SITE MEASUREMENTS AND MODELLING STUDIES OF HARMONICS ON DISTRIBUTION NETWORKS

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ABSTRACT

Distortion of voltage waveforms results in the appearance of harmonic and sometimes non-harmonic frequencies in the network voltage. Harmonic distortions on the network voltage can cause additional losses and heating of certain network equipment, faulty operation of control equipment, an increase in peak voltage and disturbance and interference in neighbouring telecommunication systems. Harmonic studies have been carried out on the proposed connection of compressor motors at two new 11 kV distribution substations, one is urban, the other rural. These substations will be fed from another two proposed new substations. The harmonic studies consist of site background harmonic measurements at the existing local distribution substations, and computer-based system modelling based on site measured results but taking into account outage conditions to calculate the background harmonics and the permissible voltage distortions for new variable speed drives at the new substations. The results of the site measurements, system studies and, recommended mitigation measures to overcome any unacceptable harmonic distortions for each connection are contained in the paper.

Key words: Background harmonic distortion, Total harmonic distortion (THD), British Engineering Recommendation G5/4-1 (ER G5/4-1), Harmonic planning levels, compatibility level, point of common coupling (p.c.c).

INTRODUCTION

Distortion of voltage waveforms results in the appearance of harmonic and sometimes non-harmonic frequencies in the network voltage. Harmonic disturbances are normally caused by non-linear elements connected to the network. These non-linear elements generate network voltages with frequencies different from the network frequency or absorb currents with non-sinusoidal waveforms. Harmonic distortions on the network voltage can cause additional losses and heating of certain network equipment, faulty operation of control equipment, an increase in peak voltage and disturbance and interference in neighbouring telecommunication systems. Thus, harmonics at the point of common coupling (p.c.c) may be required to be limited to within the harmonic planning levels as recommended in the British Engineering Recommendation G5/4-1[1].

Harmonic studies have been carried out on the proposed connection of compressor motors at two new 11 kV primary substations, one is urban, the other rural. These substations will be fed from another two proposed new Bulk Supply Point (BSP) substations; one has a rated voltage of 33 kV (urban site, referred to as Project 1) and the other of 66 kV (rural site; Project 2). The harmonic studies consist of site background harmonic measurements at the existing local distribution substations, and computer-based system modelling studies. The site measured harmonic currents were used to tune the computer models to match the site harmonic measurements. The background harmonics at the proposed BSP and primary substations under normal and outage conditions were calculated. The permissible voltage distortions for new variable speed drives at the new substations have also been recommended in this paper.

ER G5/4-1 recommends the planning levels for harmonic distortion (%) and they are summarised in Table 1. These levels are used in the process for connection of non-linear equipment into the UK distribution networks.

Table 1. Planning levels for harmonic distortion (G5/4-1)

Voltage (kV)	THD (%)	3rd (%)	5th (%)	7th (%)	11th (%)	13th (%)
21 - 145	3.0	2.0	2.0	2.0	1.5	1.5
11	4.0	3.0	3.0	3.0	2.0	2.0

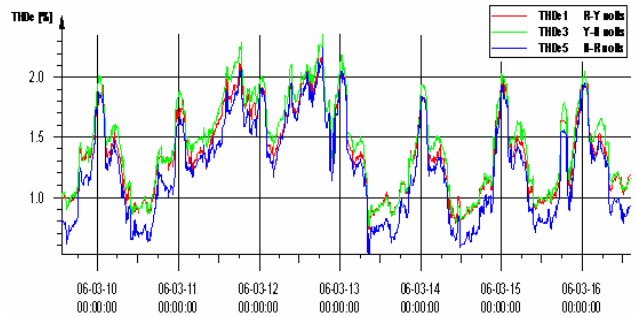
PROJECT 1

For this project, under normal running conditions there are four Super Grid Transformers (SGTs) in operation at a 132 kV Grid Supply Point (GSP) and the GSP busbar is run split. The proposed connection of the compressor motors is at a new urban 11 kV primary substation fed from two 20/40 MVA transformers. The new primary substation is supplied from a proposed new 33 kV BSP substation fed from two 132/33 kV transformers rated at 90 MVA.

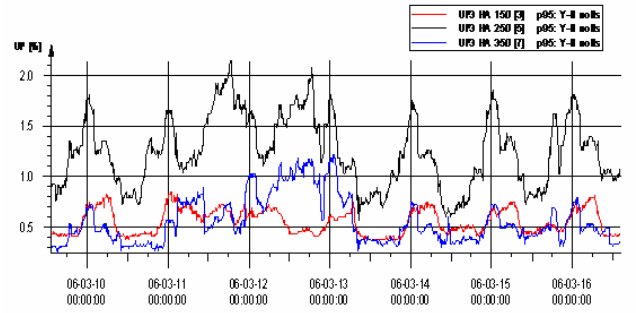
Site Measurement

Site 3-phase harmonic measurement has been undertaken at the GSP. The monitors are connected at the secondary side of a SGT over a one week period. The harmonic distortions (THD, fundamental, 2nd up to 25th order) of phase to phase voltage and line current were measured against ER G5/4-1 with a Unipower 900F monitor. There is a PQ node monitor connected at the 132 kV GSP to monitor harmonics at the GSP. This PQ node monitor follows ER G5/3, i.e. taking the 3rd highest value of harmonics during a 10 minute period. The measurement of the PQ node monitor has also been downloaded and given in this report for comparison.

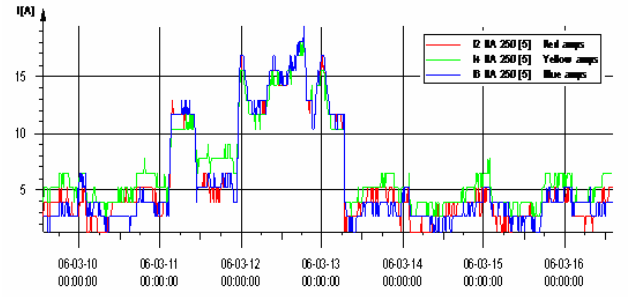
Site measured results against G5/4-1 are shown in Figure 1(a) for 3-phase total harmonic distortions and Figure 1(b) for 3rd, 5th and 7th individual harmonic distortions for phase Y-B (worst of all three phases) at the GSP over a one week period.



(a) Total harmonic distortions

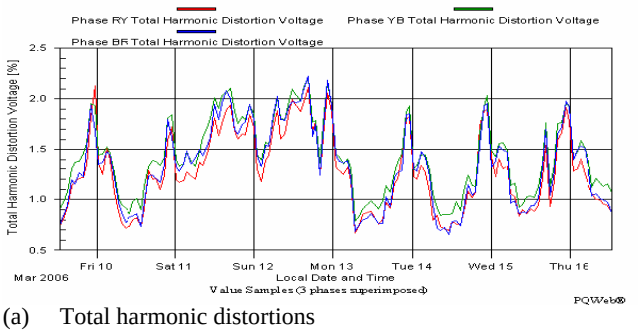


(b) 3rd, 5th and 7th harmonic voltage distortions for Y-B phase

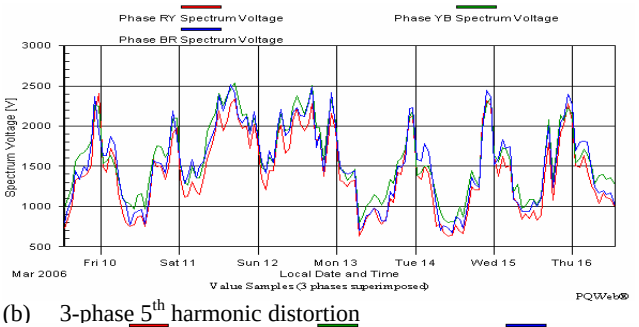


(c) 5th harmonic current

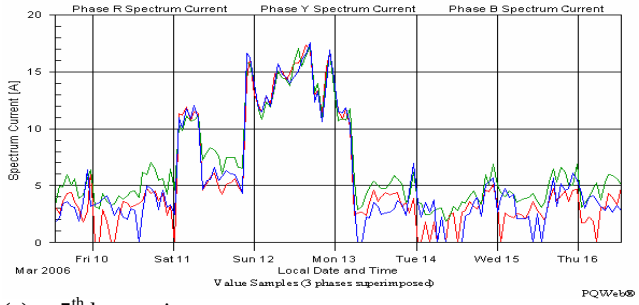
Fig 1. Site measurement against G5/4-1 at 132 kV GSP



(a) Total harmonic distortions



(b) 3-phase 5th harmonic distortion



(c) 5th harmonic current

Fig 2. Site measurement against G5/3 at 132 kV GSP

Figures 2(a) and 2(b) are corresponding measurements from the PQ node monitor against G5/3. The 3-phase total harmonic distortions are given in Figure 3(a) whereas 5th harmonic distortion is shown in Figure 3(b).

Figures 1(a) to 2(b) show that the harmonic distortions at the GSP measured against ER G5/4-1 have similar patterns and values to those against ER G5/3. The maximum THD value appears at the Y-B phase and is 2.36 % measured against ER G5/4-1, within the planning level of 3 % specified in ER G5/4-1. The maximum 5th harmonic distortion is 2.08 % measured against ER G5/4-1, which exceeds the recommended planning level of 2 %. The maximum 3rd and 7th harmonic distortions are about 0.8 % and 1.2 % respectively and within the corresponding planning levels.

The site measurement results also show that the harmonic distortions are more severe during weekend than working days.

The harmonic current measurement at the GSP is used as a harmonic current source injected in to the network for the harmonic modelling study. The study was performed using Interactive Power Systems Analysis (IPSA) program [2].

Modelling Study

In order to obtain realistic response and performance from the IPSA model the harmonic current sources must be tuned to result in similar responses obtained from the model as those obtained from site measurements. Two harmonic current sources are tuned. One has highest 5th and 7th harmonic currents resulting in highest THD, 5th and 7th harmonic voltage distortions. The other has highest 3rd harmonic current.

The maximum harmonic voltage distortions under normal and outage conditions obtained with IPSA are given in Table 2. A tolerance of 15 % is applied to the results to take account of approximations of data and calculating methodology, and initial conditions in the model.

Table 2. Computer modelling results for Project 1

Substation	Voltage distortion (%)			
	THD	3rd	5th	7th
132 kV GSP	**3.10**	0.85	**2.27**	**2.47**
33 kV BSP	2.56	0	**2.05**	1.79
11 kV primary	2.56	0	2.06	1.80
Notes	**Bold in red: Harmonic distortion exceeds limit**			

Table 2 shows that the maximum THD, 5th and 7th harmonic voltage distortions at the 132 kV GSP exceed the planning level of 3 % for THD and 2% for 5th and 7th harmonics as specified in ER G5/4-1. The 5th harmonic voltage distortion at the 33 kV BSP also exceeds the planning level of 2 %.

Table 2 also shows that 3rd harmonic distortion at the 33 kV BSP and 11 kV primary substations is zero. This is due to the delta connection of the 132/33 kV transformers at the BSP substation. Since the site measurement was only carried out at 132 kV the 3rd harmonic distortion at 33 kV and 11 kV cannot be obtained. It is recommended that site measurement at the new 11 kV primary substation should be carried out when the proposed primary is completed and in service.

The THD, 5th and 7th harmonic distortions at the primary are within planning levels. Since the THD, 5th and 7th harmonic distortions at the GSP substation exceed planning levels there is no capacity for compressor motors at the proposed primary substation. Therefore, it is recommended that the proposed connection should not make any harmonic contribution to the network, i.e. filters are needed for the proposed connection.

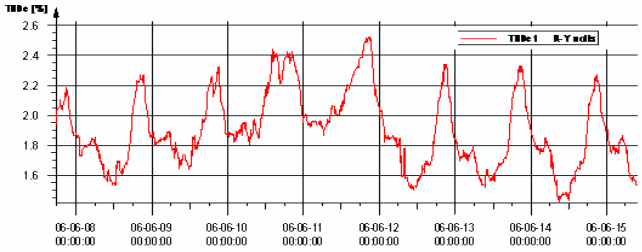
PROJECT 2

A gas compressor site is proposed at a new rural 11 kV primary substation, to be looped in to an existing 66 kV circuit. Under normal running conditions the new primary is fed from a 66 kV GSP (referred as to GSP 1) at which there are three 275/66 kV SGTs in operation (one on hot standby) and one 400/66 kV SGT. For alternative supply, the new primary is fed from another GSP (referred as to GSP 2) at which there are four 400/132 kV SGTs in operation, via a single circuit and a 132/66 kV transformer. Two 20/40 MVA 66/11 kV transformers are operated in parallel in the new primary.

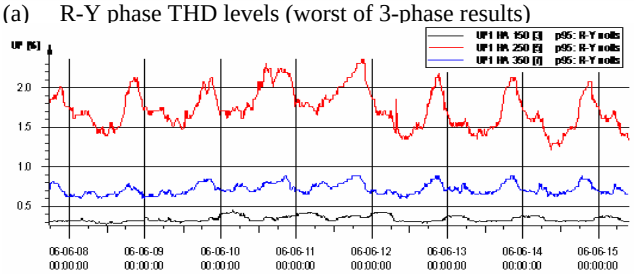
Site Measurement

Site harmonic measurement has been undertaken at a nearby substation using three monitors. One monitor (referred to as Monitor 1) was connected at the 66 kV side of 66/11 kV transformer T1, one (Monitor 2) at the 11 kV side of T1 and the other (Monitor 3) at the 11 kV side of T2 over a one-week period. Due to the planned outage of T2 at the substation, the Monitor 3 was found disconnected four and a half day after the monitor was installed, i.e. four and a half day results were obtained with Monitor 3. During the first four and a half day's measurement period, the substation was running split at the 66 kV and 11 kV, T1 was fed from GSP 1 and T2 from GSP 2. Thus, the measurement results for the first four and a half day's measurement period can be used for determining the background harmonic distortions at the new primary. The results from Monitor 1 and Monitor 2 are used for the normal running arrangement, whereas Monitor 3's results are used for the alternative running arrangement. The harmonic distortions (THD, fundamental, 2nd up to 25th order) of phase to phase voltage and line current were measured against ER G5/4-1.

Figures 3(a) and 3(b) are THD and 3rd, 5th and 7th individual harmonic levels measured from Monitor 1; Figures 4(a) and 4(b) from Monitor 2; Figures 5(a) and 5(b) from Monitor 3.

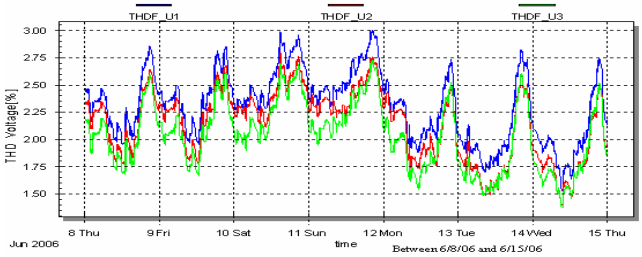


(a) R-Y phase THD levels (worst of 3-phase results)

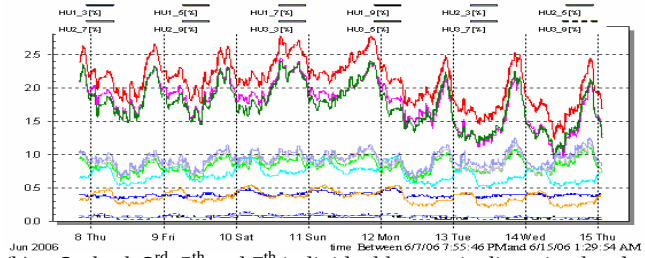


(b) R-Y phase 3rd, 5th and 7th harmonic distortion levels

Fig 3. Measured harmonic levels at 66 kV of T1 (Monitor 1)

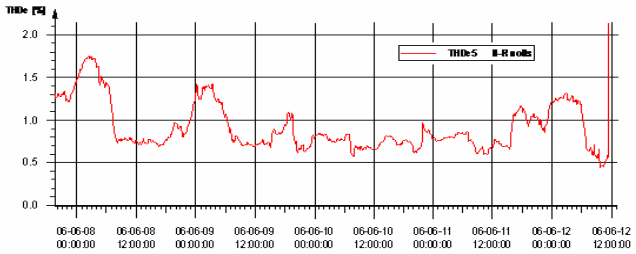


(a) 3-ph-ph THD levels

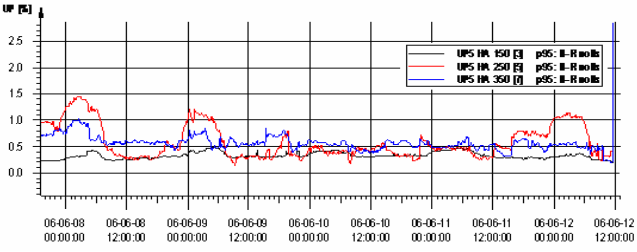


(b) 3-ph-ph 3rd, 5th and 7th individual harmonic distortion levels

Fig 4. Measured harmonic levels at 11 kV of T1 (Monitor 2)



(a) B-R phase THD levels (worst of three phase results)



(b) B-R phase 3rd, 5th and 7th harmonic distortion levels

Fig 5. Measured harmonic levels at 11 kV of T2 (Monitor 3)

Harmonic distortions shown in Figures 3 (a), 3 (b), 4 (a) and 4 (b) are higher during the weekend than those of other days. This is the normal harmonic distortion pattern. But the patterns of the harmonic distortions at the 11 kV of T2 shown in Figures 5(a) and 5(b) is different, and the highest harmonic distortions occur in the early morning of Thursday (08-06-2006), not the weekend. This might be the real harmonic pattern for the site or there might be errors for the results. In order to not under-estimate the harmonic distortions at the site, the maximum measured harmonic distortions from Monitor 3 for background harmonic distortion modelling studies have been scaled up based on the factors of Sunday's distortions against Thursday's.

The maximum measured THD and individual harmonic distortion values are summarised in Table 3. The distortion value which exceeds the planning limits specified as per G5/4-1 is highlighted in bold red.

Table 3. Measured maximum harmonic distortions

Busbar	Harmonic distortion (%)			
	THD	3rd	5th	7th
66 kV of T1	2.53	0.43	**2.37**	0.89
11 kV of T1	3.0	1.0	2.78	1.15
11 kV of T2	*1.98*	*0.53*	*1.58*	*1.12*
Notes	**Bold in red: Harmonic distortion exceeds limit** *Scaled values to be used for modeling studies*			

Figures 3 to 5 show that the measured THD values are all within the planning levels recommended as per G5/4-1. The 5th harmonic distortion values at the 66 kV of T1 during evening up to midnight of most days exceed the planning limit of 2 %. All the other individual harmonic distortions are within the corresponding planning limits.

Modelling Study

In order to obtain realistic response and performance from the IPSA model the harmonic current sources have been tuned to give similar responses of THD, 3rd, 5th and 7th harmonic distortions at the 66 kV and 11 kV of T1, and 11 kV of T2 as those obtained from site measurements.

The maximum harmonic voltage distortions at 66 kV and 11 kV of the new primary for connection of the gas compressors, including a tolerance of 15 %, under planned outage conditions obtained with IPSA are given in Table 4.

Table 4. Computer modelling results for Project 2

New primary	Existing Voltage Distortion (%)					
	THD	3rd	5th	7th	11th	13th
66kV	**4.48**	**2.28**	**3.59**	1.14	0.46	0.64
11kV	3.64	0.43	**3.40**	1.04	0.37	0.50

Table 4 shows that the maximum THD, 3rd and 5th harmonic voltage distortions at the 66 kV of the new primary substation exceed the planning level of 3 % for THD and 2 % for 3rd and 5th harmonics; apart from 3rd harmonic they are all within the compatibility levels specified as per G5/4-1 as shown in Table 5. The 5th harmonic voltage distortion at the 11 kV of the primary also exceeds the planning level of 3 %.

Table 5. Compatibility levels for harmonic distortion (G5/4-1)

Voltage (kV)	THD (%)	3rd (%)	5th (%)	7th (%)	11th (%)	13th (%)
66	5.0	2.0	4.0	2.0	1.5	1.5
11	8.0	5.0	6.0	5.0	3.5	3.0

The proportional allowable harmonic contribution of the new variable speed drives can be determined from the allowed planning limits and the background harmonic distortions shown in Table 4. Since the background THD, 3rd and 5th harmonic distortions at the 66 kV of the new primary already exceed planning limits the allowable harmonic contribution of THD, 3rd and 5th harmonics of the new variable speed drives at the 11 kV of the new primary should be zero. If the 5th harmonic can be reduced by the newly designed filters at the 11 kV, the new variable speed drives can contribute other harmonics, e.g. 7th, 11th and 13th, up to the values given in Table 6. Under such conditions, the total individual harmonic distortions at the 11 kV should be within the planning limits allowed as per G5/4-1 and the THD will not be increased.

Table 6. Permissible voltage distortions.

Substation	THD	3rd (%)	5th (%)	7th (%)	11th (%)	13th (%)
New primary	0	0	0	2.4	1.7	1.6

CONCLUSIONS AND RECOMMENDATIONS

Site measurement and modeling studies show that the existing THD, 5th and 7th (project 1 only) harmonic distortions at the grid substations exceed planning levels and there is no capacity for compressor motors at the proposed primary substations. Therefore, it is recommended that the proposed connections should not make any harmonic contributions to the networks and filters should be installed.

ACKNOWLEDGEMENTS

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[2] IPSA Power, *Interactive Power Systems Analysis (IPSA) program User's Manuals.*