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A GAMBICA TECHNICAL GUIDE

MANAGING HARMONICS

A guide to EA Engineering Recommendation G5/4

GAMBICA

ASSOCIATION FOR
CONTROL, AUTOMATION

Foreword

This Guide is a simple authoritative introduction to good practice in the application of variable speed drives, soft starters and load regulators in compliance with the requirements of the United Kingdom electricity supply utilities.

It is the result of work undertaken by GAMBICA members, interpreting the appropriate documents.

The guide should be read in conjunction with the Electricity Association (EA) Engineering Recommendation G5/4, which was introduced on the 1st. March 2001. The Recommendation will be followed by an extensive supporting guide ETR 122.

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Scope

The Guide considers the installation of single or multiple drive systems, and provides information on the manner in which applications for connection should be made with the appropriate utility.

Contents

	FOREWORD	(i)
	SCOPE	(i)
	INDEX	(iii)
1.0	BASIS	1
	1.1 Why change?	1
2.0	HARMONIC CURRENT & VOLTAGE	2
3.0	DRIVE BASICS	3
	3.0.1 Single Phase	3
	3.0.2 Three Phase	3
3.1	DRIVE TYPES	3
	3.1.1 6 pulse	3
	3.1.2 Multi-pulse	4
	3.1.3 Active Rectification	4
	3.1.4 Filters	4
4.0	SOFT STARTERS & LOAD CONTROLLERS	4
	4.1 Controller Basics	5
	4.1.1 Single Phase	5
	4.1.2 Three Phase	5
	4.2 Controller Types	5
	4.2.1 Motor Controllers	5
	4.2.2 Optimising Motor Controllers	6
	4.2.3 Load Controllers	6
5.0	POINT OF COMMON COUPLING	6
6.0	STAGES	7
	6.1 Stage 1	8
	6.1.1 $I_N \leq 16$ A	8
	6.1.2 16 A $< I_N <$ 75 A	8
	6.1.3 $I_N >$ 75 A or Multiple Equipments	9

Contents (continued)

6.0 STAGES (continued)

6.1.4 Stage 1 Typical Drive Loads 9

6.1.5 Filtering 11

6.2 Stage 2 12

6.2.1 Stage 2 Typical Drive Loads 20

6.3 Stage 3 15

6.3.1 General 16

7.0 MEASUREMENTS 16

8.0 RESOLUTION OF PROBLEMS 17

9.0 SUMMARY 18

9.1 The Equipment Supplier 18

9.2 The Supply Utility 18

9.3 The User 18

9.4 Competence 18

APPENDIX 1 19

Request to Connect Non-linear Load and Response from NOC

APPENDIX 2 21

Harmonic Prediction

1.0 Basis

The intention of the new EA Engineering Recommendation G5/4 is to try to ensure that the levels of harmonics in the Public Electricity Supply do not constitute a problem for other users of that supply.

This is a primary function of Electromagnetic Compatibility Management and Regulation.

The principle embodied in G5/4 is to set target levels for the harmonic currents imposed on a network, which are intended to place limits for the overall voltage distortion in a network at planning levels which are applied to achieve compatibility.

G5/4 identifies consumers by their point of common coupling (PCC) to the supply, and applies its limits at that point.

G5/4 therefore applies to every consumer connected to the Public Electricity Supply, including:

- Domestic
- Commercial, shop and office consumers
- Industrial users.

It is the consumer's responsibility to ensure that the appropriate procedures to agree connection of new loads are followed.

It is also very important that consumers understand the responsibilities placed on them by the supply utilities to avoid the possibility of having to implement costly remedial measures in the event of a problem.

1.1 Why change?

EA Engineering Recommendation G5/4 replaces G5/3, which was in place since 1976, and has seen a vast expansion of the numbers of rectifiers used both industrially, in terms of drives and controls, rail traction supplies, in the office environment within IT and in domestic appliances.

There has been a tendency for distortion levels, especially the 5th harmonic, to increase, although it is generally considered that consumer equipment is the main source of this distortion.

G5/4 also introduces areas new to regulation in the UK, including sub-harmonics, interharmonics, and voltage notching.

From the point of view of the user, a modern, well designed drive system will not normally produce significant levels of interharmonics or cause notching outside of the permitted levels and they are therefore not considered in further detail in this guide.

In the United Kingdom, it is possible to purchase electricity from one company, the Public Electricity Supplier (PES), and to have it delivered by another company, the Network Operating Company (NOC). It is the NOC who must agree connection of harmonic producing loads.

The harmonic levels within an individual consumer's network are not covered by this guide, and must be judged solely by the influence they will have at the point of common coupling, and the ability of other equipment on the network to operate satisfactorily.

Typically the voltage distortion limits of BS EN 50160 Table 1 should be acceptable within a single user's site. This would permit up to 8% total harmonic voltage distortion, including up to 6% of 5th. harmonic.

Any rectifier will generate harmonic currents on a network, although they will vary in magnitude according to the design of the specific circuit. It is important that all estimates, calculations, and limits assume a balanced voltage supply. Even a small imbalance can cause large changes in drawn current, particularly with uncontrolled bridge rectifiers, and the harmonic performance of the drive equipment will deteriorate in such conditions. Discussion with the NOC must emphasis this unbalanced situation which could affect meeting predicted harmonic values.

Rectifiers are incorporated in the majority of domestic and office machines, ranging from TVs, through computers and washing machines to cordless telephones, as well as industrial PLCs and drive systems.

All supply systems also have 'natural' harmonics, introduced by the generators and transformers, and may also have resonant frequencies caused by a combination of the capacitances and inductances of the system.

2.0 Harmonic Current & Voltage

It is the harmonic voltage at a given point in the supply network that determines the risk of disturbance to the load at that point.

The part of that voltage which results from the harmonic producing load, is caused by the voltage drop from the supply impedance, due to the individual harmonic currents generated by the load.

Generally the harmonic currents generated by a load are controlled by its circuit design, and these can be predicted with a reasonable degree of confidence by its manufacturer.

They will be affected to some extent by the supply impedance, especially for small drives, which often use little or no inductance in the d.c. link.

The supply impedance is primarily a function of the electricity distribution network, and can normally be predicted by the network operator for the fundamental.

There are three levels of supply impedance which are of importance:

- The minimum level, which would allow the highest possible fault current to flow
- The normal running level
- The maximum level, which would allow the highest possible harmonic voltages to appear.

The minimum value is needed to enable the design of switch and control gear to be evaluated to withstand a potential fault occurrence. This level is frequently misquoted to correspond only to the standard capabilities of switch and control gear, but the correct values are needed to predict the maximum harmonic currents.

The other values represent the normal running range, which are needed to predict the harmonic distortion.

In practice, the system impedance will vary over the course of the day, and the network operator must predict the most appropriate figure as a basis for calculation.

While the system impedance or fault level can be predicted for the fundamental frequency, it is also probable that the impedance will vary relative to the frequency.

This variation can become a source of resonance at some point within the distribution network.

It is very important to try and identify potential sources of resonance, such as power factor correction and long MV supply cables, to ensure that these can be included in calculation models.

The method of representing the system impedance is often by the maximum power that can flow in a fault condition, this is the system fault level, and is usually quoted in MVA.

The higher the fault level the lower the source impedance.

The G5/4 document uses fault level as the measure of source impedance for Stage 1 & 2 assessments.

3.0 Drive Basics

Most variable frequency drives operate by using a bridge rectifier to convert the incoming AC voltage into a DC voltage. The inverter of the drive then converts the DC voltage into a controlled voltage and frequency for speed control of the motor.

There are a multiplicity of drive topologies, the following gives a brief outline of some of the more commonly encountered types:

3.0.1 Single Phase

A typical single phase input frequency converter will be provided with a 4-diode full wave rectifier, feeding an uncontrolled d.c. link, with capacitor energy storage.

This should generate no even harmonic currents but with odd harmonics from 3rd upwards, the magnitude depending on internal impedances.

3.0.2 Three Phase

Three phase supplies will normally be used for industrial power solutions, and will use at least six semiconductors connected in a bridge.

3.1 Drive Types

3.1.1 6 pulse

A typical voltage source a.c. drive fitted with a 6-diode full wave rectifier, feeding an uncontrolled d.c. link, with capacitor energy storage, will generate no even harmonics, no triplen (multiples of 3rd) harmonics, only odd harmonics from the 5th upwards. Again the magnitude will depend on the internal impedances of the system.

Typical d.c. drives (and some 4 quadrant a.c. drives) use a full wave thyristor rectifier. These will generate no even or triplen harmonics, only odd harmonics from 5th upwards, the magnitude again depending on internal impedances.

3.1.2 Multi-pulse

12, (or 18 or 24) pulse full wave rectifier, with phase shifted supplies.

Multi-pulse rectifiers generate no even or triplen harmonics, only odd harmonics from the (n – 1) (where n is the pulse number) upwards, the magnitude depends on internal impedances.

3.1.3 Active Rectification

Most active rectifiers are based on an inverter working in reverse, with enhanced d.c. link voltage. Sometimes known as harmonicless rectifiers, regenerative rectifiers or unity power factor rectifiers.

Small amplitude residual low frequency harmonics and inter-harmonics will occur.

In all cases, some residual even and lower order odd harmonics may occur due to supply imbalances, and manufacturing tolerances in the individual components used. These are difficult to predict, and are generally so small as to be insignificant.

Different manufacturers may also apply different terminology to the different types of rectification described.

3.1.4 Filters

In addition to connecting rectifiers to a network, it is possible to fit filters, and the application of active and passive harmonic filtering as an independent means of attenuation or as part of a power factor correction scheme may provide a cost-effective solution to meeting the planning levels.

The addition of filters can change the system network characteristics, and therefore requires a great deal of care.

4.0 Soft starters and Load controllers

For the purposes of G5/4, semiconductor motor controllers (soft starters) and load controllers, which comply with EN 60947-4-2 and EN 60947-4-3, can be considered as a.c. regulators and the limits for these devices given in G5/4 will apply.

Motor and load controllers rated at more than 16A will have to be considered under the same stages of assessment as for drives. Motor and load controllers rated at less than 16A that comply with the requirements of EN61000-3-2 are exempt from assessment and can be used without restriction. However, devices rated at less than 16A that do not comply with EN61000-3-2 will be classified as professional equipment and will need to be assessed as for controllers rated greater than 16A. In practice, non-optimising motor controllers rated less than 16A will probably comply with EN61000-3-2, whereas load controllers rated up to 16A, and optimising motor controllers rated at more than 5A are unlikely to meet the harmonic emissions requirements of EN61000-3-2 and will require assessment.

4.1 Controller Basics

There are a number of controller topologies, but all employ self-commutating semiconductor switches, either as a single element or, more usually, as an anti-parallel pair inserted in each phase connection to the controlled motor or load.

Controllers having switches controlling each half-wave of the power wave are said to be fully-controlled, whereas those controlling only one half-wave of the power wave with a single switch element paralleled by an uncontrolled diode for the other half-wave in the phase connections are known as half controlled types.

Because they do not produce even harmonics, fully-controlled versions will have a less severe harmonic spectrum than their half-controlled variants. A brief outline of some of the more commonly encountered types is given:

4.1.1 Single Phase

A typical fully-controlled single-phase input controller will be provided with a single semiconductor switch in the line connection to a single-phase load.

This should generate no even harmonic currents; only with odd harmonics from 3rd upwards, the magnitude depending on internal impedances.

4.1.2 Three Phase

Three phase supplies will normally be used for industrial power applications and will use semiconductor switches either in two or three phases. Optimising motor controllers, which use phase control techniques to reduce the voltage supplied to a running motor, will always employ full control to all three phases.

A typical three-phase, fully controlled, a.c. semiconductor motor or load controller, fitted with a 6-pulse thyristor bridge will not generate even or triplen (multiples of 3rd) harmonics, but only odd harmonics from the 5th upwards. Again the magnitude will depend on the internal impedances of the system.

In all cases, some residual even and lower-order odd harmonics may occur due to supply imbalances and manufacturing tolerances in the individual components used. These are difficult to predict, but are generally so small as to be insignificant.

4.2 Controller Types

4.2.1 Motor Controllers

Because motor starting currents are measured in multiples of motor full-load current, the harmonic effects of motor controllers are at their greatest during the motor starting and accelerating phase. However, provided the controller ramp-time is set at three seconds or less, the effects can be ignored. When longer ramp-times are necessary due to higher inertia loads, or where motors with larger inertia rotors are involved, G5/4 accepts the use of soft starting ‘infrequently’ on a ‘conditional’ basis. With this concession, most soft starter installations will not need special considerations. However, if a challenge arises, consumers will need specific information regarding the levels and harmonic spectrum of the type of controller being used.

4.2.2 Optimising Motor Controllers

Optimising motor controllers will introduce odd harmonics (5th and higher) while the optimising function is active during normal running. However, the harmonic effects are greatest at the lightest loads of the motor, and since the harmonic currents are related to a line current which is significantly less than the motor full-load current (typically 35% or lower), the effects at the PCC will be minimal except in unusual circumstances.

4.2.3 Load Controllers

Load controllers are used to regulate the energy supplied to a wide variety of non-motor loads, ranging from control of resistive loads such as lighting arrays, furnaces, etc to non-resistive loads such as capacitor banks. The harmonic effects of load controllers are present all the while the load is being controlled and depend on the degree and nature of the control. Broadly speaking, there are two types of control method:

1. 'Burst firing' where energy is supplied to the load in a sequence of very short periods of a variable number of full cycles and,

2. 'Phase control', where energy is passed continuously to the load through semiconductor switches with variable delays applied to the turn-on of the devices.

Burst firing is most frequently used for the regulation of resistive loads such as furnaces, and usually involves firing the semiconductor devices at the corresponding voltage zero crossings of the supply. In this type of controller, the harmonic effects are relatively benign however, flicker and voltage drop effects can be significant.

Where phase controlled controllers are employed, the harmonic spectrum is directly related to the firing angle of the semiconductor switches in the main circuits. Fully-controlled systems will only generate odd harmonics. If there is no neutral connection, there will be no triplen harmonics with only the 5th and higher harmonics being of concern. Before any assessment of the distortion effects of this type of controller can be made, detailed knowledge of the application and the anticipated range of control are required.

Half-controlled systems have a wider harmonic spectrum and will include even harmonics. For this reason, half-controlled systems are usually limited to low-power applications. Provided the application will allow the harmonics to be restricted to the requirements of IEC 61000-3-2, they can be installed without reference to the supply authority. If this is not the case, then detailed knowledge of the application and the anticipated range of control are required before the processes outlined in G5/4 can be applied.

5.0 Point of Common Coupling

The implementation of G5/4 depends on defining the 'point of common coupling'. This is not necessarily the voltage level at which the equipment is connected.

The Point of Common Coupling (PCC) is the point at which a consumer is connected to other consumers on the Public Electricity Supply.

Generally in the United Kingdom, consumers with connected loads of less than around 15 kVA will normally be connected at 230 V single phase and up to 300 kVA at 400 V.

Consumers, with higher power demands, will normally be connected to the medium voltage network by a dedicated transformer, in which case this medium voltage level will be their point of common coupling, e.g. if a site is fed by a dedicated distribution transformer with nominal ratio 11 kV/420 V and no other consumers are fed by the 400 V system, then the PCC is at 11 kV.

The NOC will apply G5/4 at the point of common coupling (PCC).

The levels of harmonic current and voltage at intermediate points in a consumer's own network are solely at the discretion of the consumer.

6.0 Stages

G5/4 defines three stages of assessment, which increase in complexity.

It is important to note that these stages do not correspond totally to those in the previous document, The Electricity Association Engineering Recommendation G5/3, or to those in the various EN and IEC standards.

In addition, while the Planning Levels for voltage distortion have remained the same for low[1] and medium voltage, and have even increased at high voltage, the limits for some specific harmonic currents have reduced substantially, especially for the 5th harmonic.

Where a user wishes to install new equipment to extend an existing installation, and where agreement to connect has already been established under previous rules, it is possible that the connection of additional equipment could involve a new and lower limit being applied to the whole installation under the terms of a new agreement.

This would be retrospective, and therefore difficult to enforce.

In these circumstances agreement to connect without increase in the aggregate harmonic current loading should be forthcoming, although the overall connection may be for a higher power.

Where a user wishes to replace existing equipment with new equipment of similar functionality, there should be no need to repeat the application procedure, if documentary evidence exists that the levels of harmonic currents generated by the new equipment do not exceed the existing levels.

[1]*Low voltage* $U_n < 1000$ *V, medium voltage* $1000 < U_n < 35000$ *V, high voltage* $35000 < U_n$

6.1 Stage 1

Under G5/4 Stage 1, only connections to 230 V single phase and 400 V three phase supplies are considered.

G5/4 assumes that there will be no more than four harmonic producers connected to a single supply source (distribution transformer) when considering Stage 1 connections. The 'available' levels of harmonic current per point of connection have been split in accordance with this assumption.

6.1.1 $I_N \leq 16$ A[2]

Under the EMC Directive, any equipment with nominal current less than or equal to 16 A RMS (per phase), and which meets Harmonised European Standard EN 61000-3-2, will carry a 'CE mark' to this directive and may be connected without further assessment.[3]

Where a number of items of equipment are installed, the aggregate of the rated currents must be less than or equal to 16 A, and each individual piece of equipment must also comply with EN 61000-3-2.[4]

Basically, this standard covers domestic equipment such as televisions, washing machines, etc. and it is also these devices which are responsible for the bulk of harmonic voltage distortion throughout the network.

Under this standard, drives are considered to be professional equipment, and with a rated input over 1 kW they are at present accepted with no limits under this standard.

If the equipment is a conventional inverter load, and the combined total rating is under 5 kVA for a single-phase supply, it may again be connected without further assessment.[5]

6.1.2 16 A < I_N < 75 A

For three phase supplies, a maximum total of 12 kVA of standard 6-pulse diode rectifier loads can be connected without further assessment.[6]

Any single piece of equipment between 16 A and 75 A nominal current which meets Stages 1 or 2 of Technical Report IEC 61000-3-4 (which will be replaced in due course by the standard IEC 61000-3-12) can be connected without further assessment.[7]

This standard allows a single 6-pulse diode rectifier frequency converter with a.c. or d.c. chokes rated at up to 1/350 of the fault level, to be connected without further assessment. (As G5/4 assumes a fault level of 10 MVA on a 400 V network, this will permit a drive up to approximately 30 kVA).[8]

The procedures detailed refer to a single consumer having single items of harmonic generating equipment installed to a single point of common coupling.

[2] *I_N = Rated current drawn*
[3] *G5/4 Clause 6.2*
[4] *EN 61000-3-2 A14 2000*
[5] *G5/4 Clause 6.3.1.1*
[6] *G5/4 Table 6*
[7] *G5/4 Clause 6.3*
[8] *IEC 61000-3-4 Table 3, based on 10 MVA Fault Level*

6.1.3 I_N > 75 A or Multiple Equipments

The sum of the harmonic currents generated by all the equipment connected to a single point of common coupling can be calculated and checked to be below G5/4 Table 7.

This restricts the total amount of equipment that can be installed by a single consumer under the Stage 1 procedure, and includes multiple equipments meeting the harmonised standard EN 61000- 3-2.

One possible problem area in this procedure is where the standing voltage distortion level is already close to or above the planning level (5%).

In this case, the Network Operator reserves the right to examine any additional load under the Stage 2 procedure.

If a Table 7 assessment needs to be made, the drive supplier will normally provide the appropriate data for individual drives

It must also be remembered that G5/4 Table 7 is based on a system fault level of 10 MVA at 400 V.

This is fairly typical for an urban supply system. However, this must be confirmed by the supply utility.

If the fault level varies from this base level the figures in Table 7 may be varied pro-rata, as will the powers that can be connected.

It is the responsibility of the supply utility to advise the effective peak, normal running and minimum running fault levels.

This information also has implications to the electrical safety of the consumer's equipment.

6.1.4 Stage 1
Typical Drive Loads

When the levels of harmonics generated by different types of drive rectifiers are considered, at the base fault level for the system, we may expect to be able to connect the following powers:

- 6 pulse diode –
  30 kW limited by the 5th harmonic
- 12 pulse diode –
  300 kW limited by the 23rd harmonic
- Active Rectifier –
  possibly up to 500 kW.

To calculate the resulting level, the arithmetic sum of all the harmonics for a number of drives is taken. A typical calculation example is shown in Figure 1.

In practice, there will be a co-incidence factor, depending on the relative loading and method of connection of each specific rectifier, giving a small safety margin in the calculation.

This co-incidence factor may need to be more carefully considered as phase shifting and consequent summation or subtraction can occur between industrial and domestic loads.

With an uncontrolled rectifier, the 5th, 11th, and 17th (6n – 1) harmonics, on a three phase system, will always be in phase, whilst the 7th, 13th, and (6n + 1) harmonics will vary in phase with the relative loading of the rectifier. In addition, the harmonics generated on a single-phase (phase/neutral) network will also be phase displaced to the harmonics generated by a three phase (phase/phase) system.

Guidance to harmonic co-incidence factors was given in G5/3 Table A3, however, G5/4 now refers to IEC 61000-3-6.

Practical experience suggests for a number of unequally loaded uncontrolled (diode) rectifiers, the (6n – 1) harmonics will always be in phase and currents should be summed arithmetically.

The (6n + 1) harmonics, however, will vary in phase and current cancellation will allow a reduction from the arithmetic sum by a factor of up to 10%.

Application Example of Table 7

Figure 1 shows the summation of harmonics, without the use of co-incidence factors.

	Domestic Load (Lighting, PCs. Etc)	Drive 1	Drive 2	Drive 3	Sum	G5/4 Table 7	Margin
Rating (kVA)		11	80	260			
Motor Power (kW)		7.5	55	200			
Rectifier Type		6 p diode	12 p diode	Active			
Current	(A)	(A)	(A)	(A)	(A)		(A)
Harmonic							
Fundamental	12.4	12.0	83.6	299	407	N/A	
I_3	11.0	Negligible	Negligible	0.15	11.15	48.1	37.0
I_5	8.0	4.8	2.0	1.53	16.33	28.9	12.6
I_7	4.8	1.73	1.03	1.34	8.9	41.2	32.2
I_9	2.2	Negligible	Negligible	0.28	2.48	9.6	7.1
I_{11}	1.0	0.54	5.2	1.3	8.04	39.4	31.4
I_{13}	0.9	0.17	3.76	0.75	5.58	27.8	22.2
I_{17}	0.8	0.28	0.19	0.8	2.07	13.6	11.5
I_{19}	0.5	0.24	0.14	0.26	1.14	9.1	8.0
I_{23}	0.4	0.17	0.83	0.81	2.21	7.5	5.3
I_{25}	0.3	0.28	0.72	0.9	2.2	4.0	1.8
I_{29}	0.2	0.1	0.06	1.75	2.11	3.1	0.9
I_{31}	0.2	0.09	0.06	0.64	0.99	2.8	1.8
I_{35}	0.1	0.08	0.44	1.13	1.75	2.3	0.55
I_{37}	0.1	Negligible	0.38	1.32	1.7	2.1	0.4
I_{41}	0.08	Negligible	Negligible	0.92	1.0	1.8	0.8
I_{47}	0.07	Negligible	Negligible	0.27	0.34	1.4	1.1
I_{49}	0.09	Negligible	0.22	0.63	0.94	1.3	0.4

Figure 1. Example of Table 7 Calculation

While it is possible to calculate values to several decimal places, in practice it is impossible to measure even small systems to better than one decimal place. This should be considered when calculating the margin.

For even harmonics and triplens, due to three phase loads, the values will normally be negligible and need not be recorded.

The 3rd harmonic and other triplens will occur on most three phase networks due to voltage imbalance and phase sequence effects of the supply system at the rectifier terminals. These cannot be readily quantified by calculation. In addition, single phase loads may result in some triplen contribution.

G5/4 permits any two harmonics between 6th and 19th to exceed the limit by 10% or 0.5 A, whichever is the greater.

G5/4 also permits any four harmonics above the 19th to exceed the limit by 10% or 0.1 A, whichever is the greater.

In each case, the uncertainty of the measurement may well be greater than these values.

Beyond the 25th harmonic, the values are only indicative until 2005, when they will become limits, unless experience shows them to be unrealistic.

These values are normally extremely low. The currents are also significantly attenuated by the distribution system, and do not normally cause problems with the exception of a possibility of interference with older analogue telephone installations.

The example in Figure 1, which consists of over 250 kW of converter fed motor loads, meets the current limits for each harmonic and should therefore be acceptable for connection at Stage 1.

The chart, which is based on a simple spreadsheet model, provides a ready means of presenting the appropriate data.

6.1.5 Filtering

If alternative means of harmonic attenuation are being utilised, such as a closed loop active harmonic filter, which will inject anti phase harmonics, the attenuation of this device can be shown as a negative value in this table.

When calculating a suitable filter the harmonic generation of the rectifier against a true sinusoid should be considered, as the measured harmonic currents from a rectifier will be lower when a standing distortion exists on a network. As the filter will result in an improved network distortion the actual absorption may be higher than measurements predict.

The same principle may also be applied to open loop active and tuned filters if the load is non-dynamic. However, tuned filters may also import harmonic load.

The addition of tuned filters must be very carefully considered, especially with conventional voltage source PWM drives.

These filters consist of an LC (inductor and capacitor) network, tuned close to a harmonic frequency (typically 225 -235 Hz on a 50 Hz network) to provide a low impedance path to allow controlled harmonic current flow.

The filter is therefore inherently capacitive below the tuned frequency and reactive above. The low impedance at the tuned point may also allow harmonic currents to be imported from other parts of a network.

As a diode rectifier presents very little fundamental reactive load to compensate, it is relatively easy to create a system that can achieve a leading power factor, which in turn may set up a resonant condition with the d.c. link components and result in premature drive or filter failure.

The use of this type of filter with a d.c. drive provides a convenient and cost-effective means of controlling both power factor and harmonic load.

The use of power factor correction capacitors without de-tuning is not recommended on any circuits that may have a harmonic content, as they will appear as a low impedance path for any harmonics on that network.

If the connection is not acceptable at Stage 1 or is at Medium Voltage, it is possible to consider a Stage 2 assessment.

6.2 Stage 2

If the levels of harmonics exceed those for Stage 1, or the standing distortion is already close to the planning level, or the point of common coupling is at medium voltage (6.6 kV to 22 kV), then a different procedure is called for.

Firstly, for an MV PCC, if the total of converter loads is lower than 130 kVA of 6 pulse or 250 kVA of 12 pulse diode rectifier, there is no need for further assessment.

Otherwise the Network Operator is obliged to determine the network background voltage distortion.

This should be a measured value, and for a balanced load application should record as a very minimum the primary odd distorting harmonics, up to the 25th, plus the total harmonic distortion (THD) from 2nd to 50th harmonic.

The peak values of voltage harmonic distortion on the UK network will usually occur on a Saturday or Sunday evening, when very high levels of domestic television viewing co-incide with minimal levels of generation.

The measurements should therefore be taken over a period of seven days, to allow the results to be assessed realistically.

Under G5/4, if the measured distortion on a network is less than 75% of the planning level for voltage distortion, then a summation of currents can be used and compared with G5/4 Table 12.

Within the scope of G5/4, there is the provision to allow the background level to be assessed on the basis of the level that is not exceeded for 95% of the time.

If the equipment will not be in continuous operation, the background should only be considered for the hours and days of the week that the equipment will be operated.

As an example, taking an 11 kV point of common coupling, if the measured THD is less than 3% - that is less than 75% of the planning level at 4%, and the 5th harmonic distortion is less than 2.25% (75% of 3%), then we can apply G5/4 Table 12, as shown in Figure 2.

The planning levels for THD are the same as the former G5/3 levels for 400 V and 11 kV networks (5% and 4%), however, maximum 5th harmonic content is now introduced (4% and 3%).

The values of current permitted in G5/4 Table 12 are substantially lower than the previous G5/3 Stage 2 limits.

6.2.1 Stage 2 Typical Drive Loads

The current levels in Table 12 of G5/4 correspond typically to the following levels of single rectifier load:

- 6 pulse diode – 185 kW limited by the 5th harmonic
- 12 pulse diode – 2000 kW limited by the 25th harmonic
- 24 pulse diode – 2400 kW limited by the 25th harmonic
- Active Rectifier – possibly up to 3150 kW.

	Drive 1	Drive 2	Drive 3	G5/4 Table 12
Rating (kVA)	260	2750	3000	
Motor Power (kW)	175	2000	2400	
Rectifier Type	6 p diode	12 p diode	24 p diode	
Current	(A)	(A)	(A)	
Harmonic				
Fundamental	9.9	110.5	132.6	N/A
I_3	Negligible	Negligible	Negligible	6.6
I_5	3.7	2.6	2.7	3.9
I_7	1.6	1.3	1.5	7.4
I_9	Negligible	Negligible	Negligible	1.8
I_{11}	0.8	6.2	1.4	6.3
I_{13}	0.5	4.3	1.0	5.3
I_{17}	0.4	0.2	0.2	3.3
I_{19}	0.2	0.2	0.2	2.2
I_{23}	0.1	1.0	1.1	1.8
I_{25}	0.1	1.0	1.0	1.0
I_{29}	0.1	0.1	0.1	0.8
I_{31}	Negligible	0.1	0.1	0.7
I_{35}	0.1	0.5	0.3	0.6
I_{37}	Negligible	0.4	0.3	0.5
I_{41}	Negligible	Negligible	Negligible	0.4
I_{47}	Negligible	0.3	0.3	0.3
I_{49}	Negligible	0.3	0.3	0.3

Figure 2. Comparison of typical rectifier harmonic loads at 11 kV with G5/4 Table 12

If the distortion, present before the new load is connected, exceeds 75% of the appropriate voltage planning level or the currents exceed the Table 12 limits, then, it is necessary to determine the voltage distortion that is likely to be generated by the new load, and to predict the overall levels of voltage distortion that will result.

In this case the predicted harmonic currents for the load as calculated by the manufacturer should be submitted to the supply utility for them to calculate the effect of the proposed new load.

The harmonic currents are used to calculate the resultant voltage distortion, however, G5/4 uses some correction factors to allow for possible system resonances in making this calculation.

At 400 V the voltages generated by harmonic currents of the 7th order and above are reduced by 50%, and for 6.6 kV, 11 kV, and 22 kV systems voltages generated by harmonic currents up to the 7th order are doubled.

If the resultant THD and the level of 5th harmonic remain within the planning levels, then connection should be agreed.

Typical examples of a voltage distortion calculation are given in Figure 3, based on the 6 pulse drive shown in Figure 2, with the system impedances typical in a 100 MVA fault level system.

Rectifier Rating	260 kVA				
Harmonic	**Current (A)**	**Voltage**	**Correction Factor**	**Corrected Voltage**	**% Voltage**
Fundamental	9.9	11000			
5	3.7	34.45	2	68.9	0.62
7	1.6	20.80	2	41.6	0.38
11	0.8	16.31	1	16.3	0.15
13	0.5	12.05	1	12.0	0.11
17	0.4	12.60	1	12.6	0.11
19	0.2	7.04	1	7.0	0.06
23	0.1	4.26	1	4.3	0.04
25	0.1	4.63	1	4.6	0.04
29	0.1	5.37	1	5.4	0.05
35	0.1	6.48	1	6.5	0.06
THD					0.77%

Figure 3. Voltage Distortion Calculation

A clear exchange of information is needed in order that the drive supplier should be able to offer the most cost-effective solution.

The drive supplier is only indirectly a party to the application of G5/4, however, in practice to achieve the optimal solution the customer should encourage direct involvement and good communication between the utility and the supplier.

There are a number of techniques available to minimise harmonics and potential supply problems. These consist of modifications of the network or the drive, and range from phase shifting, through multi-pulse rectifiers, to filters.

The sequence for exchange of information should preferably be as shown in the Appendices. It must always be remembered that the time scale for this exchange is critical to avoid unreasonable delays in implementation of a project.

6.3 Stage 3

If the levels of harmonics exceed those for Stage 2, or if the point of common coupling is at 33 kV or over, then a different and substantially more complex procedure is called for.

In this case, measurements to determine the distortion of the local network, at least up to the 33 kV level are needed, together with detailed information on the system impedances.

This information is then used in constructing a computer model, showing the inter-relationship of the consumers' network and the local supply network, to enable the effects of the new harmonic sources to be modelled.

Currently there is little standardised methodology for undertaking this type of study, and this needs to be established between the NOC, the consumer, and the drive supplier.

A number of proprietary programs are available for network studies; most were developed to enable the safety of a system to be established by calculating worst case fault levels, and establishing the protective equipment co-ordination. Each of these programs has both strengths and limitations. It is therefore important that the most effective software and correct form of study is selected and undertaken.

Within the model, account may be taken of the variation of existing and predicted harmonic levels with time of day, and/or day of the week. This may be useful if a clear correlation can be established between the existing levels and the effect of the proposed load.[9]

According to G5/4, it is the responsibility of the network operating company (NOC) to carry out these calculations, and to determine whether the proposed load is acceptable for connection.

In practice, even with the most precise software, the validity of the model will depend absolutely on the accuracy of information input.

In practice, the user will need to plan the installation in advance to be sure that it will be accepted. This means that the

[9] *G5/4 Para 8.3.2*

information, which will be used by the NOC to carry out the estimation, must be made available during the planning phase.

These studies are inevitably time consuming and costly, and the apportionment of these costs must also be established.

6.3.1 General

If a drive installation is to be run for less than 24 hours daily, it is quite possible to consider only the standing distortion during the proposed operating period.

7.0 Measurements

Measurements can be taken of supply impedances and both harmonic currents and voltages using proprietary equipment.

The most common form of measurement is the voltage distortion over a period of time, and while G5/3 accepted measurements over 24 hours, G5/4 now looks to a seven day record in order to establish the worst case operating conditions.

The accuracy of any measurement is limited by the measuring equipment, and the method of measurement.

At low voltage, it is normal to take direct voltage measurements, but current measurements are normally made indirectly by a current transformer, Hall effect transducer, or Rogowski coil.

At medium and high voltage, the measurement voltage and current transformers forming the switchgear protection or metering provisions are normally the only facilities available to be utilised, adding their inaccuracies. They also place limitations in terms of the phase shift between current and voltage transformers, and the numbers of CTs and VTs fitted.

Most of these devices are not designed to measure accurately at frequencies other than the fundamental and any inaccuracies due to the methods of magnetic coupling must also be considered.

The equipment or an associated computer program undertakes a Fourier Analysis of the resultant waveform, and logs the results.

The standard for making measurements is currently the harmonised European Standard EN 61000-4-7, which defines the class of accuracy for measuring instruments.

The harmonic current measurement tolerances may be greater than the actual values in G5/4 Tables 7 and 12 at higher frequencies when measuring larger loads.

This may limit the validity of measurements to show compliance with Table 7 or Table 12 for higher power levels.

8.0 Resolution of Problems

G5/4 is a process for permitting connection of new non-linear loads to the public electricity supply.

If it is applied consistently, it is unlikely that problems will arise after installation and commissioning.

Firstly, it is critically important that adequate and sufficient information is available at the outset of a project, and that this information is provided in a timely manner.

As drives up to 250 kW or greater are available from most suppliers' stock, or a short delivery and even drives with ratings exceeding 1MW, are available within eight or ten weeks. Therefore, any delay in the provision of information could be critical to the implementation of a project.

Exact calculation of harmonics for drives is a difficult procedure, as the supply impedance and existing harmonic voltages will influence the magnitude and direction of harmonic current flow in a rectifier.

This is especially true where there are several rectifier combinations, variations in the supply source fault level, tap-changer settings, and installed power factor correction.

If the supply utility is unable to complete the calculations for a Stage 2 or Stage 3 connection, within a reasonable time[10], the consumer should be permitted to undertake the measurements and to submit calculations.

Normally the equipment manufacturer will be best placed to carry out the calculations and simulations. The NOC should provide such data as is available, including confirmation of the fault levels for Stage 1 or Stage 2, and the supply impedance model for Stage 3.

If a problem does occur, it is most likely to be where a measurement is made after installation, and the levels of voltage distortion are shown to be excessive.

If the current harmonics are within the levels predicted at the time of approval, it would be unreasonable to ask the consumer to contribute to remedial measures.

It is therefore incumbent on the parties to an agreement to connect to have a procedure for arbitration in the event of a problem.

[10]*A maximum time of one month would be reasonable.*

9.0 Summary

The use of intelligent power controllers, such as variable speed drives and soft starters is well accepted both in industry and by Government as one of the major means available to improve energy efficiency and productivity. It is also essential to many industries to achieve process control, so it is in the interests of all parties to co-operate to facilitate their use.

This leads to an examination of the responsibilities of the different parties involved in the use of a drive system.

9.1 The Equipment Supplier

The responsibility of the equipment supplier is to identify the harmonic currents generated by the equipment under defined conditions.

9.2 The Supply Utility

The responsibility of the Supply Utility is to provide appropriate details of the network, including the appropriate fault levels in normal and emergency operating conditions, and to identify any known limitations, including existing harmonic levels.

9.3 The User

The responsibility of the user is to ensure that the compatibility of his network, and compliance with the appropriate requirements.

9.4 Competence

Understanding the propagation of harmonics is a complex problem, and in general, the drive manufacturers have the greatest experience in the application of their products.

GAMBICA drive manufacturers have many years of experience at meeting all sorts of harmonic limitations. However, it can often be time consuming to provide associated information and other assistance.

The manufacturers' basic responsibility is to provide the detail as shown in Appendix 2.

However, most manufacturers are able to offer additional services including system studies, and to make appropriate measurements at a reasonable cost.

Appendix 1

Request to Connect Non-linear Load

To: A Network Operating Company

From: A consumer company

Contact:
Phone No:
Fax: E-mail

Installation Site

Voltage at Point of Common Coupling (If known)		kV
Connection Substation (If known)		
Site Line Diagram, showing connection.	Enclosed	Not available
Description of load		
Motor Rating		kW
Motor Voltage		V
Converter		kVA
Converter Rectifier		
Interposing Transformer (1)		
Ratio (no load)		
Rating		kVA
Impedance		%
No load loss		kW
Load loss		kW
Proposed Stage of Connection		
Proposed Method of Compliance		
	Power within Table 6 of G.5/4	
	Compliance with Table 7 of G.5/4	
	Compliance with Table 12 of G.5/4	
Enclosures	Manufacturers prediction	Appendix 2

Figure 4. Suggested Format for Application to connect to Supply.

Response from NOC

From: A Network Operating Company

To: A consumer

Agreed Point of Common Coupling voltage		kV
Connection substation		
Fault level (Peak)		MVA at PCC
Fault level (Running)		MVA at PCC
Stage of Connection	Stage 1/Stage 2/Stage 3	
For Stage 2/Stage 3 connection		
Existing worst case distortion (THD)		
Existing worst case 5th harmonic (V_5)		
95 percentile value of THD for calculation		
95 percentile value of V_5 for calculation		
For Stage 3 connection		
Supply impedance values		
Supply impedance X/R		
Complex Impedance	+ j	Ω max
	+ j	Ω min
Special conditions		

Figure 5. Suggested Format for Application to connect to Supply.

The following information is also anticipated:

i) Any available information regarding major sources of harmonics in the neighbourhood
ii) Details of any large consumer in the same network who may be affected
iii) Details of any filter networks in the same network
iv) Transient or emergency conditions which may apply additional stress to the system network - eg: likelihood of lightning strikes, large DOL motor starting loads
v) Details of any suspected resonant conditions within the local network.

In the case of large power installations and a penetration/load flow study being required, full details of each of these will be required.

Appendix 2

Harmonic Prediction

Supplier					
Type Reference					
Load power	30 kW				

Network and Transformer Data

Nominal voltage [V]	11000 (Primary side)	400 (secondary side)
Frequency	50	[Hz]
Primary Network Sk	100	[MVA]
Transformer Sn	500	[kVA]
Transformer Pk	4.7	[kW]
Transformer Zk	4.5	[%]
Secondary Network Sk	10	[MVA]

Converter Data

Converter Rating	40	[kVA]
Rectifier Device	Diode	
Pulse #	6	
Lv	440	[uH]
Cdc	1.65	[mF]
Udc	540	[V]
Idc	61	[A]

Result

Cosfii	0.999	THD Current	48.2 %
Tot. power factor	0.9	THD Voltage	1.1 %
Udmax mot.	98%		

Significant Harmonics

h	f [Hz]	Current [A]	I_h / I_1	Voltage [V]	U_h / U_1
1	50	48.1	100.0 %	399.4	100.0 %
5	250	18.9	39.3 %	3.0	0.8 %
7	350	9.8	20.3 %	2.1	0.5 %
11	550	4.2	8.8 %	1.4	0.3 %
13	650	2.8	5.9 %	1.1	0.3 %
17	850	2.1	4.3 %	1.1	0.3 %
19	950	1.3	2.8 %	0.8	0.2 %
23	1150	1.1	2.4 %	0.8	0.2 %
25	1250	0.7	1.4 %	0.5	0.1 %
29	1450	0.6	1.2 %	0.5	0.1 %
31	1550	0.4	0.8 %	0.4	0.1 %
35	1750	0.3	0.6 %	0.3	0.1 %
37	1850	0.3	0.6 %	0.3	0.1 %
41	2050	0.2	0.3 %	0.2	0.1 %
43	2150	0.2	0.5 %	0.3	0.1 %
47	2350	0.2	0.3 %	0.2	0.1 %
49	2450	0.2	0.4 %	0.3	0.1 %

Figure 6. Suggested Format for Drive Suppliers Response - (Typical data for a 30 kW Drive system).

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- Process measurement and control equipment and systems
- Environmental analysis and monitoring equipment
- Laboratory products
- Test and measurement equipment for electrical and electronics industries.

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