Mitigation of harmonic distortions in third rail electrical systems

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ABSTRACT

The extensive use of power electronic converters in the third rail system increases the harmonic distortions on the rail electrical feeding systems. Electrical machines and transformers could be overheated causing premature failures of the devices. It is therefore important to address the harmonic distortions on the electrical networks during real-time operation, which includes the degraded operation, not just the normal operation. In this paper, the harmonic distortions of a third rail system are investigated using electrical transient and analysis program (ETAP) simulation software. Four operating scenarios, namely the normal operation and three degraded operations, are considered in the studies. The degraded operations occur when one of the bulk supply transformers or 33 kV feeders is out of service. The findings of the studies showed that the 11th and 13th order harmonics are the dominant harmonic orders due to the use of 12-pulse rectifiers on the third rail system. Single-tuned harmonic filters are designed and placed in the 33 kV feeders to mitigate the individual voltage harmonic distortion (IHD_v) and the total voltage harmonic distortion (THD_v) so that it is within the statutory of IEEE 519:2014.

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1. INTRODUCTION

In urban and suburban areas that typically adopt direct current (DC) third rail systems [1]–[3], the rolling stocks are powered by a 33 kV medium-voltage (MV) distribution network through rectifiers [4]–[6]. The abundant usage of rectifiers in the third rail systems can cause severe harmonic distortion [7]–[9]. Harmonic distortions give rise to many technical issues including degradation of transformers [10], [11] and electric motors [12], low power factor, malfunction of protective relays, increase of power losses, resonance [13], [14], and interference to communication devices [15]. For example, the use of 12-pulse rectifiers in the third rail system has generated a significant amount of 11th and 13th order harmonics, resulting in significant harmonic pollution to the rail system [16]. As a result, extensive study has been conducted to reduce the harmonic distortions of the rail electrical system.

The common rectifier schemes used in the DC third rail system are 6-pulse [17], [18], 12-pulse [5], [16], [19], 18-pulse rectifiers [20] and 24-pulse rectifiers [6], [21]. These rectifiers generate the characteristic harmonics in the order of ($h = nk \pm 1$) where n is the number of pulses and k is an integer number. The harmonic distortions of a higher pulse rectifier are lower than that of the lower pulse rectifier [22], and are often due to effects of phase shift transformer [21], [23]. A transformer with delta-wye windings which with- and without the neutral windings can eliminate the tripled harmonics [24].

The most common and simple way to attenuate harmonic distortions in an existing rail system is to add a harmonic filter such as the passive filter or active filter. There are several active filters being developed nowadays for harmonic mitigation of rail systems. The authors of [25] present a detailed control strategies utilized by active filters to reduce harmonic distortions. The filtering performance of an active filter depend on its control strategies including the reference current extraction [26]–[29], DC-link voltage regulation [30], current control [31], [32], and synchronization [33], [34]. Nevertheless, active filters are more frequently used in high-speed railway (HSR) because HSR produces uncertainty of high-frequency harmonic distortions [13], [35] and harmonic resonance [14], [36] which can cause the transient instability of the high-speed train (HST) tractive drive system and disrupt the operations of sensitive devices [37].

Passive filters which are simple [38] and lower cost than active filters, are available in a number of designs such as single-tuned, multi-tuned, high-pass, and C-type filters [39]. A single-tuned filter typically provides a low impedance path for the harmonic at a specific tuned frequency to reduce the harmonic distortions. The filter additionally offers reactive power compensation at the connected network. Assefa and Kebede [16], presented a single-tuned filter is used in DC rail systems to attenuate 11^{th} and 13^{th} order harmonics which are the dominant harmonic orders for the 12-pulse rectifier scheme. However, the single-tuned filters may fail to mitigate the harmonic distortions if the harmonic orders are inconsistent due to the dynamic changes of the non-linear loads [12], [14]. A comprehensive harmonic mitigation of a power system can be attained depending on the precise positioning and size of single-tuned filters [40].

Most of the existing research works focus on the harmonic distortions for a normal operating condition of power supply to the rail system. However, the rail system may undergo a degraded operation if the transformers or feeders have failed to operate. Although the degraded operations do not happen frequently, but once it happens, the single-tuned harmonic filters may fail to mitigate harmonic distortions to the network that potentially shut down the entire electrical network. There is no research work carried out to investigate the harmonic distortions on the third rail system under degraded operation scenarios.

This paper aims to investigate the effectiveness of single-tuned passive filters in mitigating the harmonic distortions on a third rail system under the normal operation and degraded operations. This is very important because the results can confirm the effectiveness of the single-tuned filters under various degraded operations in the rail electric network. The simulation studies are carried out by using electrical transient and analysis program (ETAP) software to model the distribution network of the mass rapid transit line 2 (MRT line 2) in Malaysia. The individual voltage harmonic distortion (IHD_v) and the total voltage harmonic distortion (THD_v) obtained from the simulation studies are benchmarked against the statutory limits of IEEE 519:2014 standard [41].

The paper is organized as follows: section 2 describes the modeling of the MRT line 2 electrical network. Section 3 explains the methodology used to perform the harmonic analyses and the filter design. The results and discussion of the analyses are presented in section 4. Finally, the paper is concluded in section 5.

2. MODELING OF MASS RAPID TRANSIT LINE 2 ELECTRICAL NETWORK

In this study, the power distribution network of MRT line 2 in Malaysia is modeled in ETAP software. The total length of MRT line 2 is 52.2 km with a total of 37 stations. MRT line 2 adopts a third rail system with 750 V DC supply. There are three bulk supply substations (BSSs), 25 traction power substations (TPSSs), and 21 utility buildings (UBs) to provide power to the entire rail system as shown in Figure 1. The numbering of TPSS begins with 4 because TPSS1 to TPSS3 have been assigned to MRT line 1 which is not shown in Figure 1.

The BSS receives power supply from the local 132 kV high-voltage (HV) grid and steps down to 33 kV MV distribution network via two 40 or 50 MVA BSS transformers. The MV is further stepped down from 33 kV to 0.585 kV at the TPSS via rectifier transformers. The 0.585 kV AC supply is rectified to 750 V DC supply by rectifiers and then being supplied to the trains via the third rail. A simplified electrical network for the third rail power supply and distribution is shown in Figure 2 where it comprises of a BSS with one double-fed bulk supply substation feeders, one TPSS, and one UB.

The principle of redundancy is adopted at each TPSS to ensure the continuity of train service. A redundant ring network topology is implemented where two circuits are used for each substation. Two 6-pulse diode-uncontrolled rectifiers are connected in parallel and each pair of its rectifier transformer is configured to have a phase shift of 30˚.

The UB is equipped with two auxiliary service transformers to provide electricity to the platforms and substations. These transformers feed the fundamental loads such as the substation control system, lighting systems, and air-conditioning systems. In the simulation, the auxiliary loads are modelled as a lumped load with its power factor of 0.9 lagging. It is a common practice that the vector group of transformers with delta-wye windings is selected to suppress the third order harmonic in the rail electrical system. Therefore, in the later simulation, third order harmonic is insignificant. The vector group of the transformers are obtained from the manufacturer's datasheet [42].

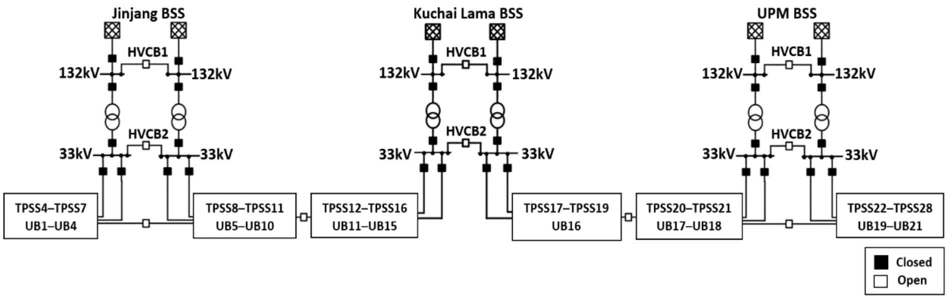

Figure 1. The power distribution network of MRT line 2

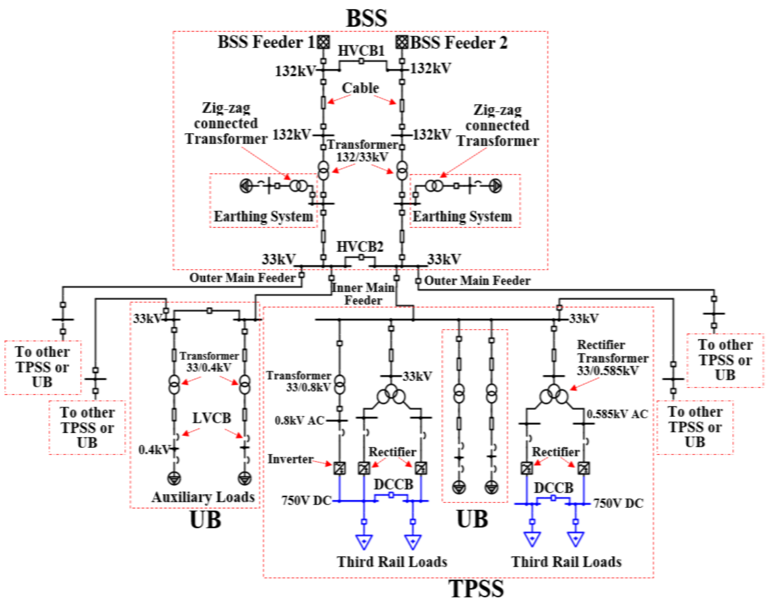

Figure 2. Simplified electrical network for the third rail power supply and distribution

3. METHODOLOGY

The power distribution network of MRT line 2 is modeled according to the data provided by the project developer. The adaptive Newton-Raphson method is used in the ETAP simulation for harmonic analyses because it is the most widely adopted method for calculating harmonic distortions. This method uses a fine iteration step to simulate the harmonic distortions of the network, hence providing a fine analysis of the harmonic distortions. Passive filters are designed and placed at the 33 kV distribution network of MRT line 2 to mitigate the harmonic distortions. The IHD_v is measured up to 50^{th} order. According to IEEE 519:2014 [41], the permissible limits for THD_v and IHD_v at 33 kV are 5% and 3%, respectively.

3.1. Single-tuned filter design

A single-tuned filter is a passive harmonic filter that can greatly attenuate a specific harmonic distortion by providing a low impedance in the network to divert harmonic current at the tuned frequency. A shunt arrangement is selected to provide reactive power compensation to the connected circuit. The harmonic mitigation of a single-tuned filter depends on the passive component selection. The single-tuned filter is designed to mitigate the 11^{th} and 13^{th} order harmonics and suppress the THD_v to within the IEEE 519:2014 standard limit of 5%. The quality-factor (Q-factor) and resistor value determine the sharpness of the filter by characterizing a resonator bandwidth close to its tuned frequency [40], [41]. In this study, the single-tuned filters are installed at the point of coupling (PCC) of Jinjang BSS and Kuchai Lama BSS as shown in Figure 3.

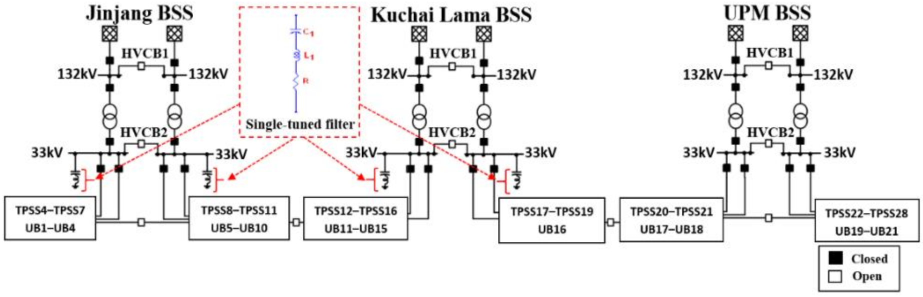

Figure 3. Single-tuned filters being installed at PCC of Jinjang BSS and Kuchai Lama BSS

3.2. Operating conditions of power supply

Harmonic analysis is carried out under four operational scenarios. Case 1 is the normal operating condition of MRT line 2 in which all the supply stations are in services. In case 2, the transformer at each BSS feeder 1 is out-of-service. The high-voltage circuit breaker 2 (HVCB2) is closed to allow the transformer at BSS feeder 2 to continue supplying the power to the loads via the main feeders, hence avoiding any power interruption to the network. Case 2 happens only when there is an unexpected transformer outage or during the maintenance of the transformer. Case 3 and case 4 have the same configuration as case 1 except that one end of the main loop feeder is in the outage condition. One end of the 33 kV main loop feeder is open-circuit to check the maximum loading. The entire load of the feeder is fed from another end. Cases 2, 3, and 4 are the three possible degraded operations that need to be investigated to understand whether the changes in the system impedance and the placement of harmonic filter could contribute to an increase in harmonic distortion to the networks or not. From the outage conditions, the changes of the HVCB or operation at reduced load may alter the level of harmonic distortions.

4. RESULTS AND DISCUSSION

4.1. Case 1: Harmonic analysis for normal operating condition

Figure 4 shows the individual harmonic voltage spectrum of Jinjang BSS under case 1 for the case with- and without harmonic filters. The result shows that the 11th and 13th order harmonic voltages are higher than the other harmonic orders due to the use of 12-pulse rectifiers. For the case without a filter, the THD_v of Jinjang BSS feeder 1 and 2 are 4.31% and 4.73%, respectively. The IHD_v of 13th order harmonic for Jinjang BSS feeder 1 is 3.86%, which has exceeded the limits of IEEE 519:2014 standard. Also, the IHD_v of 11th and 13th order harmonics for Jinjang BSS feeder 2 are 3.17% and 3.41%, respectively, which has also exceeded the limits of IEEE 519:2014 standard. When the filter is connected to the network, the THD_v of Jinjang BSS feeder 1 and 2 are 1.08% and 1.77%, respectively, which are within the limits of IEEE 519:2014 standard.

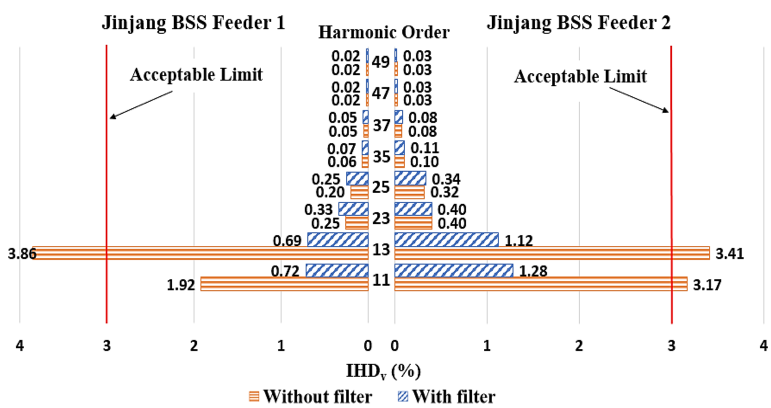

Figure 4. The harmonic spectrum for Jinjang BSS Feeder 1 and 2

Figure 5 shows the individual harmonic voltage spectrum of Kuchai Lama BSS under case 1 for the case with and without a harmonic filter. The result shows that all the IHDv of Kuchai Lama BSS is within the limit of IEEE 519:2014 standard. For the case without a filter, the THDv of Kuchai Lama BSS feeder 1 and 2 are 3.80% and 1.88%, respectively. The IHDv of 11th order harmonic for Kuchai Lama BSS feeder 1 is 2.93%, which is marginally kept within the limit of IEEE 519:2014 standard. When the filter is connected to the network, the THDv of Kuchai Lama BSS feeder 1 and 2 are 1.73% and 1.51%, respectively, which are within the limits of IEEE 519:2014 standard. Figure 6 shows the individual harmonic voltage spectrum of UPM BSS under case 1 for the case without a harmonic filter. The THDv of UPM BSS feeder 1 and 2 are 1.77% and 2.24%, respectively. No filters are required for UPM BSS since all the IHDv and THDv of UPM BSS are within the limits of IEEE 519:2014 standard.

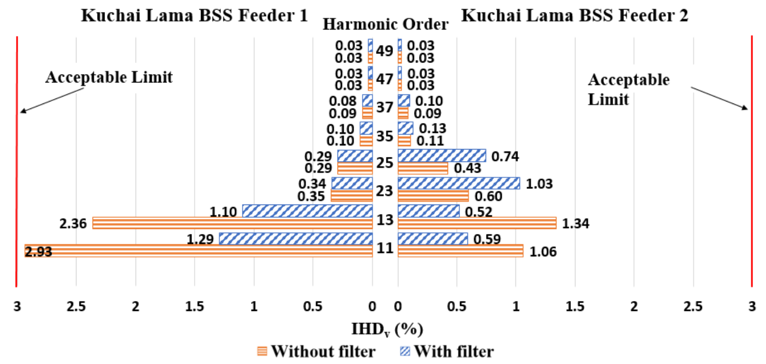

Figure 5. The harmonic spectrum for Kuchai Lama BSS feeder 1 and 2

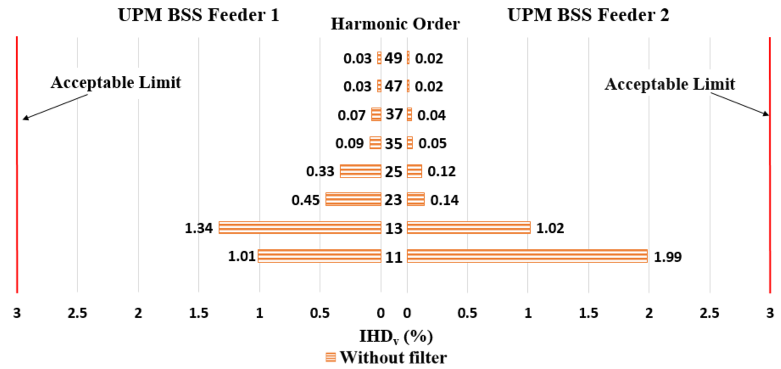

Figure 6. The harmonic spectrum for UPM BSS feeder 1 and 2

4.2. Case 2: Harmonic analysis for transformer outage condition

Figure 7 shows the individual harmonic voltage spectrum of Jinjang BSS under case 2 for the case with and without harmonic filters. The result shows that the BSS feeder 1 and 2 have the same voltage harmonic distortion because the loads are equally powered by the operating BSS transformers. For the case without a filter, the THD_v of Jinjang BSS feeder 1 and 2 are 4.84%. The IHD_v of 11^{th} order harmonic for Jinjang BSS feeder 1 and 2 is 4.16%, which has exceeded the limits of IEEE 519:2014 standard. When the filter is connected to the network, the THD_v of Jinjang BSS feeder 1 and 2 are 1.52%, which are within the limits of IEEE 519:2014 standard.

Figure 8 shows the individual harmonic voltage spectrum of Kuchai Lama BSS under case 2 for the case with and without a harmonic filter. For the case without a filter, the THD_v of Kuchai Lama BSS feeder 1 and 2 is 4.17%. The IHD_v of 11^{th} order harmonic for Kuchai Lama BSS feeder 1 and 2 is 3.46%, which has exceeded the limits of IEEE 519:2014 standard. When the filter is connected to the network, the THD_v of Kuchai Lama BSS feeder 1 and 2 are 1.48%, which are within the limits of IEEE 519:2014 standard. Figure 9 shows the individual harmonic voltage spectrum of the UPM BSS under case 2 for the case without a harmonic filter. The THD_v of UPM BSS feeder 1 and 2 is 2.20%. No filters are required for UPM BSS since all the IHD_v and THD_v of UPM BSS are within the limits of IEEE 519:2014 standard.

4.3. Summary of results for all cases with and without single-tuned filters

Table 1 shows the summary of harmonic analysis for cases 1, 2, 3, and 4. The results of harmonic analysis for case 3 and case 4 are similar to that of case 1 because case 3 and case 4 have the same configuration as case 1 except that one end of the main loop feeder is in the outage condition. The UPM BSS without filters for cases 1, 2, 3, and 4 comply with the limits of IEEE 519:2014 standard. Hence, no harmonic mitigation is required for UPM BSS.

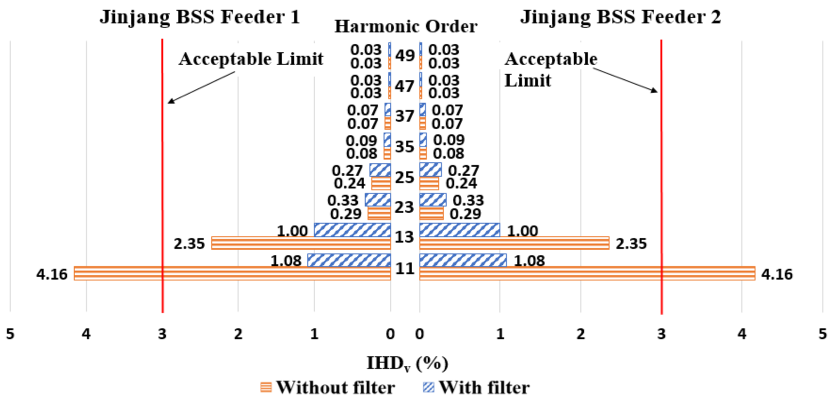

Figure 7. The harmonic spectrum for Jinjang BSS feeder 1 and 2

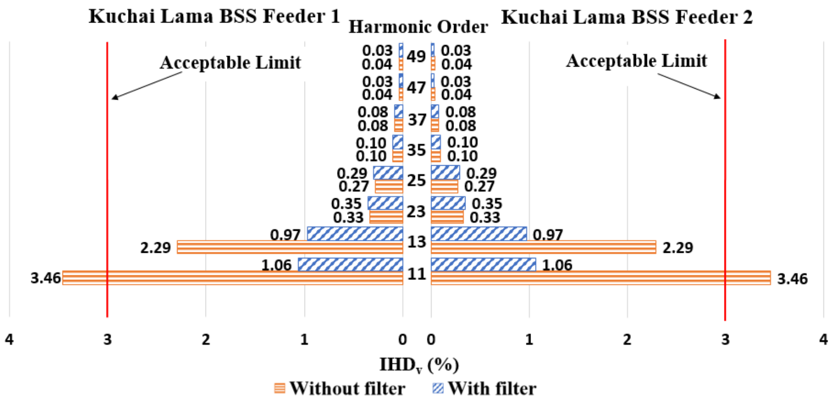

Figure 8. The harmonic spectrum for Kuchai Lama BSS feeder 1 and 2

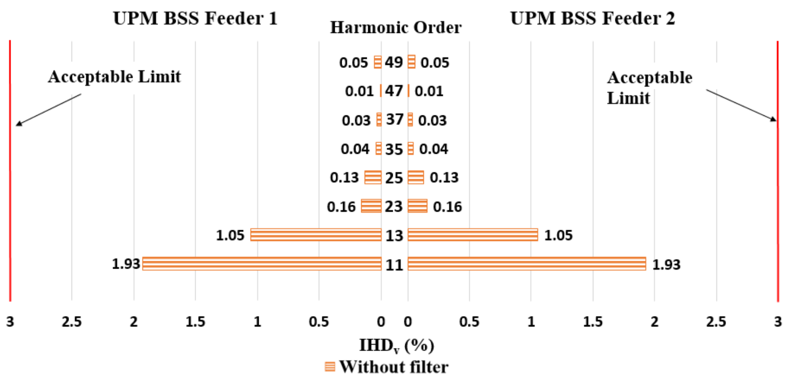

Figure 9. The harmonic spectrum for UPM BSS feeder 1 and 2

Table 1. Summary of harmonic analysis for all cases

Case	BSS	Harmonic analysis without filter	Harmonic analysis with filter
1	Jinjang	The IHD_v of 11th and 13th order harmonics have exceeded the limit	All the IHD_v is kept within the limit
	Kuchai Lama	The IHD_v of 11th order harmonic is marginally kept within the limit	
2	Jinjang	The IHD_v of 11th order harmonic has exceeded the limit	
	Kuchai Lama		
3 and 4	Jinjang	The IHD_v of 11th and 13th order harmonic exceeds the limit	
	Kuchai Lama	All the IHD_v is kept within the limit	

4.4. Harmonic analysis at each TPSS

The THD_v of each TPSS is affected by the rating and types of each TPSS. Figure 10 shows the THD_v of each TPSS for the case without filters. In case 1, the THD_v of TPSS10 and TPSS11 exceed the limits of IEEE 519:2014 standard due to the usage of high-power rating of transformer that results in a high current flow. The THD_v of TPSS fed by the Jinjang BSS is higher than that of TPSS fed by Kuchai Lama BSS and UPM BSS because there are more traction loads connected to the Jinjang BSS. In case 2, the THD_v of TPSS17 to TPSS19 is relatively high because the TPSSs are equally powered by the unaffected BSS transformer.

In case 3 and case 4, one end of the 33 kV main loop feeder experiences a power outage. The entire load is fed from the other feeder. Each BSS has two main feeder loops, namely, the BSS feeder 1 and 2. The TPSS that is nearest to the BSS will have the lowest THD_v because the line impedances are lower than that of the other TPSSs which are located further away.

For the cases with filters, all the THD_v of each TPSS is kept within the limits of IEEE 519:2014 standard as shown in Figure 11. The THD_v of TPSS fed by the Jinjang BSS feeder 1 is lower than that of TPSS fed by the Jinjang BSS feeder 2 because the BSS feeder 1 and 2 have a different rating of filters. The same goes for Kuchai Lama BSS. No filters are installed for UPM BSS. Hence, the THD_v of TPSS fed by UPM BSS remains unchanged.

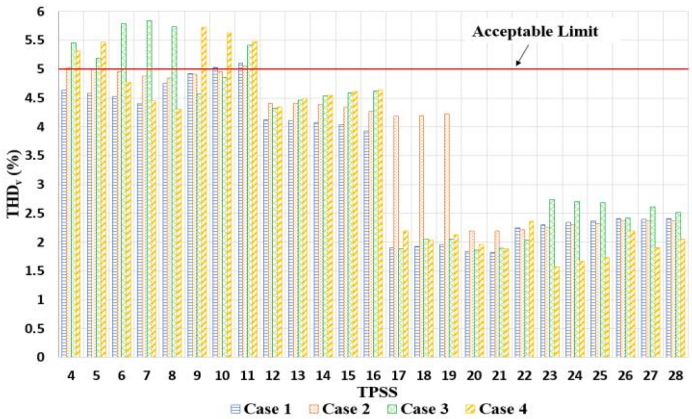

Figure 10. Total harmonic voltage spectrum (THD_v) of each TPSS without filters

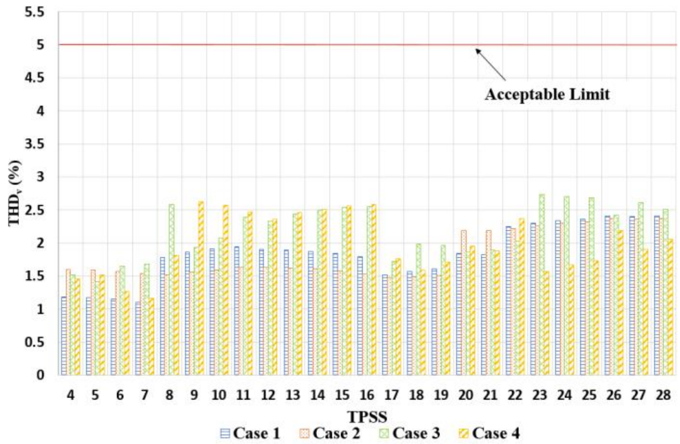

Figure 11. Total harmonic voltage spectrum (THD_v) of each TPSS with filters

5. CONCLUSION

In this study, harmonic analysis for four operational scenarios of the rail power supply, which are one normal operation and three degraded operations, have been carried out. Here, harmonic analysis of MRT line 2 Malaysia DC third rail system has been studied. The electrical network of MRT line 2 was modeled according to the real system information obtained from the railway operator. Based on the simulation result of Jinjang BSS and Kuchai Lama BSS, the IHD_v of 11^{th} and 13^{th} order harmonics have exceeded the IEEE 519:2014 standard limit of 3%. The results show that the 11^{th} and 13^{th} order harmonics of the third rail system are higher compared to that of other harmonic orders in the rail electrical network due to the use of 12-pulse rectifiers for providing the DC supply to the train. In general, the THD_v of the degraded operations is higher than that of normal operations and have exceeded the IEEE 519-2014 standard limit of 5% for some TPSS. The simulation results also show that the single-tuned filters have managed to suppress the IHD_v and THD_v to within the limits of IEEE 519:2014 standard of 3% and 5%, respectively. A mass simulation for several cases, including different operational scenarios is carried out so that the designed filter is applicable for all the cases. This study shows the importance of having harmonics mitigation devices particularly for degraded operations which are common issues in the real-time operation of third-rail power systems.

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