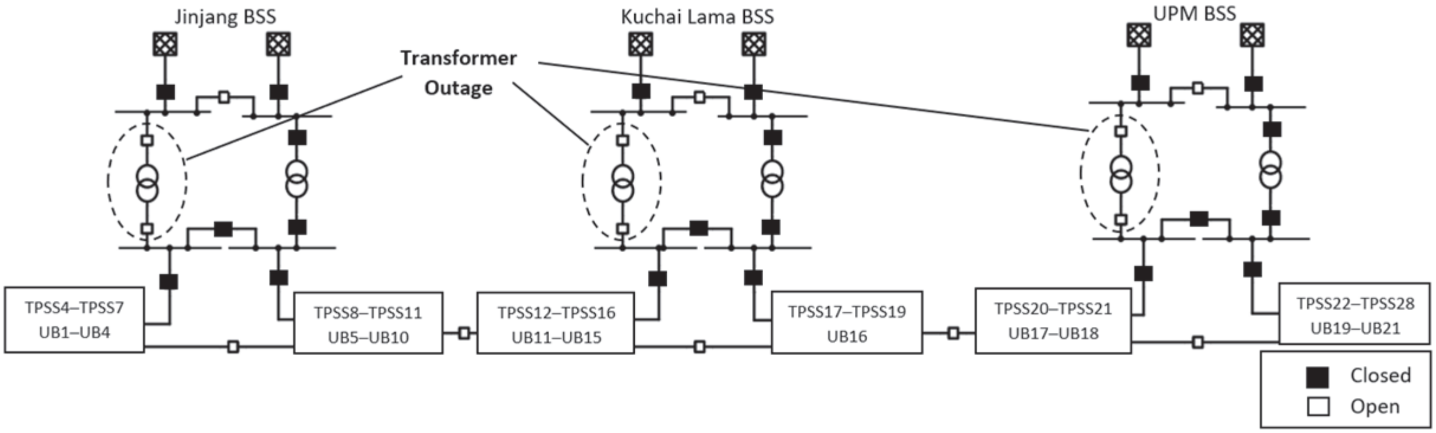

Figure 3: Degraded Operation Condition of MRT 2

C. Simulation of Different Operating Condition

Two different operating conditions of MRT 2 are considered for the harmonic analysis, namely the normal operating condition and the degraded operating condition. Both have the same electrical network but different settings.

The normal operating condition of MRT 2 is configured as in Fig. 2. The HVCB1 and HVCB2 are in open-circuit and each BSS is detached from each other. This configuration aims to assess and evaluate the harmonic analysis of the electrical network of MRT 2 under normal operating conditions.

The degraded operating condition of MRT 2 is configured as in Fig. 3. In this condition, the three BSSs are experiencing one transformer outage and all the TPSSs are powered by the unaffected BSS transformer. This can be achieved by completing the circuit of HVCB2 at the 33 kV distribution network. Consequently, the loads are equally shared.

III Standards

In this paper, the permissible limits of harmonic distortion in the electrical network of MRT 2 are referred to the IEEE 519-2014 standard [29].The measurement in THD for 132 kV and 33 kV is referred to the TNB Electricity Supply Application Handbook [30]. On the other hand, the measurement in IHD for 132 kV and 33 kV are referred to the UK Engineering Recommendation G5-4 [31]. The effects of IPT are considered as per the standard BS EN 50329 [32]. Therefore, the harmonic current emission is significantly low.

The harmonic current injection for auxiliary transformers and other non-linear loads such as uninterruptible power supply (UPS), variable-frequency drive (VFD) are ignored as the contribution from these are negligible compared to rectifiers. The contribution of VFD is minimal as it is short duration distortion as indicated in the UK Engineering Recommendation G5-4, section 9.

IV Results and Discussions

A. Harmonic Analysis for Normal Operating Condition

The harmonic analysis aims to evaluate the IHD and THD at PCCs of the electrical network of MRT 2 under normal operating condition. The PCCs are the 132 kV level and 33 kV Level of the Jinjang BSS, Kuchai Lama BSS, and UPM BSS for measurement of voltage harmonics. As for the measurement of current harmonics, the PCCs are only the 132 kV Level because it is closest to the grid.

Fig. 4 shows the harmonic spectrum of the Jinjang BSS, Kuchai Lama BSS, and UPM BSS at 132 kV level. The 11th and 13th harmonic orders are higher compared to other harmonic orders due to the usage of 12-pulse diode-uncontrolled rectifier. A 12-pulse rectifier generates the harmonics of order (h = 12k ± 1) where k is the positive integer. Hence, harmonics of the order of 11th, 13th, 23rd, 25th, 35th, 37th, 47th, and 49th are generated. The IHD_i of Jinjang BSS at 11th harmonic order is 2.98% while at 13th harmonic order is 2.72% which have exceeded the IEEE 519-2014 standard limit of 2.25%. The IHD_i of Kuchai Lama BSS at 11th harmonic order is 2.36% which has exceeded the IEEE 519-2014 standard limit of 2.25%. All the IHD_v is kept within the acceptable limits of the standard. The THD of the three BSSs at 132 kV level is kept within the IEEE 519-2014 standard limit as shown in Table VI.

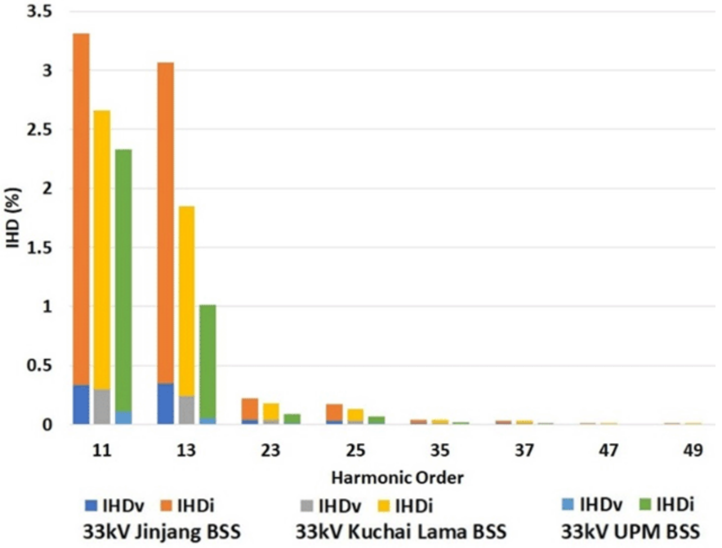

Figure 4: Harmonic Spectrum for Normal Operating Condition

TABLE VI: THD AND IHD OF NORMAL OPERATING CONDITION AT 132 KV

Harmonic Order	132 kV Jinjang BSS		132 kV Kuchai Lama BSS		132 kV UPM BSS		Limits	
	IHD_v (%)	IHD_i (%)	IHD_v (%)	IHD_i (%)	IHD_v (%)	IHD_i (%)	V (%)	I (%)
11	0.33	**2.98**	0.30	**2.36**	0.11	2.22	1.5	2.25
13	0.35	**2.72**	0.24	1.61	0.05	0.96	1.5	2.25
23	0.04	0.18	0.04	0.14	0.01	0.08	0.7	0.75
25	0.03	0.14	0.03	0.10	0.01	0.06	0.7	0.75
35	0.01	0.03	0.01	0.03	0	0.02	0.55	0.35
37	0.01	0.02	0.01	0.02	0	0.01	0.53	0.35
47	0	0.01	0	0.01	0	0	0.47	0.35
49	0	0.01	0	0.01	0	0	0.46	0.35
THD	0.482	4.04	0.384	2.86	0.120	2.42	3	6

Fig. 5 shows the harmonic spectrum of Jinjang BSS, Kuchai Lama BSS, and UPM BSS at 33 kV level. The IHD_v of Jinjang BSS at 11th harmonic order is 3.20% while at 13th harmonic order is 3.44% which have exceeded the IEEE 519-2014 standard limit of 3%. The THD_v of the three BSSs at 33 kV level is maintained within the IEEE 519-2014 standard limit of 5%. All the IHDs and THD at 33 kV level can be seen in Table VII.

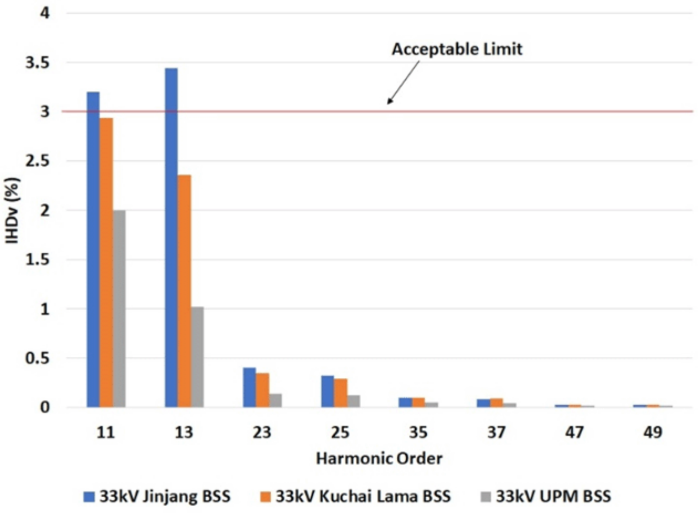

Figure 5: Harmonic Spectrum for Normal Operating Condition

TABLE VII: THD AND IHD OF NORMAL OPERATING CONDITION AT 33 KV

Harmonic Order	IHD$_v$ (%)			Limits (%)
	33 kV Jinjang BSS	33 kV Kuchai Lama BSS	33 kV UPM BSS	
11	**3.20**	2.94	2.00	3
13	**3.44**	2.36	1.02	3
23	0.40	0.35	0.14	3
25	0.32	0.29	0.12	3
35	0.10	0.10	0.05	3
37	0.08	0.09	0.04	3
47	0.03	0.03	0.02	3
49	0.03	0.03	0.02	3
THD$_v$	4.73	3.80	2.25	5

B. Harmonic Analysis for Degraded Operating Condition

The harmonic analysis aims to evaluate the IHD and THD at PCCs of the electrical network of MRT 2 under degraded operating condition. The impact of transformer outage on the harmonic distortion is considered.

Fig. 6 shows the harmonic spectrum of the Jinjang BSS, Kuchai Lama BSS, and UPM BSS at 132 kV level. The IHD$_i$ of Jinjang BSS at 11th harmonic order is 2.81% which has exceeded the IEEE 519-2014 standard limit of 2.25%. All the IHD$_v$ and THD are well-maintained within the IEEE 519-2014 standard limits as shown in Table VIII.

Fig. 7 shows the harmonic spectrum of Jinjang BSS, Kuchai Lama BSS, and UPM BSS at 33 kV level. The results show that the 11th harmonic order of Jinjang BSS and Kuchai Lama BSS is 4.20% and 3.46% respectively which have exceeded the IEEE 519-2014 standard limit of 3%. The THD$_v$ of the Jinjang BSS is 4.85% which is marginally maintained within the IEEE 519-2014 standard limit of 5%. The THD$_v$ for Kuchai Lama BSS and UPM BSS are kept within the IEEE 519-2014 standard limit of 5% which can be seen in Table IX.

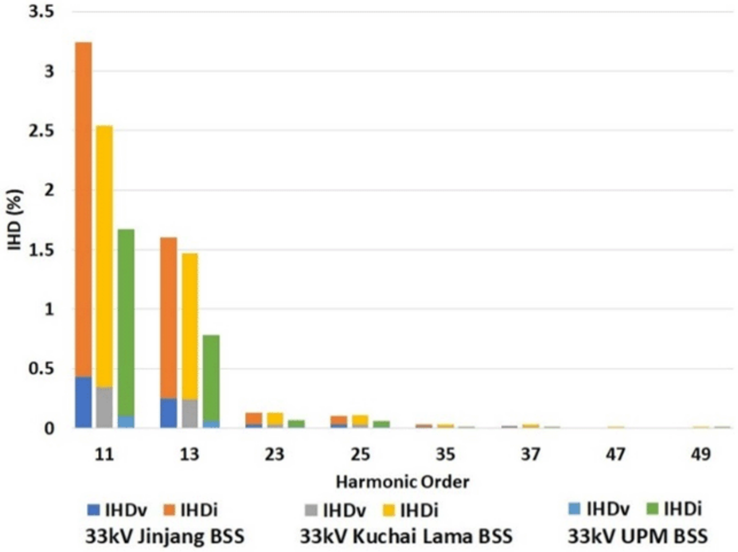

Figure 6: Harmonic Spectrum for Degraded Operating Condition

TABLE VIII: THD AND IHD OF DEGRADED OPERATING CONDITION AT 132KV

Harmonic Order	132 kV Jinjang BSS		132 kV Kuchai Lama BSS		132 kV UPM BSS		Limits	
	IHD$_v$ (%)	IHD$_i$ (%)	IHD$_v$ (%)	IHD$_i$ (%)	IHD$_v$ (%)	IHD$_i$ (%)	V (%)	I (%)
11	0.43	**2.81**	0.35	2.19	0.10	1.57	1.5	2.25
13	0.25	1.35	0.24	1.23	0.06	0.72	1.5	2.25
23	0.03	0.10	0.03	0.10	0.01	0.06	0.7	0.75
25	0.03	0.07	0.03	0.08	0.01	0.05	0.7	0.75
35	0.01	0.02	0.01	0.02	0	0.01	0.55	0.35
37	0.01	0.01	0.01	0.02	0	0.01	0.53	0.35
47	0	0	0	0.01	0	0	0.47	0.35
49	0	0	0	0.01	0	0.01	0.46	0.35
THD	0.502	3.12	0.427	2.51	0.120	1.73	3	6

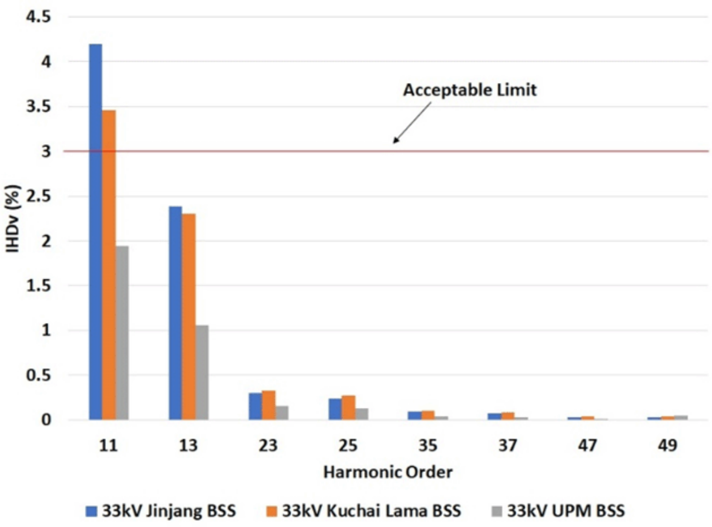

Figure 7: Harmonic Spectrum for Degraded Operating Condition

TABLE IX: THD AND IHD OF DEGRADED OPERATING CONDITION AT 33 KV

Harmonic Order	IHD$_v$ (%)			Limits (%)
	33 kV Jinjang BSS	33 kV Kuchai Lama BSS	33 kV UPM BSS	
11	**4.20**	**3.46**	1.94	3
13	2.38	2.30	1.06	3
23	0.30	0.33	0.16	3
25	0.24	0.27	0.13	3
35	0.09	0.10	0.04	3
37	0.07	0.08	0.03	3
47	0.03	0.04	0.01	3
49	0.03	0.04	0.05	3
THD$_v$	4.85	4.18	2.22	5

V Conclusions

Harmonic analyses are carried out on the electrical network of MRT 2 under the normal and degraded operating conditions. The simulations of the electrical network of MRT 2 are carried out with system information based on the actual data provided by the company. The results show that the 11th and 13th harmonic orders have the highest magnitude compared to the other harmonic orders. This is due to the use of the 12-pulse diode-uncontrolled rectifier. The THD$_v$ of Jinjang BSS is higher compared to that of Kuchai Lama BSS and UPM BSS because the traction load connected to the Jinjang BSS is higher. It is anticipated that no harmonic mitigation strategies are required despite certain IHDs have exceeded the IEEE 519-2014 standard limit because all the THD are still maintained within the IEEE 519-2014 standard limit.

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