Application Guidance Notes: Technical Information from Cummins Generator Technologies

# AGN 026 – Harmonic Voltage Distortion

***Comment;*** *The critical level of acceptable harmonic voltage distortion % is set by the capability of the NLL, not an inability of the alternator.*

**<u>DESCRIPTION:</u>**

The explanation below, used with the table and graph, will enable the required level of harmonic voltage distortion % to be estimated by selection of an appropriate alternator. To achieve this required level of system harmonic voltage distortion, the alternator must have a maximum calculated value of Sub-transient Reactance [X”d], for the kVA level [or ‘base kVA’] associated with the connected Non Linear Load. Below is a quick method to be used in conjunction with experience about typical and acceptable levels of THD, followed by the classic mathematical approach for when all the information is provided.

This ‘base kVA’ value of X”d can be calculated by:

$$\left[\frac{\text{the kVA of the Non Linear Load}}{\text{the kVA of the alternator for which the value of X”d is known}}\right] \times \sqrt{\text{the known value of X”d } \textit{[for the voltage the alternator will supply the load]}}$$

**<u>X”d Table and Graph for Alternators with Winding 311/312</u>**

There are known key alternator values of X”d that are required to achieve particular system harmonic voltage distortion levels. If we consider a typical 6-pulse system, with 30% harmonic current distortion:

- If the required level of harmonic voltage distortion is 10%, then the value of the alternator's X"d at the NLL's rated input kVA will need to be 3.5%.

- If 15% harmonic voltage distortion is acceptable, then X"d at 5.3% is needed.

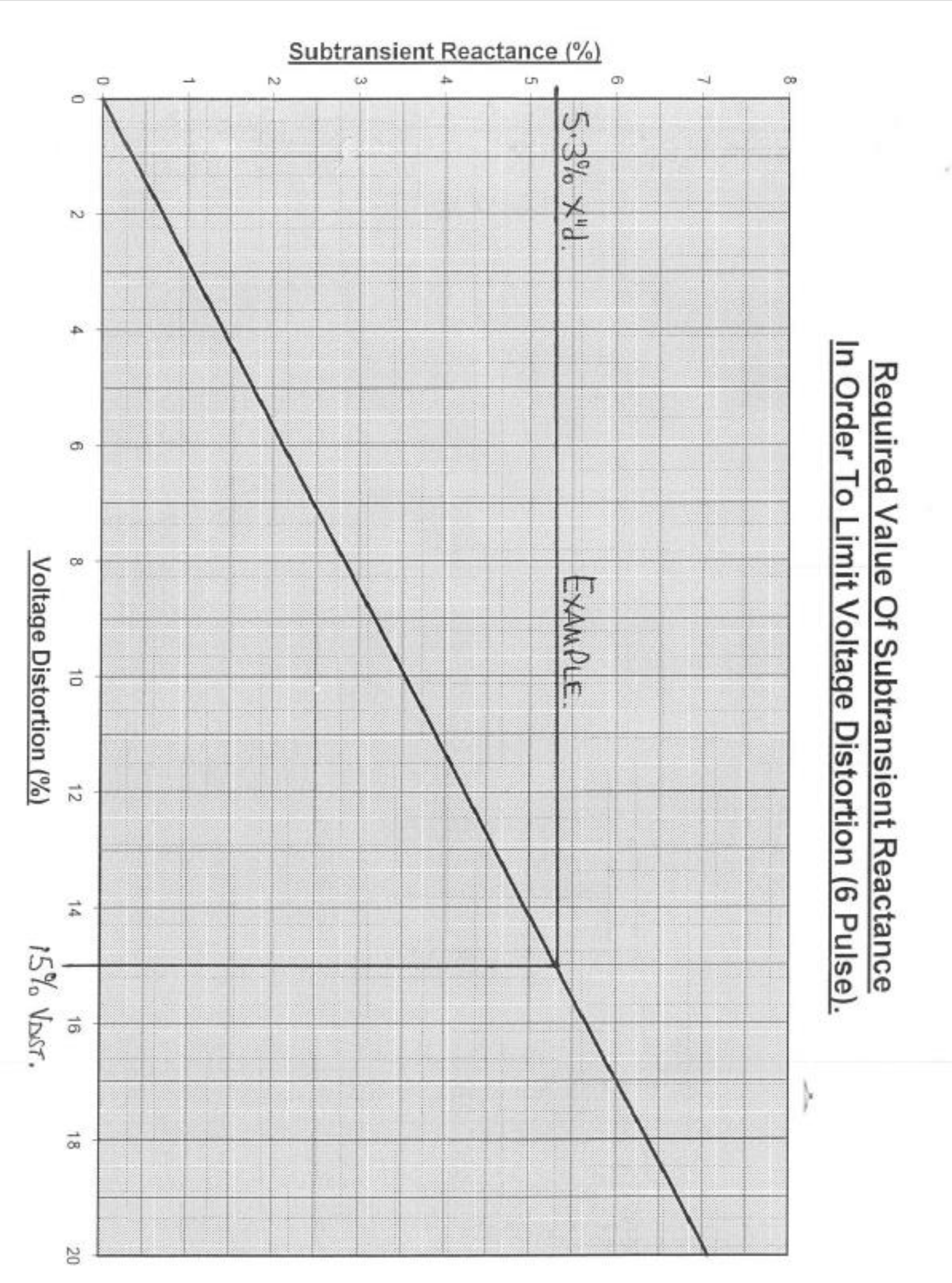
The following table provides alternator kVA ratings with X"d at 12%, 5.3% and 3.5%.

**6 pulse NLLoads**

**Considering the KVA values at the shown X"d% for reference against expectations of harmonic V.dist% for NLLoads, Winding 311/312 only.**

| | 50Hz SITUATION | | | | | | | | | | | | 60Hz SITUATION | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Volts | 380 V | 380 V | 380 V | 400 V | 400 V | 400 V | 415 V | 415 V | 415 V | 440 V | 440 V | 440 V | 416 V | 416 V | 416 V | 440 V | 440 V | 440 V | 460 V | 460 V | 460 V | 480 V | 480 V | 480 V | Volts |
| 3 Phase | | | | | | | | | | | | | | | | | | | | | | | | | 3 Phase |
| X"d | 12% | 5.3% | 3.5% | 12% | 5.3% | 3.5% | 12% | 5.3% | 3.5% | 12% | 5.3% | 3.5% | 12% | 5.3% | 3.5% | 12% | 5.3% | 3.5% | 12% | 5.3% | 3.5% | 12% | 5.3% | 3.5% | X"d |
| UC 224 C | 42 | 19 | 12 | 46 | 20 | 13 | 51 | 23 | 15 | 60 | 27 | 18 | 40 | 18 | 12 | 45 | 20 | 13 | 48.5 | 21 | 14 | 55 | 24 | 16 | UC 224 C |
| UC 224 D | 50 | 22 | 15 | 54 | 24 | 16 | 60 | 27 | 18 | 64 | 28 | 19 | 48 | 21 | 14 | 53.5 | 24 | 16 | 58 | 26 | 17 | 65 | 29 | 19 | UC 224 D |
| UC 224 E | 55 | 24 | 16 | 60 | 27 | 18 | 65 | 29 | 19 | 77 | 34 | 22 | 54 | 24 | 16 | 60 | 27 | 18 | 67 | 30 | 20 | 70 | 31 | 20 | UC 224 E |
| UC 224 F | 72 | 32 | 21 | 79 | 35 | 23 | 87 | 38 | 25 | 93 | 41 | 27 | 72 | 32 | 21 | 80 | 35 | 23 | 87.5 | 39 | 26 | 93.8 | 41 | 27 | UC 224 F |
| UC 224 G | 78 | 34 | 23 | 85 | 38 | 25 | 92 | 41 | 27 | 105 | 46 | 31 | 80 | 35 | 23 | 90 | 40 | 26 | 100 | 44 | 29 | 104 | 46 | 30 | UC 224 G |
| UC 274 C | 86 | 38 | 25 | 92 | 41 | 27 | 100 | 44 | 29 | 111 | 49 | 32 | 84 | 37 | 25 | 94 | 42 | 27 | 101 | 45 | 29 | 115 | 51 | 34 | UC 274 C |
| UC 274 D | 114 | 50 | 33 | 131 | 58 | 38 | 137 | 61 | 40 | 145 | 64 | 42 | 105 | 46 | 31 | 118 | 52 | 34 | 127 | 56 | 37 | 146 | 65 | 43 | UC 274 D |
| UC 274 E | 120 | 53 | 35 | 129 | 57 | 38 | 140 | 62 | 41 | 156 | 69 | 46 | 113 | 50 | 33 | 126 | 56 | 37 | 134 | 59 | 39 | 153 | 68 | 45 | UC 274 E |
| UC 274 F | 148 | 65 | 43 | 160 | 71 | 47 | 174 | 77 | 51 | 200 | 88 | 58 | 155 | 69 | 45 | 175 | 77 | 51 | 190 | 84 | 55 | 206 | 91 | 60 | UC 274 F |
| UC 274 G | 166 | 73 | 48 | 180 | 80 | 53 | 196 | 87 | 57 | 235 | 104 | 69 | 164 | 72 | 48 | 187 | 83 | 55 | 201 | 89 | 59 | 231 | 102 | 67 | UC 274 G |
| UC 274 H | 200 | 88 | 58 | 218 | 96 | 64 | 240 | 106 | 70 | 285 | 126 | 83 | 204 | 90 | 60 | 226 | 100 | 66 | 245 | 108 | 72 | 278 | 123 | 81 | UC 274 H |
| | | | | | 0 | 0 | | 0 | | | | | | | | | | | | | | | | | |
| HC 434 C | 214 | 95 | 62 | 231 | 102 | 67 | 250 | 111 | 73 | 273 | 121 | 80 | 211 | 93 | 62 | 235 | 104 | 69 | 257 | 114 | 75 | 289 | 128 | 84 | HC 434 C |
| HC 434 D | 253 | 112 | 74 | 272 | 120 | 79 | 295 | 130 | 86 | 336 | 149 | 98 | 270 | 119 | 79 | 300 | 133 | 88 | 335 | 148 | 98 | 346 | 153 | 101 | HC 434 D |
| HC 434 E | 300 | 133 | 87 | 325 | 144 | 95 | 364 | 156 | 103 | 390 | 172 | 114 | 326 | 144 | 95 | 364 | 161 | 106 | 406 | 179 | 119 | 419 | 185 | 122 | HC 434 E |
| HC 434 F | 380 | 168 | 111 | 414 | 183 | 121 | 456 | 202 | 133 | 507 | 224 | 148 | 410 | 181 | 120 | 456 | 202 | 133 | 505 | 223 | 147 | 570 | 252 | 166 | HC 434 F |
| | | | | | 0 | 0 | | 0 | | | | | | | | | | | | | | | | | |
| HC 534 C | 415 | 183 | 121 | 450 | 199 | 131 | 491 | 217 | 143 | 540 | 239 | 158 | 485 | 214 | 142 | 550 | 243 | 161 | 581 | 257 | 170 | 648 | 286 | 189 | HC 534 C |
| HC 534 D | 545 | 241 | 159 | 600 | 265 | 175 | 667 | 295 | 195 | 750 | 332 | 219 | 575 | 254 | 168 | 648 | 286 | 189 | 682 | 301 | 199 | 773 | 342 | 226 | HC 534 D |
| HC 534 E | 600 | 265 | 175 | 654 | 289 | 191 | 720 | 318 | 210 | 800 | 354 | 234 | 681 | 301 | 199 | 778 | 344 | 227 | 797 | 352 | 233 | 900 | 398 | 263 | HC 534 E |
| HC 534 F | 731 | 323 | 213 | 804 | 355 | 235 | 893 | 395 | 261 | 975 | 431 | 285 | 805 | 356 | 235 | 930 | 411 | 272 | 960 | 424 | 280 | 1100 | 486 | 321 | HC 534 F |
| | | | | | 0 | 0 | | 0 | | | | | | | | | | | | | | | | | |
| HC 634 G | 533 | 236 | 155 | [illegible] | 265 | 175 | 640 | 283 | 187 | 738 | 326 | 215 | 500 | 221 | 146 | 555 | 245 | 162 | 608 | 269 | 178 | 667 | 295 | 195 | HC 634 G |
| HC 634 H | 607 | 268 | 177 | 682 | 301 | 199 | 728 | 322 | 213 | 808 | 357 | 236 | 647 | 286 | 189 | 709 | 313 | 207 | 759 | 335 | 222 | 844 | 373 | 246 | HC 634 H |
| HC 634 J | 706 | 312 | 205 | 800 | 354 | 234 | 857 | 379 | 250 | 1000 | 442 | 292 | 726 | 321 | 212 | 800 | 354 | 234 | 882 | 390 | 258 | 975 | 431 | 285 | HC 634 J |
| HC 634 K | 832 | 368 | 242 | 951 | 420 | 278 | 1024 | 453 | 299 | 1110 | 491 | 324 | 850 | 376 | 248 | 944 | 417 | 276 | 1041 | 460 | 304 | 1150 | 508 | 336 | HC 634 K |
| HC 734 E | 833 | 368 | 242 | 932 | 412 | 272 | 990 | 438 | 289 | 1131 | 500 | 330 | 857 | 379 | 250 | 979 | 433 | 286 | 1059 | 468 | 309 | 1147 | 507 | 335 | HC 734 E |
| HC 734 F | 1000 | 442 | 291 | 1125 | 497 | 329 | 1200 | 530 | 350 | 1348 | 596 | 394 | 1066 | 471 | 311 | 1183 | 523 | 345 | 1288 | 589 | 376 | 1406 | 621 | 411 | HC 734 F |
| HC 734 G | 1270 | 561 | 370 | 1440 | 636 | 420 | 1543 | 682 | 451 | 1800 | 796 | 526 | 1303 | 576 | 380 | 1442 | 637 | 421 | 1562 | 690 | 456 | 1711 | 758 | 500 | HC 734 G |
| HC 734 H | 1714 | 758 | 499 | 1846 | 816 | 539 | 2000 | 884 | 584 | 2182 | 964 | 637 | 1588 | 702 | 464 | 1781 | 787 | 520 | 2000 | 884 | 584 | 2143 | 947 | 626 | HC 734 H |
| LV 824 C | 1788 | 790 | 520 | 1971 | 871 | 576 | 2125 | 939 | 621 | 2389 | 1056 | 698 | 1992 | 880 | 582 | 2234 | 987 | 652 | 2246 | 993 | 656 | 2658 | 1175 | 776 | LV 824 C |
| LV 824 D | 1987 | 878 | 578 | 2190 | 968 | 639 | 2362 | 1044 | 690 | 2652 | 1172 | 774 | 2216 | 979 | 647 | 2483 | 1097 | 725 | 2717 | 1201 | 793 | 2963 | 1305 | 862 | LV 824 D |
| LV 824 E | 2225 | 983 | 647 | 2452 | 1084 | 716 | 2646 | 1170 | 773 | 2972 | 1314 | 868 | 2482 | 1097 | 725 | 2772 | 1225 | 809 | 3043 | 1345 | 889 | 3307 | 1462 | 966 | LV 824 E |
| LV 824 F | 2622 | 1159 | 763 | 2890 | 1277 | 844 | 3118 | 1378 | 910 | 3505 | 1549 | 1023 | 2925 | 1293 | 854 | 3265 | 1443 | 963 | 3587 | 1585 | 1047 | 3898 | 1723 | 1138 | LV 824 F |
| LV 824 G | 3020 | 1335 | 879 | 3328 | 1471 | 972 | 3590 | 1587 | 1046 | 4037 | 1784 | 1179 | 3372 | 1490 | 985 | 3757 | 1661 | 1097 | 4138 | 1829 | 1208 | 4488 | 1984 | 1310 | LV 824 G |

The following graph sets Sub-transient Reactance against Voltage Distortion levels.




## Non Linear Load Characteristics

The requirement to achieve a particular system harmonic voltage distortion level is determined by the alternator's value of X"d, which in turn, is influenced by the characteristics of the NLL and the operating parameters. One characteristic of a NLL is number of power devices in the converter bridge:

- Three phase fully controlled system indicates a 6 pulse converter stage.
- Six phase fully controlled system indicates a 12 pulse converter stage.

Insulated-gate bipolar transistor (IGBT) technology may be used in the converter stage of modern electronic power devices. For calculation purposes, use the method adopted for 12 pulses systems.

Refer to AGN025 Non Linear Loads, for comprehensive guidance on NLL characteristics and how those characteristics determine the X''d of the alternator.

**VOLTAGE DISTORTION CALCULATIONS:**

***Comment;*** *It is often found that voltage regulation, quantified as a '+/- value', is mistaken for harmonic voltage distortion, quantified as a pure '% value'. Any stated required 'voltage' performance should always be clarified during preliminary data gathering to ensure the correct information has been provided.*

The level of harmonic voltage distortion on a system can be considered to be the result of the following:

- A product of the source impedance of the supply and for an alternator; this is quantified as the value of the alternator's Sub-transient Reactance (X"d).
- The amount of distorting Non Linear Load to be supplied, identified in kVA.
- The characteristics of the current taken by the Non Linear Load, described by the NLL's number of pulses and the current harmonic distortion, identified in THD %.

The following formula can be used in order to calculate the harmonic voltage distortion by considering each individual harmonic number, although this is usually restricted to 5$^{th}$, 7$^{th}$ 11$^{th}$, 13$^{th}$, 17$^{th}$, 19$^{th}$ 23$^{rd}$, 25$^{th}$ hamonics:

$$Vn = I \, . \, n \, . \, X''d \;\; p.u.$$

| | | |
|---|---|---|
| Vn | - | Harmonic Voltage |
| I | - | Harmonic Current |
| n | - | Harmonic Number |
| X"d | - | Sub-transient Reactance |

Example: A 7$^{th}$ harmonic current equal to 0.1 p.u. [or 10%] rated current supplied from an alternator having a mean Sub-transient Reactance of 0.12 p.u. will produce a 7$^{th}$ harmonic voltage of: 0.1 x 7 x 0.12 = 0.084 p.u. (8.4% of rated voltage).

The individual harmonic voltage distortion levels can be established by performing this calculation for the p.u. current associated with each harmonic number.

The Voltage Total Harmonic Distortion [THD] is then calculated by establishing the square root of the sum of the squares of these individual Voltage harmonics.

It is then necessary to introduce a K factor to take into account the number of pulses of the NLL equipment and so, the resulting pattern of the current harmonic levels and how they are distributed against the harmonic numbers must be taken into account.

- For 6 pulse equipment, apply a K factor of 1
- For 12 pulse equipment, apply a K factor of 0.5

*The level of harmonic voltage distortion, from the 'Square root of the sum of the squares' calculation is then multiplied by the K factor to predict the typical harmonic voltage distortion on the alternator supplied NLL system.*

The tables on the following pages provide typical voltage distortion for given harmonic currents on 3-phase 6-pulse and 12-pulse NLLs and also single phase 2-pulse NLLs:

## 3 PHASE, 6 PULSE

Estimation of voltage distortion, given harmonic currents.

| X"d @ FLC OF LOAD | n | %I | %V |
|---|---|---|---|
| 3.5 % | 3 | | 0.00 |
| | 5 | 20 | 3.50 |
| | 7 | 14.3 | 3.50 |
| | 9 | | 0.00 |
| | 11 | 9 | 3.47 |
| | 13 | 7.7 | 3.50 |
| | 15 | | 0.00 |
| | 17 | 5.9 | 3.51 |
| | 19 | 5.3 | 3.52 |
| | 21 | | 0.00 |
| | 23 | 4.3 | 3.46 |
| | 25 | 4 | 3.50 |
| | Distortion Factor = | 29.02 % | 9.89 % |

Estimation of voltage distortion, given harmonic currents.

| X"d @ FLC OF LOAD | n | %I | %V |
|---|---|---|---|
| 5.3 % | 3 | | 0.00 |
| | 5 | 20 | 5.30 |
| | 7 | 14.3 | 5.31 |
| | 9 | | 0.00 |
| | 11 | 9 | 5.25 |
| | 13 | 7.7 | 5.31 |
| | 15 | | 0.00 |
| | 17 | 5.9 | 5.32 |
| | 19 | 5.3 | 5.34 |
| | 21 | | 0.00 |
| | 23 | 4.3 | 5.24 |
| | 25 | 4 | 5.30 |
| | Distortion Factor = | 29.02 % | 14.97 % |

# 3 PHASE, 12 PULSE

Estimation of voltage distortion, given harmonic currents.

X"d @ FLC OF LOAD: 5 %

| n | %I | %V |
|---|---|---|
| 3 | | 0.00 |
| 5 | | 0.00 |
| 7 | | 0.00 |
| 9 | | 0.00 |
| 11 | 9.1 | 5.01 |
| 13 | 7.7 | 5.01 |
| 15 | | 0.00 |
| 17 | | 0.00 |
| 19 | | 0.00 |
| 21 | | 0.00 |
| 23 | 4.3 | 4.95 |
| 25 | 4 | 5.00 |
| Distortion Factor = | 13.29 % | 9.98 % |

Estimation of voltage distortion, given harmonic currents.

X"d @ FLC OF LOAD: 7.5 %

| n | %I | %V |
|---|---|---|
| 3 | | 0.00 |
| 5 | | 0.00 |
| 7 | | 0.00 |
| 9 | | 0.00 |
| 11 | 9.1 | 7.51 |
| 13 | 7.7 | 7.51 |
| 15 | | 0.00 |
| 17 | | 0.00 |
| 19 | | 0.00 |
| 21 | | 0.00 |
| 23 | 4.3 | 7.42 |
| 25 | 4 | 7.50 |
| Distortion Factor = | 13.29 % | 14.97 % |

# 1 PHASE, 2 PULSE

Estimation of voltage distortion, given harmonic currents.

| X"d @ FLC OF LOAD | n | %I | %V |
|---|---|---|---|
| 2.9 % | 3 | 33.3 | 2.90 |
| | 5 | 20 | 2.90 |
| | 7 | 14.3 | 2.90 |
| | 9 | 11 | 2.87 |
| | 11 | 9.1 | 2.90 |
| | 13 | 7.7 | 2.90 |
| | 15 | 6.7 | 2.91 |
| | 17 | 5.9 | 2.91 |
| | 19 | 5.3 | 2.92 |
| | 21 | 4.8 | 2.92 |
| | 23 | 4.3 | 2.87 |
| | 25 | 4 | 2.90 |
| | Distortion Factor = | **46.28** % | **10.05** % |

Estimation of voltage distortion, given harmonic currents.

| X"d @ FLC OF LOAD | n | %I | %V |
|---|---|---|---|
| 4.3 % | 3 | 33.3 | 4.30 |
| | 5 | 20 | 4.30 |
| | 7 | 14.3 | 4.30 |
| | 9 | 11 | 4.26 |
| | 11 | 9.1 | 4.30 |
| | 13 | 7.7 | 4.30 |
| | 15 | 6.7 | 4.32 |
| | 17 | 5.9 | 4.31 |
| | 19 | 5.3 | 4.33 |
| | 21 | 4.8 | 4.33 |
| | 23 | 4.3 | 4.25 |
| | 25 | 4 | 4.30 |
| | Distortion Factor = | **46.28** % | **14.90** % |

## REDUCING THE HARMONIC VOLTAGE DISTORTION %

To reduce the harmonic voltage distortion, the following options may be considered:

- Reduce the source Impedance of the supply, which in effect means reducing the value of the alternator's Sub-transient Reactance [X"d]. This can be achieved by using special windings within the alternator, or staying with the standard winding design but then choosing a bigger alternator.

- Change the NLL unit from 6 to 12 pulse, or consider some of the new IGBT technology power electronic packages that have minimal input harmonic current distortion by 'switching' design.

- Reduce the loads Harmonic Current Distortion % by use of power factor correction capacitors or harmonic filters, but now care needs to be taken with the possibility of a leading power factor (kVAr) situation.

## Power Factor Correction Capacitors

*Consideration should always be given to operating conditions which are likely to subject an alternator to a load condition that may result in an alternator operating under a condition of leading Power Factor. The effective level of air-gap flux resulting from armature reaction associated with a condition of an excess of stator winding load current with a leading Power Factor, can induce a level of 'self-excitation' into the main rotor winding, which can result in a situation of over-excitation. Under such a critical condition the output voltage of the alternator will rise outside the control of the alternator's AVR excitation system and the level of voltage rise becomes cumulative as the level of leading pf load current rises in proportion to the system voltage level. The generator output voltage level could become some 180% of the nominal voltage.*

The critical level of acceptable leading power factor (kVAr) is identified by observing the alternator's Operating Chart, sometimes called a Capability Diagram. Typically, most alternators will remain 'stable' and under normal AVR excitation control if the level of applied leading power factor kVAr (Zpf lead) does not exceed 30% of the alternator's rated kVA.

Under conditions of leading power factor nearer to unity, the Operating Chart displays that the alternator's capability, at levels of 0.95pf (lead) to 1.0pf, is virtually at rated kVA levels.
For the reasons outlined above, the common recommendation is that when a Generating Set is to be used to power a site load, which includes pf correction Capacitors, then the simplest guidance is that the pf correction equipment is disabled during loss of mains situations.

However, if a competent Generating Set provider can access the site loads characteristics and establish the operating benefits of keeping the pf correction equipment active, then with due consideration of the pf correction equipment performance data and alternator manufacturers Operating Chart, it is possible to calculate a safe mode of operation.

With regard to situations where the site load incorporates harmonically distorting Non Linear Loads, further consideration is required about allowing the power factor correction Capacitors to be connected. Capacitors are frequency sensitive and therefore, are sensitive to the harmonics generated by NLLs. If too much harmonic voltage distortion is present on the electrical supply system, any capacitor will naturally 'draw' more than designed current. At best the pf correction Circuit Breaker will trip, at worst permanent damage will be done to the capacitive element.

## Harmonic Filters

If the site load where the NLL is present incorporates a harmonic filter aimed at reducing the overall system harmonic distortion levels, then this can be considered to be an asset to the overall scheme and so, beneficial to have it connected when the alternator is powering the site load. Whilst accepting that harmonic filters incorporate capacitors - their characteristics fully discussed above - well designed harmonic filters will also make use of Inductors.

This means that the unit has elements of Zpf lagging and Zpf leading, so the overall resultant could be virtually unity pf. Therefore as such, the harmonic filter should not cause the alternator to enter the critical zone of 'self-excitation'.

The reduction to the overall harmonic current distortion levels of the sites NLL will be reduced with the filter in circuit and so correspondingly, will the overall harmonic voltage distortion levels. This therefore, must be considered to be an ideal, beneficial situation, as it presents to the power supply a load with characteristics nearer to the ideal non-distorting linear load.

It is well known that, if an alternator is used to power a site load, the system source impedance of that site supply will be higher than when a mains supply is used. The overall systems Voltage Total Harmonic Distortion [THD] level has a directly proportional relationship to the level of source Impedance of the supply system.

Therefore, the levels of harmonic voltage distortion that will occur supporting a given NLL by an alternator will inevitably be higher than when mains supply is being used. This is because the alternator must be a cost effective choice for the application and therefore, small [in capacity] when compared to the mains supply.

When considering the levels of THD that NLL have been designed to tolerate, the common guide is G5/4. Achieving levels this low for an alternator supply situation is an extremely difficult and costly exercise and in real world fact, in practice, rarely occurs. Typically, most NLL can tolerate twice G5 / 4 levels and so this becomes the target when nominating alternators for NLL applications. However, with a scheme that now has twice the 'expected' harmonic voltage distortion applied to all the connected loads the design capability of the harmonic filter may now need to be carefully (re-)considered.

Harmonic filters consist of Capacitors & Inductors [chokes]; these are frequency sensitive and therefore, also harmonically sensitive. With a twice expected 'harmonic voltage' being applied to the harmonic filter components, there is a risk that the chokes and capacitors may start to ‘draw’ more than designed current, possibly resulting in their Circuit Breaker’s tripping [fuses blowing], therefore INCREASING the system harmonic voltage distortion.

A further risk is that their protection circuit doesn’t operate; leaving the chokes to operate outside their designed working temperature and so damaging their insulation systems and high capacitor currents promoting damage their ‘end connections’ and severely stressing their dielectric.

In conclusion; it is beneficial to have the harmonic filter in circuit, but during the first occasion that the scheme of alternator and site loads are operated, the input current to the harmonic filter unit should be measured and compared with normal mains supply current levels. Any differences should be discussed with the harmonic filter manufacturer.