Ensuring EMC between Power Supply
And Signalling Assets on DC Transit Systems

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Contents

1. INTRODUCTION

In DC powered rail transit systems, converter equipments are used to transform AC supply voltage into DC voltage. In such systems, AC track circuits are used for signalling and communications purposes. The sharing of the same electrical conductors (i.e. the running rails) between power supply and track circuits necessitates careful consideration of electromagnetic compatibility, since the DC supply voltage contains a range of harmonics. The reference books available are mainly concerned with harmonics under ideal supply conditions at the lower range of frequencies, up to 2 kHz. The uncharacteristic harmonics are not addressed in any detail. In order to assess uncharacteristic harmonics, time domain simulations are carried out, so that the relevant waveforms and their harmonic spectrums can be obtained.

2. DC SIDE HARMONICS UNDER IDEAL SUPPLY CONDITIONS

The basic building block of converter equipment is a 6 pulse rectifier. A typical 6 pulse rectifier is shown in Fig.1. Under ideal supply voltages its dc output voltage waveform and harmonic spectrum are also shown in Fig. 1.

Most transit power systems are now supplied by 12 pulse rectifiers in order to reduce harmonic distortion to the ac supply system. Both parallel and series bridges are used, which are shown in Fig. 2. As a result of the pulse number increase, dc side output voltage harmonics that are odd integer multiples of 300 Hz are eliminated. In practice, some residues of these harmonics still exist due to asymmetries between the two rectifier bridges. For example, one can never obtain a perfect ratio of √√3 between the two windings on the secondary side of the transformer.

DC side voltage and its harmonics for a 12 pulse series bridge are shown in Fig. 3.

There are now tendencies of using even higher pulse numbers, e.g., 24 pulse, to further reduce the harmonic distortion to supply voltages in order to comply with pertinent regulations. (One way of achieving this is to have two identical units of 12 pulse rectifiers, with the exception that the primary windings of the transformers are displaced by 15^o: one transformer's primary windings are displaced by $+7.5^o$ and the other's by -7.5^o.). In this case, dc side harmonics that are odd integer multiples of 600 Hz are eliminated. In practice, some residues of these harmonics exist due to various asymmetries between the two units.

3. NON IDEAL AC SUPPLY VOLTAGES

In reality, the ac supply voltages are never perfect. There are always two forms of imperfection: unbalanced 3 phase voltages and voltage waveform distortions. In addition, supply system frequency varies within a certain range of the nominal frequency. These are discussed in more details as below.

3.1 UNBALANCED 3 PHASE VOLTAGES

Due to the uneven loading on the 3 phases, the 3 phase voltages are not perfectly balanced. The unbalanced 3 phase voltages can be decomposed into 3 sequences according to Symmetrical Theorem:

- positive phase sequence (PPS)
- negative phase sequence (NPS)
- zero phase sequence (ZPS)

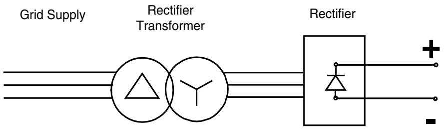
3.2 VOLTAGE WAVEFORM DISTORTION

The supply voltage does not have an ideal sinusoidal waveform, due to non-linearities in the system. The distortion can be described by harmonics. For each phase voltage, the waveform can be decomposed into a series of harmonics (including dc element and the fundamental frequency) according to Fourier Theorem.

If the three voltages of the power supply have the same wave shape, only "characteristic sequence" systems exist for all harmonics (IEC-1000-4-7, 10.3):

- harmonics of order n=3 x m (m=1,2,3 ...) only form a zero sequence system;
- harmonics of order n=3xm-2 (m=1,2,3 ...) only form a positive sequence system;
- harmonics of order n=3xm-1 (m=1,2,3 ...) only form a negative sequence system;

If the voltage waveforms are not identical in the three phases, "non-characteristic sequence" harmonics exist.



BLOCK DIAGRAM OF A 6 PULSE RECTIFIER

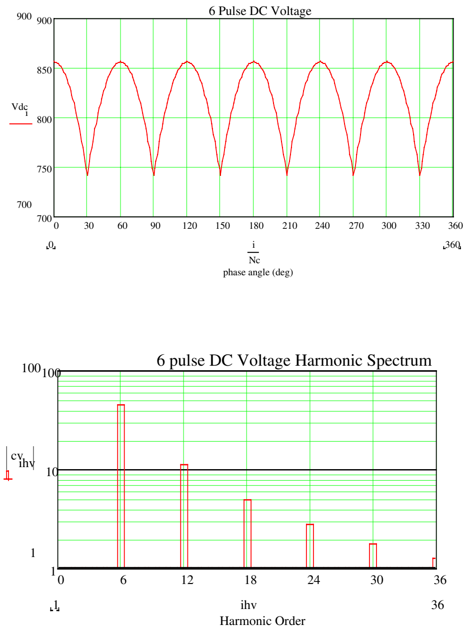
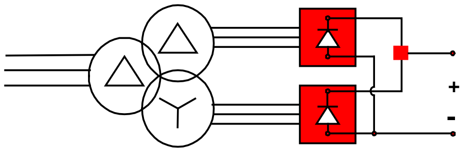
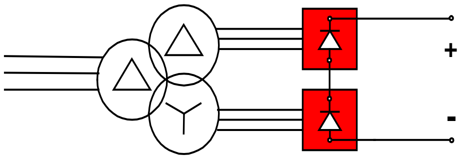


Fig. 1. 6 pulse rectifier and dc voltage harmonics



12 PULSE RECTIFIER, PARALLEL BRIDGE



12 PULSE RECTIFIER, SERIES BRIDGE

Fig. 2. Schematic diagrams for 12 pulse rectifier configurations

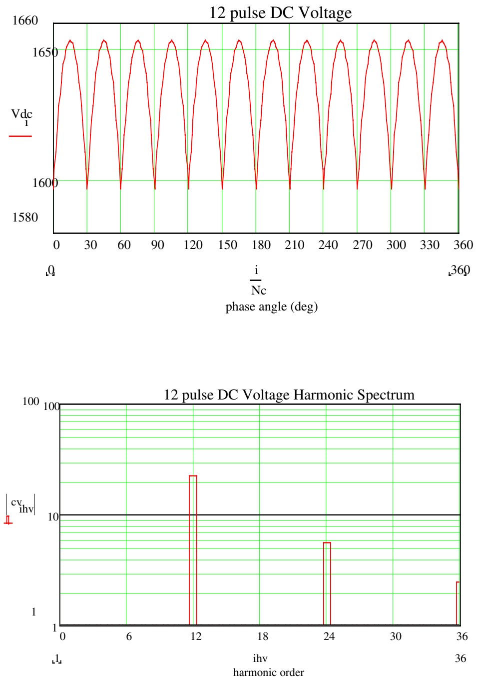


Fig. 3. 12 pulse dc voltage harmonics

On low voltage mains, the “non-characteristic sequence” harmonics may reach, in relation to their “characteristic sequence” harmonics:

- for orders n ≠ 3 x m: up to 20%
- for orders n = 3 x m: up to 50%

Taking into account the unbalances between the 3 phases, the overall unbalance and distortion are described by three sequences of harmonics as in the case of fundamental frequency:

- PPS harmonics
- NPS harmonics
- ZPS harmonics

3.3 SUPPLY FREQUENCY VARIATION

The supply voltage is rarely at a given nominal frequency. In fact, it varies within a range around the nominal frequency. Different supply authorities adhere to different standards.

3.4 ENGINEERING RECOMMENDATION G.5/3

Engineering Recommendation G.5/3 in the UK covers limits for harmonics for voltages at 132 kV and below.
The harmonic voltage distortion limits for 132 kV and 33 kV are listed in the following table (in % of fundamental frequency voltage).

Table 1. G5/3 Harmonic Voltage Limits

Harmonic Order	33 kV and 66 kV	132 kV
Odd	2	1
Even	1	0.5
Total Harmonic Distortion	3	1.5

Note: The Electricity Association is making revisions to this document to G5/4.

4. CASE STUDY: NATIONAL GRID VOLTAGE CHARACTERISTICS

The National Grid Company (NGC) of UK issued a document entitled "Technical and Operational Characteristics of the NGC Transmission System" in June 1998. The characteristics described primarily relate to the NGC transmission system operating at nominal voltages of 400 kV and 275 kV.

4.1 SYSTEM FREQUENCY

Under normal conditions, the frequency of the NGC transmission system is required to be within 1% of the nominal 50 Hz frequency, i.e., from 49.5 to 50.5 Hz.

In exceptional circumstances, the frequency could rise to 52 Hz or fall to 47 Hz. Design of user's plant and apparatus must enable operation within this range with the following conditions:

- 47.5 - 52 Hz: continuous operation is required
- 47 - 47.5 Hz: operation for a period of at least 20 seconds is required each time the frequency is below 47.5 Hz.

4.2 HARMONICS

The grid code currently specifies maximum levels of voltage harmonic distortion, which are only to be exceeded under abnormal conditions or for infrequent short durations. Grid code and derogated harmonic limits for 275 kV systems are listed in the following table (in % of fundamental frequency voltage).

Table 2. NGC Harmonic Voltage Limits

Harmonic Order	Grid Code	Derogation
3	1.5	1.5
5	1.5	3
7	1.5	1.5
Others	1.5	1
Total Harmonic Distortion	2	3.5

4.3 VOLTAGE UNBALANCE

Under planned outage conditions, the negative phase sequence (NPS) voltage component should remain below 1%. Short duration peaks up to 2% are permitted with the prior agreement of NGC.

5. MODULATION OF AC SUPPLY VOLTAGE HARMONICS BY A 12 PULSE RECTIFIER

Due to the supply voltage unbalance and distortion, a converter will produce uncharacteristic harmonics in the dc side voltage. This is called harmonic modulation by the converter equipment and is in addition to the inherent uncharacteristic harmonics caused by converter equipment asymmetries. The effects of each supply harmonic are different on the production of dc side harmonics. In order to assess their effects, some definitions are made first for dc side harmonics.

5.1 DEFINITIONS FOR DC SIDE HARMONICS FOR A 12 PULSE RECTIFIER

The following definitions are made for dc side harmonics, based on a 12 pulse rectifier and a fundamental frequency of 50 Hz.

- Characteristic harmonics series: Nx600, N=1,2,3… (characteristic harmonics)

- super 100 series: Nx600+100, N=0,1,2,3… (uncharacteristic harmonics)
- super 200 series: Nx600+200, N=0,1,2,3… (uncharacteristic harmonics)
- odd 300 series: Nx600+300, N=0,1,2,3… (inherent uncharacteristic harmonics due to equipment parameter asymmetry from manufacturing tolerances.)
- sub 100 series: Nx600-100, N=1,2,3… (uncharacteristic harmonics)
- sub 200 series: Nx600-200, N=1,2,3… (uncharacteristic harmonics)
- Similar definitions are given for other series of uncharacteristic harmonics, e.g.
  - ♦ Odd integer multiples of 50 Hz:
    sub 50, 150, 250 series,
    super 50, 150 , 250 series.
  - ♦ Odd integer multiples of 25 Hz
    sub 25, 75, 125, 175, 225, 275 series,
    super 25, 75, 125, 175, 225, 275 series

5.2 MODULATION OF PPS HARMONICS BY A 12 PULSE RECTIFIER

The modulation of PPS harmonics by a 12 pulse rectifier is listed in table 3. The fundamental frequency is assumed to be 50 Hz.

5.3 MODULATION OF NPS HARMONICS BY A 12 PULSE RECTIFIER

The modulation of NPS harmonics by a 12 pulse rectifier is listed in table 4. This include the NPS voltage at the fundamental frequency (50Hz).

ZPS harmonics have little effect on dc side harmonics.

6. SIMULATION RESULTS AND DISCUSSIONS

Time domain is necessary to assess the harmonic modulation by converter equipment.
A software package PSpice has been used for this purpose. Simulation studies have been carried out on the basis of a 12 pulse rectifier (series bridge). The fundamental frequency used is 50 Hz. The converter is loaded to about 88% of full load current.

Ideal Supply Voltages

First of all, the ideal supply voltage is applied and the harmonic spectrum for dc side voltage is shown in Fig. 4. Apart from the characteristic harmonics (Nx600 series), odd 300 series exist in the spectrum, which are caused by the equipment asymmetries. The amplitudes of the odd 300 harmonics are initially low but become comparable with those of the Nx600 series when the frequency is above 18 kHz.

Supply Voltage Unbalance

When 1% of NPS (fundamental frequency) voltage is added to the supply voltages (without the presence of any other distortions), the dc side voltage spectrum is shown in Fig. 5. Starting at 3 kHz, the amplitudes of uncharacteristic harmonics (both super 100 and sub 100 series) become comparable with those of characteristic harmonics. Above this frequency, the uncharacteristic harmonics are dominant in the spectrum.

3rd Harmonic Voltage

When 1% of 3rd PPS harmonic voltage is added to the supply voltages (without the presence of any other distortions), the dc side voltage spectrum is shown in Fig. 6A. Starting at 8 kHz, the amplitudes of uncharacteristic harmonics (both super 100 and sub 100 series) become comparable with those of characteristic harmonics. Above this frequency, the uncharacteristic harmonics are dominant in the spectrum. This has a similar effect as the NPS fundamental frequency voltages.

If the 3rd harmonic voltage is NPS at 1%, the dc side voltage spectrum is shown in Fig. 6B. Starting at 7 kHz, the amplitudes of uncharacteristic harmonics (both super 200 and sub 200 series) become comparable with those of characteristic harmonics. Above this frequency, the uncharacteristic harmonics are dominant in the spectrum.

5th Harmonic Voltage

When 0.4% of 5th PPS harmonic voltage is added to the supply voltages (without the presence of any other distortions), the dc side voltage spectrum is shown in Fig. 7A. Starting at 14 kHz, the amplitudes of uncharacteristic harmonics (both super 200 and sub 200 series) become comparable with those of characteristic harmonics. Above this frequency, the uncharacteristic harmonics are dominant in the spectrum. This has a similar effect as the 3rd NPS harmonic voltages.

If the 5th harmonic voltage is NPS at 2%, the dc side voltage spectrum is shown in Fig. 7B. Starting at 300Hz, the amplitudes of uncharacteristic harmonics (odd 300 series) become comparable with those of characteristic harmonics. Above this frequency, the uncharacteristic harmonics are dominant in the spectrum.

Combination of Harmonic Voltages

In practice, a combination of harmonics exists in the supply voltages at the same time, the predominant orders being the odd harmonics: 3rd, 5th, 7th, 11th and 13th, in coexistence with NPS voltage of the fundamental frequency.

These harmonics and the NPS fundamental frequency voltage will interfere with each other in their modulation to the dc side.

Table 3 – Modulation of PPS Harmonics by a 12 Pulse Rectifier

DC Side Harmonics			Supply Harmonics Order and Frequency (PPS)									
			2	3	4	5	6	7	8	9	10	11
Order	Freq.	Category	100	150	200	250	300	350	400	450	500	550
1	50	sup 50	*									
2	100	sup 100		*								*
3	150	sup 150			*						*	
4	200	sup 200				*				*		
5	250	sup 250					*		*			
6	300	odd 300						*				
7	350	sub 250					*		*			
8	400	sub 200				*				*		
9	450	sub 150			*						*	
10	500	sub 100		*								*
11	550	sub 50	*									

Table 4 - Modulation of PPS Harmonics by a 12 Pulse Rectifier

DC Side Harmonics			Supply Harmonics Order and Frequency (NPS)									
			1	2	3	4	5	6	7	8	9	10
Order	Freq.	Category	50	100	150	200	250	300	350	400	450	500
1	50	sup 50										*
2	100	sup 100	*								*	
3	150	sup 150		*						*		
4	200	sup 200			*				*			
5	250	sup 250				*		*				
6	300	odd 300					*					
7	350	sub 250				*		*				
8	400	sub 200			*				*			
9	450	sub 150		*						*		
10	500	sub 100	*								*	
11	550	sub 50										*

Notes for tables 3 and 4: The patterns repeat every 600 Hz on the dc side.

Figs. 8A, 8B and 8C show the dc side voltage harmonic spectrum with the following ac supply voltage combinations (measured values at a given instant of time):

- NPS fundamental frequency: 0.9%
- 3rd harmonic: 0.8%
- 5th harmonic: 1%
- 7th harmonic: 0.3%
- 9th harmonic: 0.1%
- 11th harmonic: 0.9%
- 13th harmonic: 1.1%

In order to represent the true 3 phase supply voltage with unbalance and distortion, the following parameters are required:

- phase angles of NPS voltage of fundamental frequency relative to the fundamental voltage
- for each harmonic voltage: the three phase amplitudes and phase angles relative to the fundamental voltage.

In reality these are rarely known and the following assumptions are taken: In Fig. 8A it is assumed that all the supply harmonics behave as PPS harmonics. In Fig. 8B it is assumed they are all NPS harmonics. In Fig. 8C it is assumed they are all harmonics of their characteristic sequence, i.e. all three phase harmonics are balanced.

A further assumption is made that all harmonics are in phase with the fundamental voltage in one of the phases.

Fig. 8A shows that the sub 100 series of harmonics become the dominant harmonics when the frequency is in the range of 3-9 kHz. Above 9kHz, the sub 200 series of harmonics become dominant.

Fig. 8B shows that the sub 100 series of harmonics become the dominant harmonics when the frequency is in the range of 4-8kHz. Above 8kHz, the super 200 series of harmonics become dominant.

Fig. 8C shows that the odd 300 series of harmonics become the dominant harmonics when the frequency is in the range of 4-7kHz. Above 7kHz, both the sub 200 and the super 200 series of harmonics become dominant.

Even Harmonics

Even harmonics in the supply voltage are usually at a comparably lower level than the odd harmonics. The modulation of even harmonics in the supply voltage by the rectifier is not presented in detail. Their effects are indicated in tables 3 and 4.

7. IMPLICATIONS AND POSSIBLE MITIGATION MEASURES

7.1 INTERFERENCE WITH TRACK CIRCUITS

The simulation results presented above indicate the existence of a full range of harmonics in the dc circuit, depending on the contents of the supply voltage in the form of unbalance and waveform distortion.

With the presence of harmonic voltages at the rectifier dc output terminal, harmonic current will flow in the running rails, which is usually shared between power circuit and track circuits. The amplitudes of harmonic currents depend on the dc side circuit parameters.

In the low frequency range, it is possible to choose a track circuit frequency in such a way that the converter equipment cannot produce it. For example, if the track circuit is tuned to 83.3 Hz, the nearest frequency of the harmonic produced by a 12 pulse rectifier is 100 Hz (super 100 series) by odd harmonics in the supply voltage. The track circuit frequency is sufficiently away from it so that it is immune from interference.

In the higher frequency range, it is inevitable that some of the harmonic currents' frequency will be near or coincide with the frequency of a track circuit. For example, a track circuit may be tuned to 8333 Hz. It is likely the track circuit has a pass band of, say 100 Hz, i.e, the track circuit will work within the range of 8283 to 8383 Hz.

A 12 pulse rectifier will produce a harmonic voltage at 8300 Hz (sub 100 series). This falls within track circuit frequency pass band.

Even if the track circuit frequency pass band is narrowed considerably, e.g., to the range of 8313 to 8353 Hz (40 Hz band), it is still possible that the 8300 Hz harmonic will interfere with it, in a way described below.

8300 Hz is an uncharacteristic harmonic frequency obtained under nominal supply frequency of 50 Hz. It only takes a variation of 0.4% in the nominal supply frequency, i.e., from 50 Hz to 50.2Hz, for the 8300 Hz harmonic to become 8333 Hz.

Conclusion. In the higher frequency range it is impossible to choose a track circuit frequency that is not near or at a harmonic frequency produced by the rectifier equipment.

7.2 POSSIBLE MITIGATION MEASURES

One way to avoid possible interference to a track circuit is to raise the track circuit immunity levels, having taken account of the background harmonics in the circuit that are likely to be generated by substation rectifiers.

The other solution is to install dc filters at the output terminal of the substation rectifiers.
DC filters will be very effective in reducing all harmonics produced by the rectifiers to required levels.

AC supply side filters are ineffective, as they do not solve the voltage unbalance problem. It is also uneconomical.

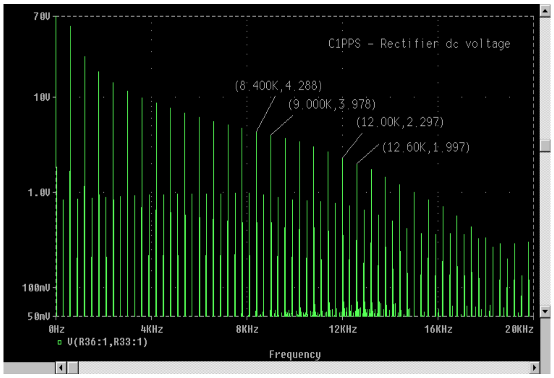


Fig. 4. DC side voltage harmonics with ideal supply voltages

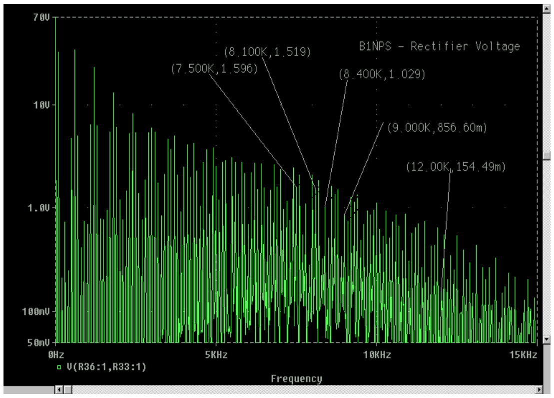


Fig. 5. DC side voltage harmonics with 1% NPS (fundamental frequency) in the supply voltages

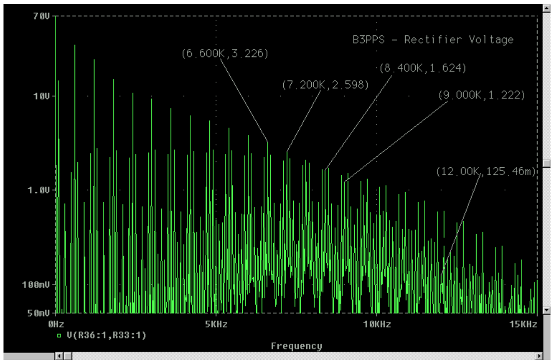


Fig. 6A. DC side voltage harmonics with 1% 3rd PPS harmonic in the supply voltages

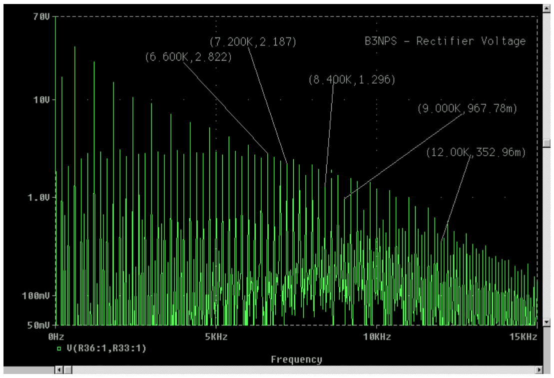


Fig. 6B. DC side voltage harmonics with 1% 3rd NPS harmonic in the supply voltages

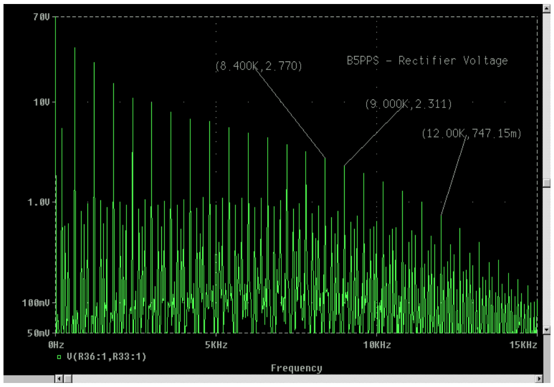


Fig. 7A. DC side voltage harmonics with 0.4% 5th PPS harmonic in the supply voltages

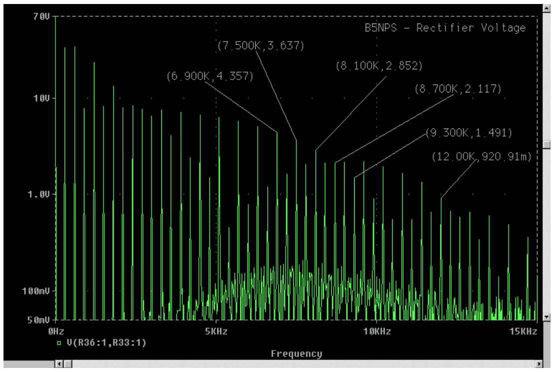


Fig. 7B. DC side voltage harmonics with 2% 5th NPS harmonic in the supply voltages

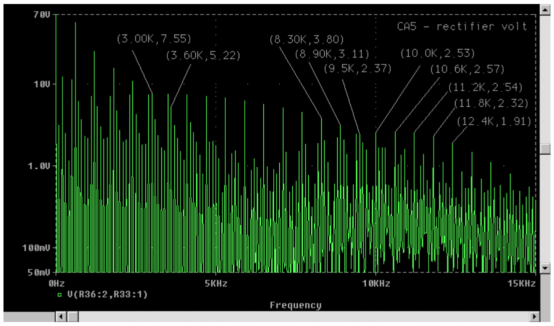


Fig. 8A. DC side voltage harmonics with a combination NPS voltage of fundamental frequency and PPS harmonics in the supply voltages

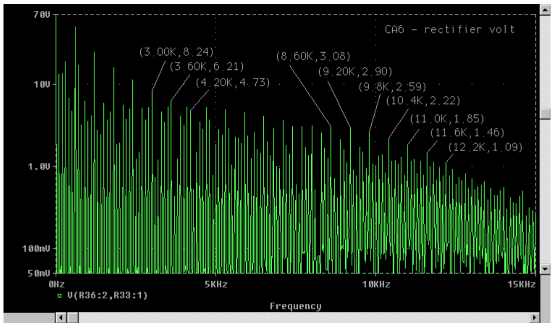


Fig. 8B. DC side voltage harmonics with a combination NPS voltage of fundamental frequency and NPS harmonics in the supply voltages

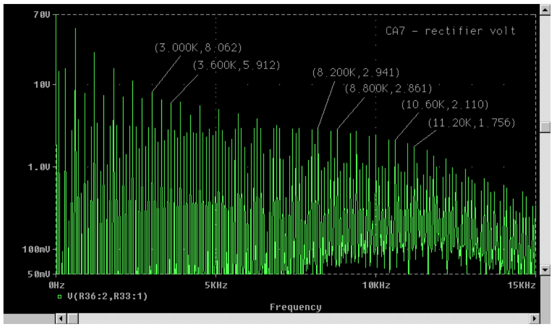


Fig. 8C. DC side voltage harmonics with a combination NPS voltage of fundamental frequency and characteristic sequence of harmonics in the supply voltages

8. CONCLUSIONS

- A substation rectifier will produce a whole range of harmonics on the dc side due to supply voltage unbalance and distortion.
- In the low frequency range, it is possible to choose a track circuit frequency in such a way that the converter equipment cannot produce it.
- In the higher frequency range it is impossible to choose a track circuit frequency that is not near or at a harmonic frequency produced by the rectifier equipment.
- In setting track circuit immunity levels the background harmonics in the circuit that are likely to be generated by substation rectifiers should be taken into account.
- DC filters at the output terminal of the substation rectifiers are effective in reducing all harmonics produced by the rectifiers to required levels.
- AC supply side filters are considered ineffective and uneconomical in reducing dc side harmonics.

9. ACKNOWLEDGEMENT

The work described in this paper was carried out while the author was with ALSTOM Drives & Controls Ltd, UK. However, the opinion expressed in the paper is entirely the author's own.

10. REFERENCES

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6) IEC 1000-4-7 (1991) Part 4 - Testing and measurement techniques. Section 7 - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.
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11. APPENDIX – CATEGORISATION OF DC SIDE HARMONICS

Category	Frequencies (Hz)							
sup 100	100	3700	7300	10900	14500	18100	21700	25300
sup 200	200	3800	7400	11000	14600	18200	21800	25400
odd 300	300	3900	7500	11100	14700	18300	21900	25500
sub 200	400	4000	7600	11200	14800	18400	22000	25600
sub 100	500	4100	7700	11300	14900	18500	22100	25700
Chr. 600	600	4200	7800	11400	15000	18600	22200	25800
sup 100	700	4300	7900	11500	15100	18700	22300	25900
sup 200	800	4400	8000	11600	15200	18800	22400	26000
odd 300	900	4500	8100	11700	15300	18900	22500	26100
sub 200	1000	4600	8200	11800	15400	19000	22600	26200
sub 100	1100	4700	8300	11900	15500	19100	22700	26300
Chr. 600	1200	4800	8400	12000	15600	19200	22800	26400
sup 100	1300	4900	8500	12100	15700	19300	22900	26500
sup 200	1400	5000	8600	12200	15800	19400	23000	26600
odd 300	1500	5100	8700	12300	15900	19500	23100	26700
sub 200	1600	5200	8800	12400	16000	19600	23200	26800
sub 100	1700	5300	8900	12500	16100	19700	23300	26900
Chr. 600	1800	5400	9000	12600	16200	19800	23400	27000
sup 100	1900	5500	9100	12700	16300	19900	23500	27100
sup 200	2000	5600	9200	12800	16400	20000	23600	27200
odd 300	2100	5700	9300	12900	16500	20100	23700	27300
sub 200	2200	5800	9400	13000	16600	20200	23800	27400
sub 100	2300	5900	9500	13100	16700	20300	23900	27500
Chr. 600	2400	6000	9600	13200	16800	20400	24000	27600
sup 100	2500	6100	9700	13300	16900	20500	24100	27700
sup 200	2600	6200	9800	13400	17000	20600	24200	27800
odd 300	2700	6300	9900	13500	17100	20700	24300	27900
sub 200	2800	6400	10000	13600	17200	20800	24400	28000
sub 100	2900	6500	10100	13700	17300	20900	24500	28100
Chr. 600	3000	6600	10200	13800	17400	21000	24600	28200
sup 100	3100	6700	10300	13900	17500	21100	24700	28300
sup 200	3200	6800	10400	14000	17600	21200	24800	28400
odd 300	3300	6900	10500	14100	17700	21300	24900	28500
sub 200	3400	7000	10600	14200	17800	21400	25000	28600
sub 100	3500	7100	10700	14300	17900	21500	25100	28700
Chr. 600	3600	7200	10800	14400	18000	21600	25200	28800