EPRI

Impact of Nonlinear Loads on Motor Generator Sets

Technical Report

Impact of Nonlinear Loads on Motor Generator Sets

1006489

Final Report, November 2001

EPRI Project Manager
B. Banerjee

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EPRI PEAC Corporation

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Customer Fulfillment, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2.

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. ELECTRIFY THE WORLD is a service mark of the Electric Power Research Institute, Inc.

Copyright © 2001 Electric Power Research Institute, Inc. All rights reserved.

CITATIONS

This report was prepared by

EPRI PEAC Corporation
942 Corridor Park Blvd.
Knoxville, TN 37932

Principal Investigators
T. Short
A. Mansoor
R. Langley

This report describes research sponsored by EPRI

The report is a corporate document that should be cited in the literature in the following manner:

Impact of Nonlinear Loads on Motor Generator Sets, EPRI, Palo Alto, CA: 2001. 1006489.

REPORT SUMMARY

Using backup generators with loads that create high harmonics can cause power quality problems. This report describes how to calculate voltage distortion based on the different impedance characteristics of a generator and the harmonic current characteristics of loads and discusses options for reducing the harmonics and mitigating their impact.

Background
The use of backup generators with loads that create high harmonics can cause power quality problems. Under most circumstances, the utility typically is a stiff source—voltage distortion usually under 5% even if the loads such as computers or adjustable-speed drives draw nonlinear (non-sinusoidal) current. Many locations that have critical power needs use backup generators as a way to ensure availability when the utility source is interrupted. Generators are a weaker source compared to the utility: given the same harmonic current, the voltage distortion will be higher during islanded (backup) operation. This increased voltage distortion may impact the operation of other loads inside a facility and may even cause problems with the proper operation of the generator.

Objective
To offer guidelines on how to calculate the voltage distortion for different loads and types of connection to help end-users determine the size of the generator required in order to keep the voltage distortion to the specific load requirement.

Approach
The project team first evaluated the different impedance characteristics of synchronous generators and their impact on voltage distortion. Based on this evaluation, the team developed a guideline and procedure for calculating voltage distortion under different harmonic loading. They used the procedure to calculate voltage distortion in some examples. They assessed the impact of unbalance and capacitors on distortion and augmented the calculation procedure to handle unbalance current and capacitors. The team discussed various options to reduce the harmonics and/or reduce the impact of the harmonics and identified future research to better solve these power quality problems.

Results
The relevant characteristics of the synchronous machine are the effective inductances (or reactance) as seen from the terminals of the machine. The impedances that are of interest for voltage distortion calculation for positive and negative sequence harmonic current are negative sequence impedance (X_2), direct-axis sub transient reactance (X_d"), and the average of X_d" and quadrature-axis sub transient reactance (X_q"). Normally, these are all close since X_d" and X_q" are

usually close to each other. This is especially true if the machine has significant fully connected damper windings. For zero sequence, voltage distortion of the machine zero sequence impedance is the impedance of interest. Preliminary calculation shows that the voltage distortion when non-linear loads are supplied from generators could be several times more than the voltage distortion when the loads are supplied from a stiff utility bus. The methodology developed as part of this research work will be further refined based on actual test data and validation of the model that will be conducted in the future by the EPRI Power Quality target.

EPRI Perspective

Stand-by power systems are extremely valuable to many industrial and commercial industries. Unfortunately, incompatibility between the stand-by power system and the critical loads can lead to power quality problems resulting from an increased voltage distortion. By sponsoring continued research this important area, utilities can provide extraordinary value to their customers and to the industry as a whole through the increased awareness and understanding of stand-by power systems and their applications.

Keywords

Motor-Generator Set
Harmonics
Voltage Distortion
System Compatibility
Power

ABSTRACT

Using backup generators with loads that create high harmonics can cause power quality problems. Many locations that have critical power quality needs use backup generators as a way to ensure availability when the utility source is interrupted. During backup generator operation, excessive voltage distortion can disrupt sensitive devices. This report offers guidance on how to calculate the voltage distortion for different loads and types of connections. Based on this procedure end-users can determine the size of the generator required in order to keep the voltage distortion to the specific load requirement. Various options to reduce the harmonics and/or reduce the impact of the harmonics are considered along with comments on manufacturer's guidelines. Lastly, future work to better solve this problem has been identified.

CONTENTS

1 **INTRODUCTION 1-1**

2 **GENERATOR CHARACTERISTICS 2-1**

Positive- and Negative-Sequence Harmonic Impedances 2-4

Zero-Sequence Harmonic Impedance 2-6

Harmonic Model of a Synchronous Machine 2-8

Advanced Considerations 2-9

3 **HARMONIC VOLTAGE CALCULATIONS 3-1**

Balanced Example 3-1

Unbalanced Example 3-3

General Guidelines 3-6

Effect of Capacitors 3-8

4 **HARMONIC PROBLEMS 4-1**

Case Study: Effect of Generator Impedance on Voltage Distortion (Islanded-Mode) 4-2

Site Description 4-2

Measurement Results 4-2

Case A: UPS Powered from Utility (Generator Out) 4-2

Case B: UPS Powered from Standby Generator (Utility Out) 4-2

Analysis and Conclusion 4-3

5 **SOLUTIONS 5-1**

General Solutions 5-1

Generator-Specific Solutions 5-1

UPS-Specific Solutions 5-2

Manufacturer Guidelines for Applying Generators in the Presence of Harmonics 5-3

_6_ SUMMARY 6-1
Generator Calculations 6-1
Solutions 6-1
Future Work 6-1

_A_ MANUFACTURER'S INFORMATION A-1
Generator Manufacturers A-1
Data Sheets for Caterpillar Generators A-2

_B_ TYPES OF NONLINEAR LOADS B-1
Commercial Nonlinear Load Characteristics B-1
Industrial Nonlinear Load Characteristics B-4

LIST OF FIGURES

Figure 2-1 Generator Rotor Showing the Damper Winding 2-5

Figure 2-2 Basic Impedances of Different Magnetic Circuits 2-6

Figure 2-3 Comparison of a Full-Pitch and a Two-Thirds Pitch Stator Winding for a Two-Pole Machine with a Double-Layer Stator Winding with One Slot per Phase per Pole 2-7

Figure 2-4 Synchronous Machine Model Used for Harmonic Analysis 2-8

Figure 3-1 Harmonic Voltage Distortion at the Generator Terminals for the Balanced Electronic Load Example for a Loading Equal to 25% of the Generator Rating 3-3

Figure 3-2 Harmonic Voltage Distortion at the Generator Terminals (phase-to-ground voltages) for the Unbalanced Electronic Load Example for a Loading Equal to 10% of the Generator Rating on Phase A and 25% on Phases B and C 3-5

Figure 3-3 Ranges of Total Harmonic Voltage Distortion at the Generator Terminals for a Balanced Nonlinear Load as a Function of the Size of the Load Relative to the Generator Rating for Electronic Power Supplies and UPS's (for X_0=0.05 and X_2=0.15 to 0.35) 3-7

Figure 3-4 Ranges of Total Harmonic Voltage Distortion at the Generator Terminals for a Balanced Nonlinear Load as a Function of the Size of the Load Relative to the Generator Rating for Adjustable-Speed Drives (for X_0=0.05 and X_2=0.15 to 0.35) 3-7

Figure 3-5 Resonant Circuit with a Local Capacitor and Backup Generator 3-8

Figure 3-6 Resonance Point as a Function of Capacitor Size and X_2 3-9

Figure 4-1 UPS Input Voltage From (a) Utility Supply and b) During Generator Operation 4-3

Figure B-1 PC Power Supply Circuit Diagram B-1

Figure B-2 PC Power Supply Current and Spectrum B-2

Figure B-3 Commercial Building Distribution System B-3

Figure B-4 Typical AC Drive Topology, Input Current, and Spectrum B-5

Figure B-5 DC Drive Input Current and Spectrum B-6

Figure B-6 Semiconverter with Voltage and Current Waveforms and Spectra B-7

Figure B-7 Simplified One-line Diagram of Industrial Plant B-8

LIST OF TABLES

Table 2-1 Reactance and Time Constant Parameters for Synchronous Generators.....2-2
Table 2-2 Small Synchronous Generator Constants (In Per Unit on the Machine Base) 2-3
Table 2-3 Normal Sequence of Harmonics on Three-Phase Quantities With the Same Phase Angle of the Given Harmonics 2-6
Table 3-1 Typical Harmonic Current Spectra of Different Types of Loads 3-1
Table 3-2 Voltage Distortion (THD and the Given Odd Harmonics) on a Generator for the Given Load Type with X_0=0.05 and X_2=0.28 for a Load of 100% of the Generator Rating – Scale the Results by the Actual Nonlinear Loading.....3-6
Table 5-1 Generator Impedance Data from Caterpillar Generator Manufacturer Information 5-2
Table 5-2 Manufacturer Recommendation for Generator Oversizing Based on Different Loads 5-4
Table 5-3 Manufacturer Recommendation for Generator Oversizing Based on Different Loads 5-4

1
INTRODUCTION

Using backup generators with loads that create high harmonics can cause power quality problems. Under most circumstances, the utility source is a stiff source – a sinusoidal voltage is produced even if the loads (such as computers or adjustable-speed drives) draw nonlinear (nonsinusoidal) current. Many locations that have critical power needs use backup generators as a way to ensure availability when the utility source is interrupted. Generators are a weaker source compared to the utility, so given the same harmonic current, the voltage distortion will be higher during islanded (backup) operation.

Many loads that cause harmonics are also sensitive to harmonics. The most important (or notorious) example is the uninterruptible power supply (UPS). A UPS is often a high harmonic producer. It may also be sensitive to voltage distortion. If the voltage distortion exceeds some threshold, the UPS will switch to battery operation. After the batteries are exhausted, the critical load may drop offline.

The most common way to avoid problems due to harmonics is to oversize the generator, which makes it a stiffer source. However, in this case, cost becomes an issue. The objectives of this research project are to offer guidelines on how to calculate the voltage distortion for different loads and types of connection. Another solution would be to use harmonic filters (traditional passive filters or active filters). Also possible is to specify loads (especially UPSs) that will operate satisfactorily under high levels of voltage distortion.

The objectives of this research project are to offer guidelines as how to calculate the voltage distortion for different loads and types of connection. Based on these guidelines end-users can determine the size of the generator required in order to keep the voltage distortion to the specific load requirement.

2
GENERATOR CHARACTERISTICS

The characteristics of the synchronous machine are the effective inductances (or reactances) as seen from the terminals of the machine. These, when associated with the fundamental frequency, determine the currents during sustained as well as transient and sub-transient fault conditions and the response to harmonics.

In addition to these inductances, there are corresponding time constants that determine the rate of decay of currents and voltages relative to the steady-state parameters. Together these parameters define the synchronous machine's electrical characteristics and can be used in specifying or modeling a machine. Definitions for the various machine reactances and their effects on operation are summarized below.[1]

Direct-Axis Reactance X_d
Lower values of direct axis reactance are desirable in order to achieve machine operation at low power angles for a given power output.

Quadrature-Axis Reactance X_q
For salient pole machines, the value of X_q is slightly lower than the value of X_d. During normal machine operation at low power angles (δ), the lower value of X_q results in improved machine stability. If a machine is operated below its design power factor, resulting in a high power angle (δ), a low value of X_q is a detriment to machine stability.

Subtransient Reactance Xd"
This is the value of reactance that is effective immediately after a sudden change in the load current such as during a fault condition.

Transient Reactance Xd'
This is the value of reactance that is effective 6-8 cycles after a sudden change in the load current such as during a fault condition.

Synchronous Reactance X_s
This is the value of reactance that is effective during steady state conditions.

Negative-Sequence Reactance X_2
This is the value of reactance encountered by negative-sequence currents. The negative-sequence reactance affects the thermal withstand capability of a generator against negative-sequence

[1]Connecting Small Generators to Utility Distribution Systems, CEA Report Number 128 D 767.

currents, which are caused by negative-sequence voltages resulting from unbalanced loads and some harmonic current components. These negative-sequence currents cause heating of the pole faces, which can ultimately lead to machine damage. The maximum RMS value of negative-sequence current permissible is 10%-15%.

Zero-Sequence Reactance X_0
This is the value of reactance encountered by zero-sequence currents. The zero-sequence reactance is on the order of 15% to 75% of the value of the sub-transient reactance, *Xd"*, which is the effective positive-sequence impedance under fault conditions. The low value of zero-sequence impedance results in a high prospective fault current under line-to-ground fault conditions. This is avoided by not solidly grounding the neutrals on generators.

Ranges for these parameters for hydraulic units (prime source of energy is kinetic energy of water) and thermal units (prime source of energy derived from fossil fuels) are given in Table 2-1.

Table 2-1
Reactance and Time Constant Parameters for Synchronous Generators[2]

Parameter		Hydraulic Units	Thermal Units
Synchronous Reactance	X_d	0.6 – 1.5	1.0 – 2.3
	X_q	0.4 – 1.0	1.0 – 2.3
Transient Reactance	Xd'	0.2 – 0.5	0.15 – 0.4
	X'_q	-	0.3 – 1.0
Subtransient Reactance	Xd"	0.15 – 0.35	0.12 – 0.25
	X''_q	0.2 – 0.45	0.12 – 0.25
Transient Open Circuit Time Constant	T'_{d0}	1.5 – 9.0 s	3.0 – 10.0 s
	T'_{q0}	-	0.5 – 2.0 s
Subtransient Open Ciruict Time Constant	T''_{d0}	0.01 – 0.05 s	0.02 – 0.05 s
	T''_{q0}	0.01 – 0.09 s	0.02 – 0.05 s
Stator Leakage Inductance	X_l	0.1 – 0.2	0.1 – 0.2
Stator Resistance	R_a	0.002 – 0.02	0.0015 – 0.005

Notes: Reactance values are in per unit with stator base values equal to the corresponding machine rated values and Time constants are in seconds.

[2] P. Kundur, Power System Stability and Control, Power System Engineering Series, Electric Power Research Institute, ISBN 0-07-03598-X.

Table 2-2 shows the constants for four different sizes of small synchronous generators in per unit of the machine base. The constants are provided as an indication of the ranges the constants may have. Machine A is presented as typical, and yet the sub-transient constants are low. This is a result of the use of a substantial damper winding. Likewise Machine B is presented as typical and yet the constants are all high, especially X_d. This high X_d is not unusual as the machine windings were designed for a high current exciter. Thus the four machines represent a range of constants rather than constants that vary according to the machine rating.

Table 2-2
Small Synchronous Generator Constants (In Per Unit on the Machine Base)[3]

Machine	**A**	**B**	**C**	**D**
kVA	69	156	781	1044
kW	55	125	625	835
V	240/480	240/480	240/480	240/480
pf	0.80	0.80	0.80	0.80
X_d	2.02	6.16	2.43	2.38
X_d'	0.171	0.347	0.254	0.264
X_d''	0.087	0.291	0.207	0.201
X_q	1.06	2.49	1.12	1.10
X_q''	0.163	0.503	0.351	0.376
T_{do}' (sec)	0.950	1.87	1.90	2.47
T_d' (sec)	0.080	0.105	0.198	0.273
T_{do}'' (sec)	0.078	0.013	0.024	0.018
T_d'' (sec)	0.004	0.011	0.020	0.014
T_{qo}'' (sec)	0.045	0.020	0.016	0.009
T_q'' (sec)	0.007	0.004	0.005	0.003
r_a (per unit)	0.011	0.034	0.017	0.013
T_a (sec)	0.014	0.022	0.038	0.032
X_0	0.038	0.054	0.051	0.074
X_2	0.125	0.375	0.279	0.260
RPM	1800	1800	1800	1800
Inertia Constant H_{gen}	0.26	0.20	0.40	0.43

[3] W.B. Gish, "Small Induction Generator and Synchronous Generator Constants for DSG Isolation Studies, IEEE Transaction on Power Systems, Vol. PWRD-1 No.2, pp. 231-239, April 1986.

Positive- and Negative-Sequence Harmonic Impedances

Normally, the negative-sequence impedance is used for positive- and negative-sequence harmonics. Other impedances can be used if X_2 is not available. The use of a constant impedance that linearly increases with frequency has been shown to be relatively accurate.[4] The recommended approximations for the harmonic impedance are as follows in order of preference:[5,6,7]

- X_2
- $(X_d" + X_q")/2$ (which is a common approximation to X_2)
- $X_d"$

Normally, these are all close since $X_d"$ and $X_q"$ are usually close to each other. This is especially true if the machine has a significant fully-connected damper windings.

More complicated frequency-dependent models for harmonics have been developed.[8,9] The main problem with these is that the data is never available for smaller machines, and testing is almost never justified based on the costs for small machines.

If no other information is available, it is advisable to use a value of $X_2 = 0.28$ per unit (based on Machine C in Table 2-2). This is on the high side of the range of impedances usually found, but the higher number is more conservative. The appendix also gives manufacturer data for a few different generator sets.

Two types of subtransient reactances are sometimes specified for synchronous generators:

> $X_d"_v$ – The *saturated* subtransient reactance, used for short-circuit studies and for harmonics. The subscripted "v" means constant voltage; the impedance is the value of V/I at *rated voltage* for a short circuit on the generator terminals (which is a high-current condition that saturates the magnetic core which results in a lower impedance).
>
> $X_d"_i$ – The *unsaturated* subtransient reactance is used for stability studies. The subscripted "i" means constant current; the impedance is the value of V/I at *rated current* for a short circuit on the generator terminals.

---

[4] R. Arseneau, E. F. Hill, R. Szabados, and D. Ferry, "Synchronous Motor Impedances Measured at Harmonic Frequencies," IEEE paper A 79 514-1, Summer Power Meeting, Vancouver, Canada, July, 1979.

[5] "Modeling and simulation of the propagation of harmonics in electric power networks. I. Concepts, models, and simulation techniques," IEEE Transactions on Power Delivery, vol. 11, no. 1, pp. 452-465, Jan. 1996.

[6] IEEE Tutorial on Harmonics Modeling and Simulation, TP-125-0, 1998.

[7] J. Arrillaga, D. A. Bradley, and P. S. Bodger, Power System Harmonics, John Wiley & Sons, 1985.

[8] A. Semlyen, J.F. Eggleston and J. Arrillaga, "Admittance Matrix Model of a Synchronous Machine for Harmonic Analysis", IEEE Transaction on Power Systems, Vol. PS-2, Nov. 1987, pp. 833-840.

[9] J.M. Canay, "Determination of the Model Parameters of Machines from the Reactance Operators $x_d(p)$, $x_q(p)$ (Evaluation of Standstill Frequency Response Test), " IEEE Transaction EC-8(2), June 1993, pp. 272-279.

$X_d"_v$ is smaller than $X_d"_i$ (the ratio between the unsaturated and saturated values is about 0.6 to 0.7). Usually, if it is not indicated which value it is, it is the saturated value, $X_d"_v$ (which is the convention used in this report). There are also saturated and unsaturated $X"_q$, but these are often not available.

The harmonic impedance is determined primarily by the damper windings. Damper windings react to dampen out transients on the machine. The torque produced by the damper windings slows down fast machines and speeds up slow machines. Damper windings are like the rotor on a squirrel-cage induction machine (in fact a squirrel-cage induction machine is a synchronous machine with damper windings and no field on the rotor). At synchronous speed, no current will flow in the damper windings since the flux on the rotor is DC, but if transients act to change the frequency relative to the synchronous speed, currents will flow in the damper windings and create torque to counteract the disturbance. The damper windings will also react to other stator currents that are not 60-Hz positive-sequence currents (significantly, negative-sequence currents and harmonic currents). Figure 2-1 shows the location of the damper windings in a synchronous generator.

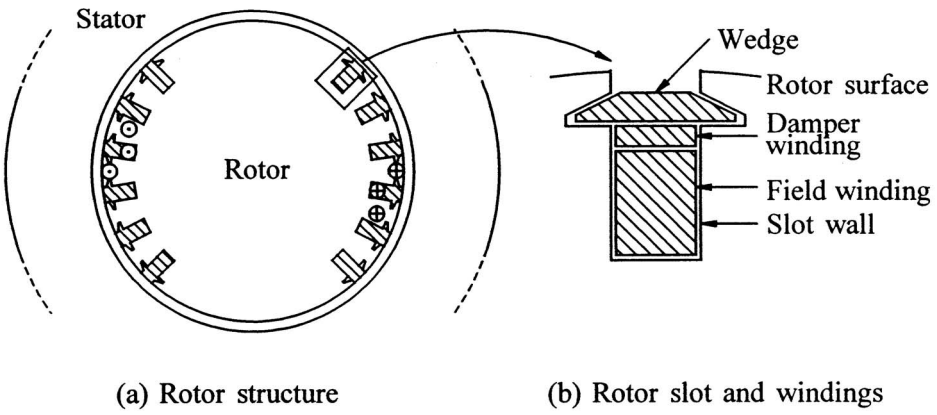


Figure 2-1
Generator Rotor Showing the Damper Winding

As another way of explaining why the negative-sequence impedance is a good approximation for harmonics is that the negative-sequence impedance is the impedance to 120 Hz (the second harmonic). A negative-sequence voltage on the stator produces a rotating magnetic field, but it rotates in the opposite direction of the rotor, so double-frequency rotor currents (mainly in the damper windings) of 120 Hz are created.

To visualize the effect of the damper winding, imagine that the rotor is not moving (and it won't be moving fast relative to the 5th harmonic for example). If the rotor isn't moving, the armature winding on the stator forms a coupled circuit with the damper winding on the rotor. In the accompanying magnetic circuit, the flux is completed by the iron in the stator, the iron in the rotor, and the airgap between them. This forms a transformer with a shorted secondary winding (the damper winding is the shorted secondary). It is useful to review some basics of magnetic circuits that relate to this discussion. Several turns of wire (an air core reactor) have a fairly low

reactance (see Figure 2-2). If the same turns are wrapped around an iron core, the reactance is much higher (see Figure 2-2). If a shorted winding is attached to the core, the shorted winding will greatly lower the impedance (the circulating winding provides a back-emf that cancels much of the flux in the core) see Figure 2-2. The damper winding acts like the shorted winding on a transformer – it provides a low-impedance path. Also, if the currents are high enough to saturate the core, then the impedance becomes like that of the air-core reactor (the impedance is lower).

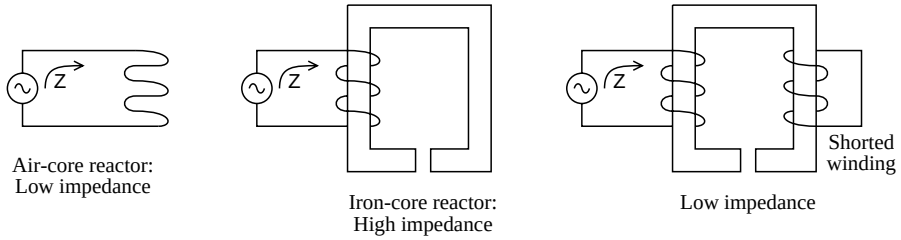


Figure 2-2
Basic Impedances of Different Magnetic Circuits

Zero-Sequence Harmonic Impedance

It is well known that balanced in-phase 3rd harmonic values are zero sequence (so $V_a=V_b=V_c$ for voltages and $I_a=I_b=I_c$ for currents). Table 2-3 shows the sequence of each harmonic. The zero-sequence harmonic impedance of a synchronous machine is a special case that has even lower impedance. Most generators have low zero-sequence impedance. It is enough of a problem that many generators are ungrounded (or grounded through an impedance) to prevent the flow of zero-sequence current. Many large generators are not braced to handle the fault current for a line-to-ground fault at the terminals of the machine. The fault current will be significantly higher for ground faults than for a three-phase fault (E/X" vs. $3E/(2X"+X_0) \approx 1.3E/X"$). The zero-sequence impedance is the same whether it is under steady-state, transient, or subtransient conditions.

Table 2-3
Normal Sequence of Harmonics on Three-Phase Quantities With the Same Phase Angle of the Given Harmonics

n	sequence	n	sequence	n	sequence
1	+	7	+	13	+
2	–	8	–	14	–
3	0	9	0	15	0
4	+	10	+	16	+
5	–	11	–	17	–
6	0	12	0	18	0

The reason that the impedance is so low is that zero-sequence currents in the stator winding tend to cancel each other. If the currents cancel, there will be very limited magnetic coupling to the rotor, so the impedance will be very low.

The zero-sequence impedance varies significantly with design. The most prominent difference is due to the pitch of the stator winding. A pole pitch is the number of degrees that the rotor has to move to change from one pole to the other. In a 2-pole machine, one pole pitch is 180°, and in a 4-pole machine, it is 90°. The *pitch factor* (or just the *pitch*) of the stator winding is the portion of the pole pitch that the stator winding spans. A full-pitch stator winding would span the full pitch. A fractional-pitch winding spans less than the full pitch. Figure 2-3 shows a comparison of a full-pitch winding and a two-thirds pitch winding. Other common pitch factors are five-eighths and three-fourths. The two-thirds pitch winding reduces the zero-sequence impedance the most, since the two conductors in each slot have current that goes in opposite directions, so the fields cancel almost completely (since a = b = c = -a ′ = -b ′ = -c ′).

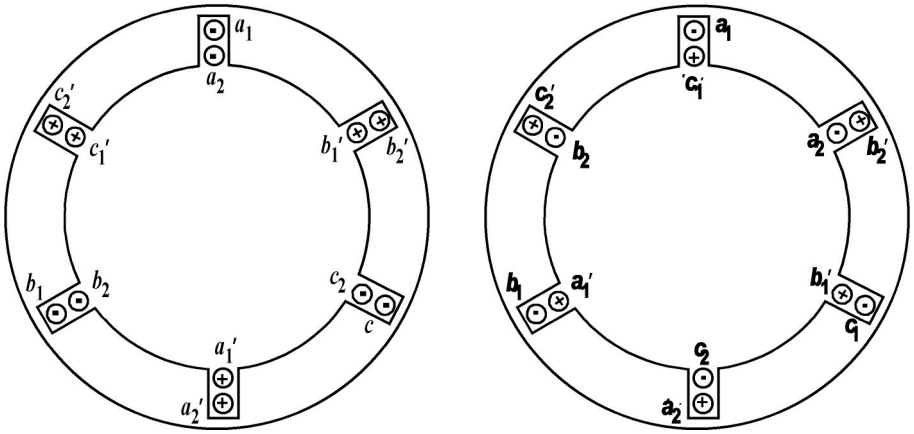


Figure 2-3
Comparison of a Full-Pitch and a Two-Thirds Pitch Stator Winding for a Two-Pole Machine with a Double-Layer Stator Winding with One Slot per Phase per Pole

In the absence of information regarding the synchronous generator of interest, use a value of 0.05 per unit for the zero-sequence impedance (based on Machine C in Table 2-2).

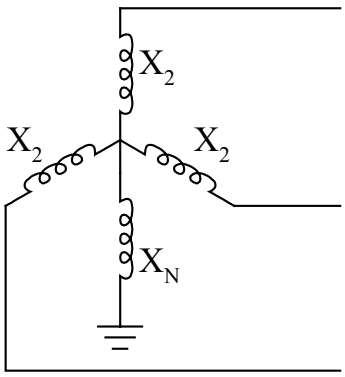
Note, if the generator is ungrounded and all line-to-ground connected load is fed through delta-wye grounded transformers, then zero-sequence current will not flow in the generator. Thus, the 3rd, 6th, 9th, … and other zero-sequence harmonic currents will not cause distortion at the generator terminals. This is true for balanced load conditions. Unbalanced load on the generator will cause zero-sequence current to flow regardless of the downstream transformer connection.

A low, zero-sequence harmonic impedance is usually an advantage because it keeps the voltage distortion low for third-harmonic load currents. One problem of circulating 3rd harmonic current is occasionally seen when two generators in parallel are feeding load and they are separated from the utility. Generators also create harmonics. If the generators have different characteristics or

are loaded differently, a 3rd-harmonic current can circulate on the neutral between the generators. This can cause one or both generators to trip on high neutral current. The circulating current is pronounced when one generator has a three-fourths pitch stator winding (which acts as a harmonic voltage source that is relatively high in 3rd harmonics) and the other generator has a two-thirds pitch stator winding (which has a low impedance to harmonics).

Harmonic Model of a Synchronous Machine

The recommended model for harmonic calculations is shown in Figure 2-4. It consists of wye-connected reactances with a neutral reactor.



$X_N = (X_0-X_2)/3 + X_{GN}$

If X_2 is not available, use $(X_d" + X_q")/2$ or $X_d"$.

If no data is available, use:
$X_2 = 0.28$
$X_0 = 0.05$
$X_N = -0.077$

X_2, generator negative-sequence reactance
X_0, generator zero-sequence reactance
X_{GN}, reactance of the generator neutral reactor (equals zero if there isn't one)
$X_d"$, generator direct-axis subtransient reactance
$X_q"$, generator quadrature-axis subtransient reactance

Figure 2-4
Synchronous Machine Model Used for Harmonic Analysis

The positive and negative-sequence reactances of the model are both equal to X_2. The zero-sequence equivalent of this model is X_0+3X_{GN}. The normal harmonic-calculation procedure assumes that the nonlinear loads are current injections. The voltage at the nth frequency is calculated using Equations 2-1, 2-2, and 2-3:

$$V_n = n \cdot X \cdot I_n \qquad \textbf{Equation 2-1}$$

For positive or negative-sequence harmonics, Equation 2-2 should be used.

$$X = X_2 \qquad \textbf{Equation 2-2}$$

For zero-sequence harmonics, Equation 2-3 should be used.

$$X = X_0 + 3X_{GN} \qquad \textbf{Equation 2-3}$$

Superposition can be used to calculate the harmonic voltage distortion due to multiple loads. Note, in the absence of a generator neutral reactor, X_N will be negative, and the negative value should be kept in the calculations.

Advanced Considerations

There are some second-order effects that are ignored in this model.[10,11] An unbalanced linear load can cause harmonic voltages and currents. As an example, consider an unbalanced load that causes linear (60Hz only) negative-sequence current. The negative-sequence current will cause 120-Hz currents to flow in the field winding on the rotor (because the negative-sequence field is rotating in the opposite direction of the rotor). This in turn will induce a 180-Hz voltage component in the stator winding (it adds another 60 Hz because of the rotation of the rotor relative to the stator). So, even though the load was linear, the unbalance will create harmonics. The way it works out is that fundamental-frequency negative-sequence stator currents will create 3_{rd} harmonic voltages (the 3_{rd} harmonics generated are actually positive sequence) along with the fundamental-frequency values. The equations for the voltages are shown in Equations 2-4 and 2-5.

$$V(1) = \frac{X_d'' + X_q''}{2} I(1)$$ **Equation 2-4**

$$V(3) = 3 * \frac{X_q'' - X_d''}{2} I(1)$$ **Equation 2-5**

If negative-sequence n^{th}-harmonic currents are injected into the stator, (n) and (n+2) positive-sequence harmonic voltages will appear on the stator winding (of most interest, the 5^{th}-harmonic currents create 5^{th}-harmonic voltages along with 7^{th}-harmonic voltages – likewise, the 11^{th} creates 11^{th} and 13^{th} voltages). The equations for the coupling are given Equations 2-6 and 2-7. The (X_d'' + X_q'')/2 term is the expression for the negative-sequence impedance used in the model that was described in the previous section.

$$V(n) = n * \frac{X_d'' + X_q''}{2} I(n) \qquad \text{for } n \geq 1$$ **Equation 2-6**

$$V(n+2) = (n+2) * \frac{X_q'' - X_d''}{2} I(n) \qquad \text{for } n \geq 1$$ **Equation 2-7**

If positive-sequence n^{th}-harmonic currents are injected into the stator, (n) and (n-2) negative-sequence harmonic voltages will appear on the stator winding (of most interest, the 7^{th} and 13^{th} create 5^{rd} and 11^{th} harmonics respectively). For example, positive-sequence 7^{th} harmonic currents

[10] Wilsun W. XU, Hermann W. Dommel, Jose R. Marti, "A Synchronous Machine Model for Three-Phase Harmonic Analysis and EMTP Initialization, Transactions on Power Systems, Vol. 6, No. 4, November 1991.

[11] E. Clarke, *Circuit Analysis of A-C Power Systems*, vol. II, General Electric Company, 1950.

will cause a rotating magnetic field to rotate at seven times the speed of the rotor in the same direction. This will induce 6th-harmonic currents in the rotor in the damper winding and the field windings – it is 6th harmonic because the rotor is moving relative to the rotating magnetic field at a 7 to 1 ratio in the same direction, so the difference is six. The 6th-harmonic current on the rotor will induce a 5th-harmonic voltage on the stator. The equations for the coupling are given Equations 2-8 and 2-9.

$$V(n) = n * \frac{X_d'' + X_q''}{2} I(n) \qquad \text{for } n \geq 1 \qquad \textbf{Equation 2-8}$$

$$V(n-2) = (n-2) * \frac{X_q'' - X_d''}{2} I(n) \qquad \text{for } n \geq 1 \qquad \textbf{Equation 2-9}$$

Zero-sequence harmonics (the 3rd is the value of most interest) stay decoupled and do not cause other harmonics. If harmonic loads are not balanced, then a 5th-harmonic current (which is normally a negative-sequence harmonic) may contain positive, negative, and zero-sequence components, so the 5th harmonic could create 3rd, 5th, and 7th harmonic voltages with the 5th-harmonic being the largest component.

The phase angle of all voltages is leading the current that created it by 90° at $\theta = 0$ (since the current and voltage are at different frequencies, the angle has to be specified at one position in time for the angle to mean anything – see [11] for details). This means that if a drive creates 5th and 7th harmonic currents that are in phase, the 5th harmonic voltage created by the 7th harmonic current will be in phase (so it will directly add) with the 5th harmonic voltage created by the 5th harmonic current.

If the X_d'' and X_q'' are close in value, these effects will be minor (given the $X_d'' - X_q''$ term). X_d'' and X_q'' will be close in value if the rotor has a fully-connected damper winding. The reason that the second-order effects are a function of the ($X_d'' - X_q''$) term is that it is due to rotating magnetic field spinning around a changing impedance (as the magnetic field rotates, it alternately interacts with the direct axis and the quadrature axis impedance). If the direct-axis and the quadrature-axis impedance are the same, there will not be a changing impedance as the rotor rotates, and there will not be second-order harmonics. Usually, X_d'' and X_q'' are close enough to neglect the second-order terms. Although the second-order terms can be calculated by hand, it is complicated enough that a computer model is usually necessary (and, unfortunately, most harmonic programs do not model generators to this degree). If the load is modeled with something other than an ideal current source, then it becomes even more complicated. To precisely solve this, an iterative approach would be needed with a more accurate load representation. Since more accurate load representations are not usually available, it is not worth the effort to use a more precise generator model.

3
HARMONIC VOLTAGE CALCULATIONS

The following sections contain some example calculations for a generator in standalone operation that is supplying harmonic loads. Table 3-1 shows typical harmonic characteristics of several common harmonic-producing loads.

Table 3-1
Typical Harmonic Current Spectra of Different Types of Loads

Harmonic Current Source Magnitude and Phase Angle Spectra																
Harmonic	***Adjustable Speed Drives***				***Electronic Loads***				***Fluorescent Lighting***							
									Electronic				Magnetic			
	High		Low		High		Low		High		Low		High		Low	
	|I|	θ	|I|	θ	|I|	θ	|I|	θ	|I|	θ	|I|	θ	|I|	θ	|I|	θ	|I|	θ
1	1	-13	1	-11	1	-5	1	1	1	8	1	3	1	-6	1	-3
3	.044	85	.047	101	.658	158	.548	165	.199	-152	.082	-48	.197	-99	.064	-76
5	.765	118	.321	113	.377	-41	.367	-30	.074	-173	.116	-49	.062	-46	.103	-59
7	.627	-90	.162	-148	.127	116	.183	128	.032	131	.028	9	.009	56	.028	3
9	.029	57	.004	-158	.044	-93	.066	-103	.024	23	.017	91	.002	-167	.020	68
11	.248	31	.065	-72	.053	-102	.050	-3	.018	-7	.011	-175	.002	-9	.017	131
13	.127	169	.057	-38	.025	-2	.040	133	.008	-60	.007	-110	.003	72	.008	-145
15	.005	126	.003	-18	.019	148	.025	-117	.004	-174	.005	-26	.003	173	.006	-76
17	.071	-163	.037	84	.018	-75	.024	3	.001	170	.004	32	.003	-102	.005	-7
19	.084	-34	.027	87	.011	-16	.017	140	.002	76	.003	115	.002	-22	.004	70
21	.009	93	.002	85	.006	78	.011	-114	.001	2	.003	-178	.002	58	.003	131
23	.044	60	.019	-140	.004	-51	.013	10	.001	-19	.002	-104	.001	133	.002	-156
25	.033	176	.019	-136	.004	-67	.008	116	.001	-140	.001	-42	.001	-160	.002	-97

Balanced Example

Consider the following as an example of a balanced three-phase load. The assumptions are:

- The load on a generator consists of electronic loads (i.e. computers) equal to 25% of the generator rating.
- The load is assumed to follow the "*Low* Electronic Loads" column in Table 3-1.
- All three phases are balanced.
- The phase angles of the loads are ignored.
- The generator impedances are taken from the default values in Table 2-2 ($X_2 = 0.28$, $X_0 = 0.05$ and $X_n = -0.077$).

The voltages at each harmonic frequency need to be calculated. Since the three phases are balanced, the actual circuit in Figure 2-4 does not need to be evaluated. The following simplified equations can be used:

$$V_n = n \cdot X \cdot I_n$$

where $X=X_2=0.28$ for positive or negative-sequence harmonics, and $X=X_0+3X_{gn}=0.05$ for zero-sequence harmonics (mainly for the 3rd). Since the loading on the generator is 25% of its rating, the percentage current values from Figure 2-4 must be multiplied by 0.25.

For the 3rd harmonic, the voltage distortion on all three phases is:

$$V_3 = 3 \cdot X_0 \cdot I_3 = 3\ (0.05)\ (0.25)\ (0.548) = 2.06\%$$

Similarly, for the 5th harmonic, the voltage is:

$$V_5 = 5 \cdot X_2 \cdot I_5 = 5\ (0.28)\ (0.25)\ (0.367) = 12.84\%$$

And for the 7th harmonic, the voltage is:

$$V_7 = 7 \cdot X_2 \cdot I_7 = 7\ (0.28)\ (0.25)\ (0.183) = 8.97\%$$

The results for the odd harmonics to the 19th are shown in Figure 3-1. The voltage THD is 16.8% for this example. Note that these are rather high values of harmonics and illustrate what can happen to a generator that has considerable nonlinear load. All of the values scale linearly, so if the loading relative to the size of the generator is 50% instead of 25%, all of the values would double (so THD = 33.6%).

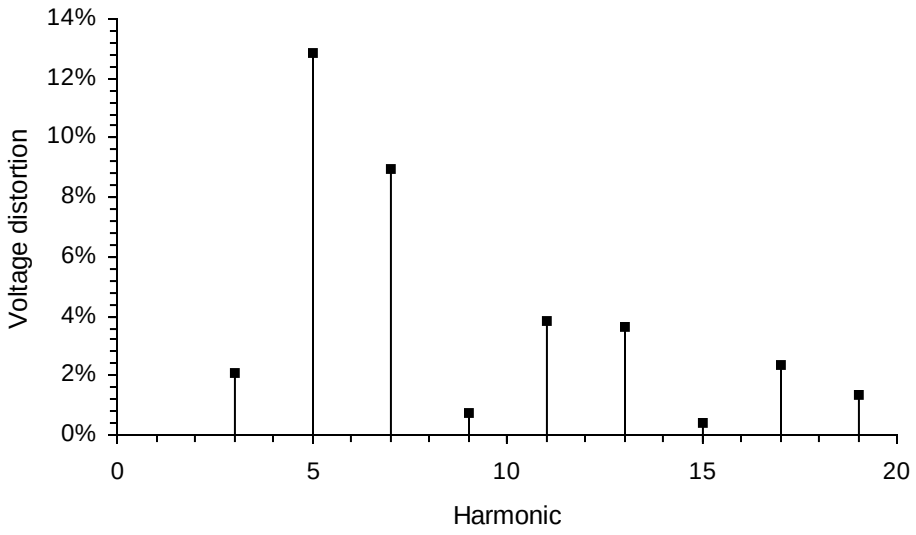


Figure 3-1
Harmonic Voltage Distortion at the Generator Terminals for the Balanced Electronic Load Example for a Loading Equal to 25% of the Generator Rating

Unbalanced Example

Calculations get more complicated for an unbalanced situation. Consider the following as an example:

- The load on a generator consists of electronic loads (i.e. computers) taken from the "*Low* Electronic Loads" column in Table 3-1.
- The load on phase A is equal to 10% of the generator rating.
- The load on phase B is equal to 25% of the generator rating.
- The load on phase C is equal to 25% of the generator rating.
- The phase angles of the loads are all taken to be in phase.
- The generator impedances are taken from the default values in Table 2-2 ($X_2 = 0.28$, $X_0 = 0.05$ and $X_N = -0.077$).

Again, each harmonic is calculated separately. Because of the unbalance, the circuit of Figure 2-4 needs to be evaluated. The 3rd harmonic currents are zero sequence, which means they add directly in the neutral (phase angles aren't needed), so the current in the neutral is:

$$I_{N3} = (0.1 + 0.25 + 0.25)\ (0.548) = 0.3288 \text{ in per unit on the machine base}$$

The neutral point voltage is:

$$V_{N3} = 3 \cdot X_N \cdot I_{N3} = 3\ (-0.077)\ (0.3288) = -0.0760 \text{ pu}$$

The voltage between phase A and the neutral, V_{AN}, is:

$$V_{AN3} = 3 \cdot X_2 \cdot I_3 = 3\ (0.28)\ (0.1)\ (0.548) = 0.046 \text{ pu}$$

This means the line-to-ground voltage on phase A is:

$$V_{A3} = V_{AN3} + V_{N3} = 0.046 + (-0.076) = -0.03 \text{ pu} = -3\%$$

For phase B,

$$V_{BN3} = 3 \cdot X_2 \cdot I_3 = 3\ (0.28)\ (0.25)\ (0.548) = 0.115 \text{ pu}$$

$$V_{B3} = V_{BN3} + V_{N3} = 0.115 + (-0.076) = 3.9\%$$

For phase C,

$$V_{CN3} = 3 \cdot X_2 \cdot I_3 = 3\ (0.28)\ (0.25)\ (0.548) = 0.115 \text{ pu}$$

$$V_{C3} = V_{CN3} + V_{N3} = 0.115 + (-0.076) = 3.9\%$$

So, the phase-to-ground voltage distortion magnitudes are:

$$V_{A3} = 3.0\%,\ V_{B3} = 3.9\%,\ V_{C3} = 3.9\%$$

The only difference between this case and the previous balanced case is that the Phase A current is decreased from 25% to 10%. Even though the current on one phase dropped, the overall distortion for the third harmonic increased (from 2% in the balanced case to 3% or more in the unbalanced case). This is due to the higher impedance seen for the unbalanced third harmonic (which is no longer strictly zero sequence, so it has a higher impedance). This is an important consideration for situations with high levels of computer loads (because of the high level of 3rd harmonic). It also suggests that one way to reduce the problem is to evenly balance the three phases. Balancing will cause the effective impedance of the generator to be the zero-sequence impedance, which is significantly lower than X_2.

The magnitudes of the 3rd-harmonic phase-to-phase distortions are (e.g. $V_{AB3} = |V_{A3} - V_{B3}|/\sqrt{3}$):

$$V_{AB3} = 4.0\%,\ V_{BC3} = 0.0\%,\ V_{CA3} = 4.0\%$$

Now, consider the 5th harmonics which are negative-sequence, but since it is unbalanced, they no longer cancel in the neutral as negative-sequence quantities normally do. The phase angles must be included in the neutral calculations:

$$I_{N5} = I_{A5} + I_{B5} + I_{C5} = (0.1 + 0.25a + 0.25a^2)\ (0.367) = -0.055$$

Remember that $a = \angle 120°$; the equation above includes the phase angles of the normal negative-sequence phase rotation (A-C-B). We are fortunate in this case that the phase B and phase C

quantities are equal which makes the calculations easier (the complex portions cancel each other). The voltages are found as:

$V_{N5} = 5 \cdot X_N \cdot I_{N5} = 5\ (-0.077)\ (-0.055) = 0.0212$ pu

$V_{AN5} = 5 \cdot X_2 \cdot I_5 = 5\ (0.28)\ (0.1)\ (0.367) = 0.0514$ pu

$V_{A5} = V_{AN5} + V_{N5} = 0.0514 + 0.0212 = 7.2\%$

$V_{BN5} = 5 \cdot X_2 \cdot I_5 = 5\ (0.28)\ (0.25)\ (0.367)\ (a) = 0.128 \angle 120°$ pu

$V_{B5} = V_{BN5} + V_{N5} = 0.128 \angle 120° + 0.0212 = 11.9\% \angle 111°$ pu

$V_{CN5} = 5 \cdot X_2 \cdot I_5 = 5\ (0.28)\ (0.25)\ (0.367)\ (a^2) = 0.128 \angle -120°$ pu

$V_{C5} = V_{CN5} + V_{N5} = 0.128 \angle 120° + 0.0212 = 11.9\% \angle -111°$

The 7th harmonics would be calculated in a similar manner to the 5th harmonics, except that the 7th harmonics are positive sequence, so the positive-sequence rotation would be used for the phase currents (i.e. use $0.1 + 0.25a^2 + 0.25a$ (A-B-C sequence) for the neutral current).

The results for the odd harmonics to the 19th are shown in Figure 3-2. The voltage THDs are:

$V_{A,\,THD} = 10\%$, $V_{B,\,THD} = V_{C,\,THD} = 16\%$

$V_{AB,\,THD} = V_{CA,\,THD} = 12.8\%$, $V_{BC,\,THD} = 16.8\%$

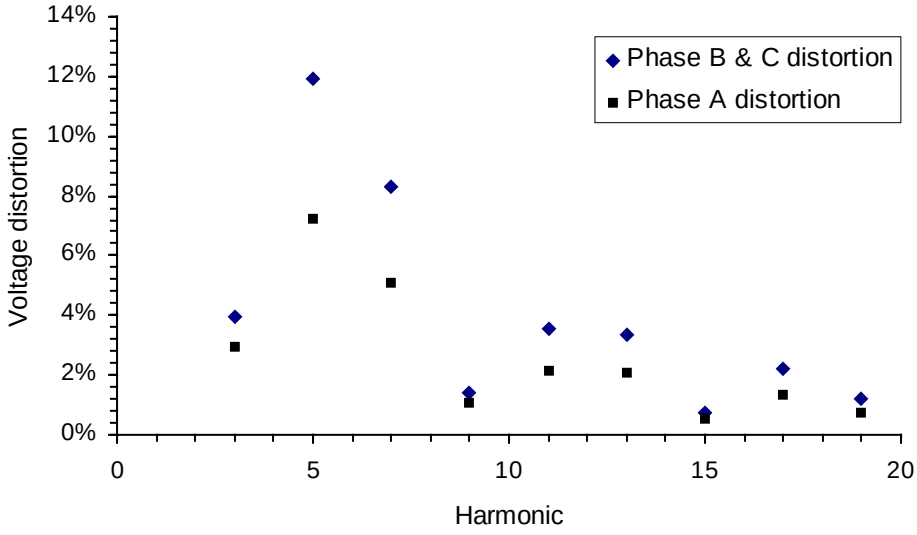


Figure 3-2
Harmonic Voltage Distortion at the Generator Terminals (phase-to-ground voltages) for the Unbalanced Electronic Load Example for a Loading Equal to 10% of the Generator Rating on Phase A and 25% on Phases B and C

General Guidelines

The model in Figure 2-4 can be used to find the voltage distortion on a generator given the harmonic loading. Table 3-2 shows a summary of the voltage distortion seen with different balanced nonlinear loads. All are specified with loadings of 100% of the generator rating. The values in the table should be scaled by the actual percentage loading on the generator. As an example, for an adjustable speed drive with no choke is equal to 25% of the rating of the generator (there may be other linear load that is not included), multiply the first row of the table by 0.25. If more than one nonlinear load is present, the individual harmonic values in the table may be added linearly (this assumes that the phase angles are equal which is a conservative assumption). For example if 10% of the load is a UPS and 15% is single-phase electronic supplies, the total 5th harmonic voltage would be 0.1(0.181) + 0.15(0. 514) = 0.095. The THD cannot be found by adding the columns in the table, but it can be found by:

$$THD = \sqrt{(k_1 \cdot THD_1)^2 + (k_2 \cdot THD_2)^2} = \sqrt{(0.1 \cdot 0.416)^2 + (0.15 \cdot 0.676)^2} = 0.11$$

Table 3-2
Voltage Distortion (THD and the Given Odd Harmonics) on a Generator for the Given Load Type with X_0=0.05 and X_2=0.28 for a Load of 100% of the Generator Rating – Scale the Results by the Actual Nonlinear Loading

	THD	3	5	7	9	11	13	15	17	19
ASD with no choke	194.1%	0.7%	107.1%	122.9%	1.3%	76.4%	46.2%	0.4%	33.8%	44.7%
ASD with a choke	63.3%	0.7%	44.8%	31.4%	7.2%	0.0%	23.7%	4.3%	0.0%	19.7%
Single-phase switchmode power supply	67.6%	8.2%	51.4%	35.9%	3.0%	15.4%	14.6%	1.5%	9.5%	5.3%
UPS	41.6%	0.1%	18.1%	9.0%	0.1%	30.8%	2.9%	0.0%	14.3%	12.8%

For generators with different impedances than the defaults in Table 3-2, the individual harmonics can be scaled by the ratio of the actual values to the default impedances. The negative-sequence impedance may range from 0.15 to 0.35. This range of voltage THD that may commonly be seen are shown in Figure 3-3 for single-phase electronic supplies and UPSs and in Figure 3-4 for adjustable-speed drives.

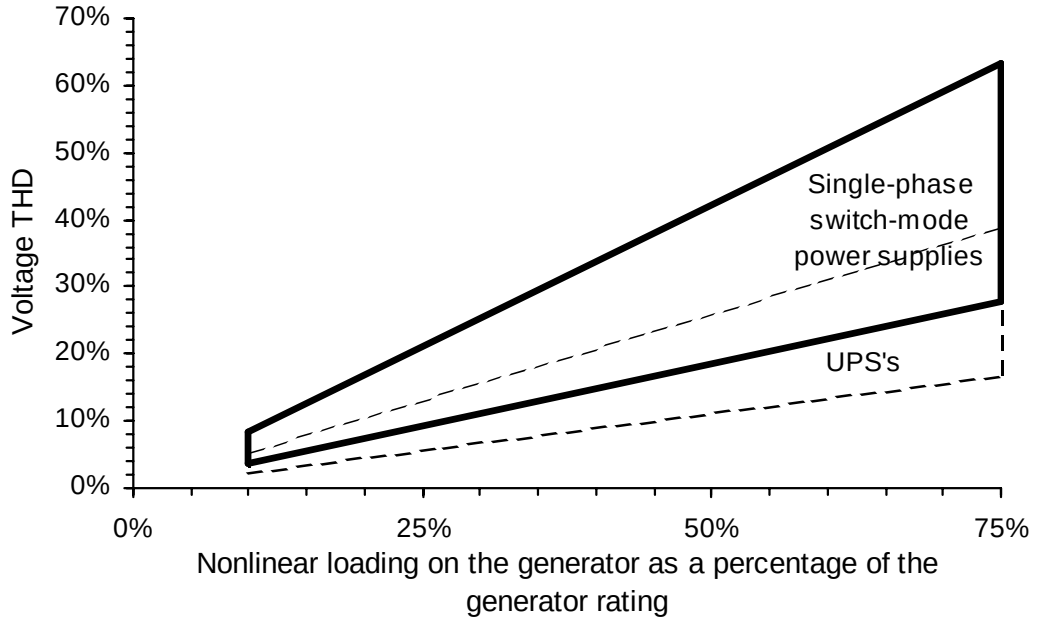


Figure 3-3
Ranges of Total Harmonic Voltage Distortion at the Generator Terminals for a Balanced Nonlinear Load as a Function of the Size of the Load Relative to the Generator Rating for Electronic Power Supplies and UPS's (for X_0=0.05 and X_2=0.15 to 0.35)

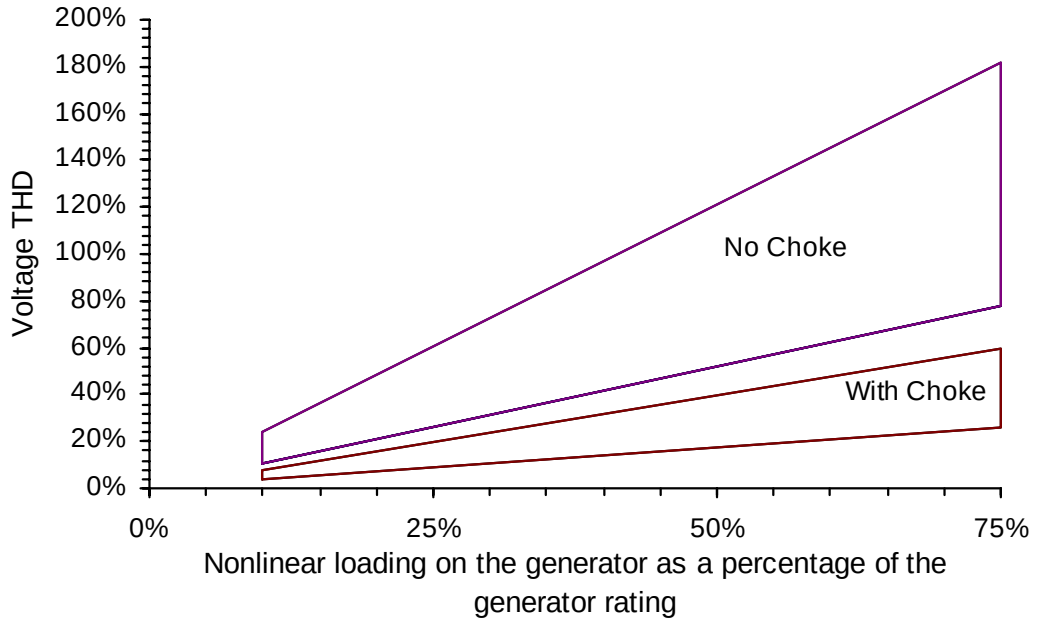


Figure 3-4
Ranges of Total Harmonic Voltage Distortion at the Generator Terminals for a Balanced Nonlinear Load as a Function of the Size of the Load Relative to the Generator Rating for Adjustable-Speed Drives (for X_0=0.05 and X_2=0.15 to 0.35)

It is difficult to come up with generic guidelines for voltage distortion because sensitive loads react differently to harmonics. As a general recommendation without any other information, it is advised that the total harmonic distortion of the voltage be limited to 10%.

Effect of Capacitors

Capacitors often cause resonances that amplify harmonics. Facility capacitors are often used to correct the power factor to avoid power factor penalties. A capacitor bank will form a parallel resonance with a generator as shown in Figure 3-5. If the resonant frequency happens to be at one of the harmonic frequencies created by the load, very high voltage distortions can be created. The resonant frequency can be determined using Equation 3-1.

$$n = \sqrt{\frac{kVA_{gen}}{X_2} * \frac{1}{kVAR_{cap}}}$$

Equation 3-1

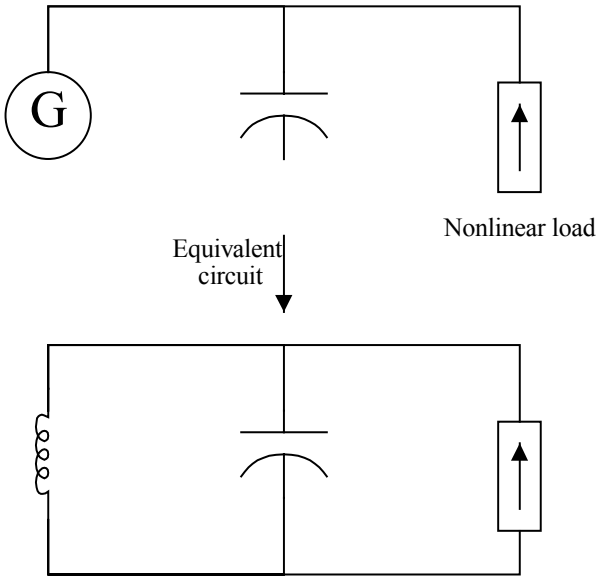


Figure 3-5
Resonant Circuit with a Local Capacitor and Backup Generator

The resonant frequency depicted as a function of the capacitor size relative to the generator size is shown in Figure 3-6 for different values of X_2. The critical resonances are the 3rd if single-phase electronic loads are present and the 5th and 7th harmonics for most electronic loads including UPSs, ASDs, fluorescent lighting, and computers. As seen in Figure 3-6, it does not take much capacitance to cause resonance at one of the critical low frequencies.

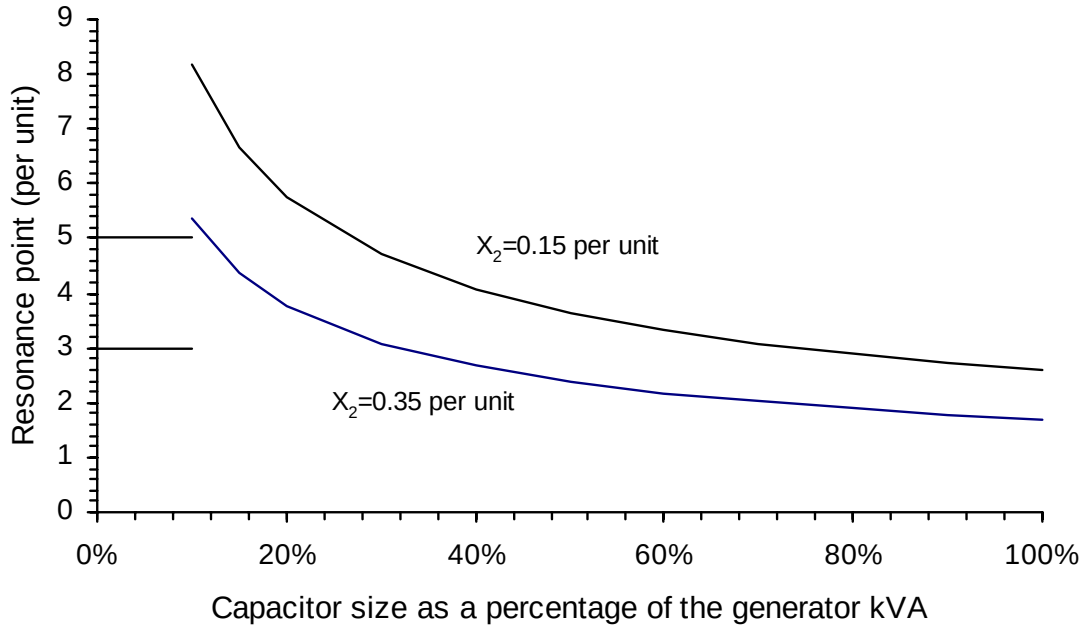


Figure 3-6
Resonance Point as a Function of Capacitor Size and X_2

Under normal operations with the generator offline and the load fed from the utility, this may not cause any problems. When the generator operates with the utility out, the impedances (and resonances) change, so problems with severe distortion can occur when the generator comes on. Under some circumstances, it may be better to switch the capacitors off while the backup generators are supplying the facility to avoid unwanted resonances.

4
HARMONIC PROBLEMS

The increased voltage distortion resulting from a relatively weak source such as a generator can cause potential problems for customer load. The main issues are as follows:

- The voltage-sensing circuit in an uninterruptible power supply that determines the transfer from utility line to battery during an undervoltage condition may be susceptible to a distorted voltage waveform, causing the UPS to go to battery power. Its batteries may be depleted after only a short time during the operation of the generator.
- Increased voltage distortion will reduce the life of induction motors and other customer loads.
- A building power-line carrier signal, clock-synchronizing signal, or other communication signal within the customer premises may be susceptible to increased voltage distortion.
- Equipment that uses a front-end filter with capacitors such as lighting ballasts may be damaged due to increased voltage distortion.
- Power factor correction capacitors within the customer premises may also be damaged due to excessive harmonic current due to increased voltage distortion.

The generator regulator may also interact with voltage distortion created by nonlinear generator loading. This leads to unstable generator voltage that may oscillate because of the distorted voltage waveform at the generator terminals. Also, the voltage error caused by the distortion may cause the generator to shut down. In order to minimize the impact of the voltage distortion on the generator, the voltage regulator must be capable of operating correctly under the distorted load. This requires the following characteristics for the voltage regulator circuit:

- *Regulator Voltage Sensing*: The sensing circuits of the regulator need to respond appropriately to the fundamental component of the voltage waveform. It must be rapid enough to maintain control and not so fast that it is affected by the distortion caused by the load. Three-phase sensing and averaging makes the circuit less sensitive to distortion on individual phases.
- *Regulator Power Supply*: Power for the exciter field may be obtained from the generator output or from a separate source such as a permanent magnet (PM) pilot exciter. The PM pilot exciter has the advantage that its output is not affected by the generator load current. When the exciter field power is obtained from the generator output, care must be taken to ensure that any waveform distortion due to load current does not produce changes in the regulator output.

Existing solutions such as oversizing generators, harmonic filtering for nonlinear loads, improved control loop stability of generator, and UPS control/sensing circuits are all geared to provide a temporary solution rather than addressing the root cause of the problem. New research into

innovative methods of active impedance matching and localized short-term energy storage to match load inrush current requirement offer more attractive and permanent solutions to this problem.

Case Study: Effect of Generator Impedance on Voltage Distortion (Islanded-Mode)

In this case study, during islanded or standby generator operation, some uninterruptible power supplies (UPSs) would switch to battery. After the standby generator operated for about 10 minutes, the UPS batteries would run down, resulting in the shutdown of critical computer loads.

Site Description

- 1.1-MW commercial customer
- The supply voltage to service is 13.8 kV.
- The system includes one feeder from 13.8-kV bulk substation.
- The load at customer facility is fed through one 2000-kVA step-down transformer (13.8 kV to 480 V) that has its primary windings connected in a "delta" configuration.
- The customer owns a 500-kVA diesel standby generator for emergency loads connected to the customer 480-V bus.

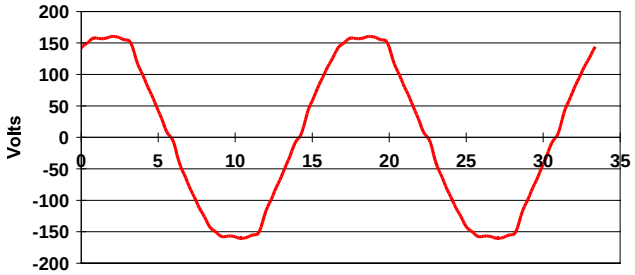
Measurement Results

Case A: UPS Powered from Utility (Generator Out)

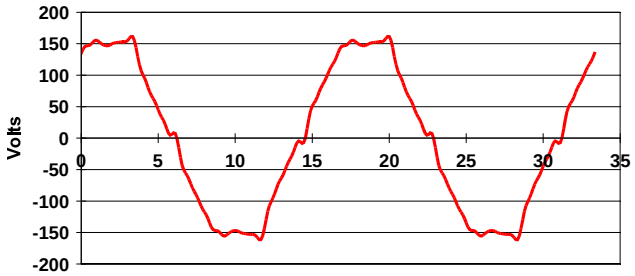
- Measurement Location: 120V Panel (Input Voltage to UPS)
- Measurement Results: Voltage THD 4.3% (See Figure 4-1a)

Case B: UPS Powered from Standby Generator (Utility Out)

- Measurement Location: 120V Panel (Input Voltage to UPS)
- Measurement Results: Voltage THD 8.5% (See Figure 4-1b)



(a) 120V Bus Voltage From Utility Supply. (V_{thd} = 4.3%)



(b) 120V Bus Voltage During Generator Operation. (V_{thd} = 8.5%)

Figure 4-1
UPS Input Voltage From (a) Utility Supply and b) During Generator Operation

Analysis and Conclusion

The voltage distortion at this site effectively doubled when operating on the standby generator in an islanded mode. The UPS load would not tolerate this level of distortion and transferred to battery, leading to a system shutdown when the battery was depleted.

5
SOLUTIONS

General Solutions

Many of the standard solutions to harmonic problems can be applied to generators serving harmonic loads. The solutions include:

- *Passive harmonic filters*: Passive tuned filters are the most widely used solution to harmonics. Each tuned filter consists of a capacitor in series with an inductor. At the tuned frequency, the circuit is a very low path for the harmonics. Tuned filters are typically provided for the 5^{th} and 7^{th} harmonics (and the 3^{rd} if that is created by the load). A drawback to the application for harmonic loads with backup generators is that the filters are only needed occasionally, so the expense may be high. If capacitors are needed for power factor correction, then the cost is less because the capacitors are justified for this reason (so the cap banks can be turned into tuned filters).
- *Active harmonic filters*: Active harmonic filters inject a current with harmonics that cancels the harmonics created by the load. They are becoming more widely available. They are more expensive than their passive counterpart.
- *Delta-wye transformer*: Balanced third-harmonic currents can be blocked by a transformer with a delta winding on the generator side and a grounded-wye winding on the load side. Third harmonics are zero-sequence quantities, and the delta-wye connection will block them (they will circulate in the delta winding, so the transformer must be rated to handle them). This is especially helpful for facilities with large amounts of single-phase computer loads that are high in third harmonics. One caution is that the loads must be balanced for the delta-wye transformer to block them. If they are unbalanced, the harmonics will get through the transformer and see a higher impedance at the generator.

Generator-Specific Solutions

Generator-specific solutions are often the most appropriate. If some care is taken during the selection of the generator, then problems can be minimized. Specific solutions for back-up generator applications are as follows:

- *Generator Oversizing*: The most common way to deal with generators applied for harmonic loads is to oversize generators. See for example, the manufacturer recommendations given later in this section. A larger generator will have a lower impedance to harmonics.
- *Specify Low Subtransient and Negative-Sequence Reactances*: The voltage distortion is directly proportional to the generator impedance (X_d", X_q" and X_2), so lower impedance will

result in lower voltage distortion. Table 2-2 shows results of tests where negative-sequence reactances ranged from 0.125 to 0.375. Table 5-1 shows catalog data for Caterpillar (see Appendix A). If possible, specify that the negative-sequence impedance should be less than 0.15 per unit.

Table 5-1
Generator Impedance Data from Caterpillar Generator Manufacturer Information

Generator	X_2	X_d"	X_q"
SR4B, frame 443, 480 V, 175-440 kW, 1800 rpm	0.188	0.180	0.197
SR4, frame 683, 480 V, 500 kW, 1200 rpm	0.237	0.231	0.242
SR4, frame 815, 480 V, 2000 kW, 1200 rpm	0.191	0.192	0.191
SR4, frame 2919, 6900 V, 2500 kW, 1800 rpm	0.231	0.228	0.234
SR4, frame 2919, 13800 V, 2500 kW, 1800 rpm	0.283	0.280	0.287

- *Specify a Two-Thirds Pitch Stator Winding*: A two-thirds pitch generator winding will result in a low, zero-sequence impedance. This will be very helpful if there is a lot of single-phase computer load on the generator that are high in third harmonics. It will not help with 5^{th} or 7^{th} harmonics
- *Conditioned Power for the Generator Controls*: One of the problems with harmonic loads on a generator is that the controls can be affected by voltage distortion that can lead to generator misoperation or shutdown. For example, the voltage regulator may be confused by the voltage harmonics and create erratic voltage. If the generator controls are provided conditioned power or the manufacturer can verify operation under high voltage distortion, then these problems can be minimized.
- *Switch Out Capacitors During Standby Generator Operation*: If capacitors are switched off during generator operation, then problems with resonances are avoided. For poor power factor loads, with the capacitors off line, the generator will have to be sized to handle the total current (which will be higher without the capacitors).

UPS-Specific Solutions

If the load is primarily a UPS, some specific solutions are available:

- *Specify a UPS that is Tolerant of Voltage Distortion*: If a UPS does not transition to the battery because of the harmonics, then the voltage distortion will not affect the UPS or its loads (if it is a back-to-back type UPS). Different UPSs will switch to batteries at different voltage distortion levels. Finding a UPS that can tolerate high input voltage harmonics will reduce the chances of malfunction when operating on the standby generator.
- *Specify a UPS that Produces Low Harmonics*: If the UPS generates low harmonic levels, then the generator will have less voltage distortion (of course, other nonlinear load on the same

generator can cause voltage distortion that could effect the UPS). UPS topology will be a factor here. Off-line UPSs will have lower harmonics due to the UPS (they would mainly be battery charging harmonics), but they will transfer the load harmonics to the system (if the load is high in harmonics, this will be passed to the generator). Different on-line UPSs will have different harmonic characteristics. A 6-pulse bridge on the front end will create significant harmonics. A 12-pulse front end will create less. A pulse-width modulated front end using IGBTs will create very low harmonic levels (the significant harmonics will be high frequency harmonics at the IGBT switching frequency).

- *Specify Harmonic Filters*: Many UPSs can be specified with passive filters on the input of the UPS. This will greatly lower the harmonics that will flow to the generator. There are two situations that warrant attention if a UPS has harmonic filtering:

  1. If other harmonic producing load is present on the same circuit (e.g. other UPSs or computer load not connected to the UPS), the harmonics from the other loads will want to flow to the filters on the UPS. This may overburden the UPS filters and cause failures.

  2. If two UPSs are paralleled and they both have input-side filters, the tuning of each filter needs to be checked. If one of the filters happens to be tuned to n=4.9, and another is tuned to the n=5.1, there will be a sharp high-impedance resonance point somewhere between 4.9 and 5.1, which can cause very high 5^{th}-harmonic voltages on the circuit. This is also a concern if standalone passive filters are adjacent to a UPS with input-side filtering.

- *Specify Active Harmonic Filtering*: UPSs are available that have active filtering on the power conversion on the input side of the UPS. Since the power electronics are already available, the filtering capability is much more cost effective than a standalone active filter.

- *Delay Battery Charging Until After the Utility Source is Restored*: Charging the UPS batteries will increase the load on the generator (and increase the harmonic loading), so if the battery charging can be delayed until the utility source is restored, the voltage distortion will be lower.

Manufacturer Guidelines for Applying Generators in the Presence of Harmonics

Generator manufacturers give recommendations for applying generators for harmonic-producing loads. Table 5-2 shows one recommendation for oversizing a generator feeding UPS loads from one generator manufacturer. The UPS input kW includes battery recharge load and UPS losses as shown in Equation 5-1.

$$\text{UPS Input kW} = \frac{\text{Output kW + Battery Recharge kW}}{\text{UPS Efficiency}} \qquad \textbf{Equation 5-1}$$

If the UPS efficiency is not known, use 0.85 for UPS < 100 kW, 0.875 for 100 to 500 kW, and 0.9 for sizes greater than 500 kW.

Table 5-2
Manufacturer Recommendation for Generator Oversizing Based on Different Loads[12]

UPS type	Minimum standby rated generator set
6-pulse rectifier/charger	UPS input kW × 1.6
12-pulse rectifier/charger	UPS input kW × 1.4

Note: UPS input kW includes output kW, battery recharge kW, and UPS losses

Table 5-3 shows another recommendation for oversizing a generator based on different types of nonlinear load.

Table 5-3
Manufacturer Recommendation for Generator Oversizing Based on Different Loads[13]

Type of Load	Oversize Factor
SCR Controls – Resistive or Motor Load:	
1 Phase ½ Wave (1 pulse)	2.0
1 Phase Full Wave (2 pulse)	1.6
3 Phase ½ Wave (3 pulse)	2.0
3 Phase Full Wave (6 pulse)	1.5
6 Phase Full Wave (12 pulse)	1.3
SCR Controls – Capacitive or Battery Load:	
1 Phase ½ Wave (1 pulse)	1.6
1 Phase Full Wave (2 pulse)	1.3
3 Phase ½ Wave (3 pulse)	1.4
3 Phase Full Wave (6 pulse)	1.3
6 Phase Full Wave (12 pulse)	1.2
Rectifiers:	
1 Phase ½ Wave (1 pulse)	1.4
1 Phase Full Wave (2 pulse)	1.3
3 Phase ½ Wave (3 pulse)	1.4
3 Phase Full Wave (6 pulse)	1.3
6 Phase Full Wave (12 pulse)	1.2
Inverter Drives, UPS Systems, Switching Power Supplies:	
SCR Input – Use values for SCR with Capacitive Load	
Rectifier Input – Use Rectifier Values	
Unity P.F. Type Power Supplies	1.0
Discharge Lighting, Fluorescent Lighting:	
Unity P.F. Types	1.0
Other Types: 1 phase.	1.2
3 phase.	1.15
(Note: Check neutral current.)	

[12] G. Minor, Caterpillar, Inc., "UPS System & Generator Set Considerations," *Power Quality Assurance*, May/June 1995, pp. 29-33.

[13] G. R. Phillips, MagneTek, Inc., "Non-Linear Loads on Standby Generator Sets," Power Quality, Sept. 1991 Proceedings, pp. 362-377.

Even when following manufacturer's recommendations for oversizing, harmonic problems may still occur. Possible scenarios include:

- Very sensitive equipment – Even if the generator is oversized, there still may be enough voltage distortion to trip or disrupt some loads if the equipment is very sensitive to harmonic distortion.
- Capacitor banks – cap banks can cause resonances that amplify the harmonics. Although the generator is oversized, resonances can still occur.

Also, power quality problems could be caused not by harmonics but by other reasons including:

- Frequency deviations are much more pronounced when operating with the generator.
- Motor starts or other large changes in loading can cause voltage swings (usually sags) and/or short duration frequency swings.
- Pulsating loads that occur with similar time constants to the generator (1 to 5 changes per second) could interact with the generator and engine control systems causing voltage and frequency swings.

6
SUMMARY

Generator Calculations

The voltage distortions can be easily calculated based on the harmonic current created by the load as:

$$V_n = n \cdot X \cdot I_n$$

The harmonic impedance of the generator for harmonics other than the third is the negative-sequence impedance (X_2). This is usually between 0.15 and 0.35 per unit. For third harmonics, the harmonic impedance is the zero-sequence impedance (X_0). This is usually quite low, ≈ 0.05 per unit. If the phases are not balanced, the distortion calculations become more complex, and the circuit of Figure 2-4 must be used to calculate the distortion.

Solutions

The most effective solutions are done when the generator is specified. The best way to limit harmonic distortion is to specify a generator with low subtransient and negative-sequence impedances and to specify a two-thirds pitch stator winding. Capacitors can also be switched out during standby generator operation to minimize the chance for resonance conditions and high voltage distortion. Oversizing the generator is also an option (or limiting the load during standby operation).

Future Work

Additional research is needed to more accurately identify the harmonic characteristics of available generators and solutions for harmonic loads on generators. During this research project, EPRI will test different generators under linear and nonlinear loads. The objective of the tests will be to verify the harmonic models given in this report and verify the calculation procedure with test results. The goal is to better understand the compatibility issues between the generator and harmonic-generating loads, such as variable-frequency drives, computer power supplies, and UPSs.

A
MANUFACTURER'S INFORMATION

Generator Manufacturers

Company	Address	City	St	Zip	Phone	URL
Capstone Turbine Corporation	18700 Oxnard Street	Tarzana	CA	91356	(818) 598-5715	www.capstoneturbine.com/
Caterpillar International Power	P.O. Box 610	Mossville	IL	61552	(309) 578-8328	www.cat.com
Caterpillar International Power	3701 State Road	Lafayette	IN	47905	(765) 448-5518	www.cat.com
Caterpillar, Inc.	8300 FM 1960 W., Suite 340	Houston	TX	77070	(281) 677-2528	www.cat.com
Detroit Diesel Corp.	13400 W. Outer Drive	Detroit	MI	48239	(313) 592-5990	www.detroitdiesel.com
Dresser Industries/Waukesha Engine	1000 West St. Paul Ave.	Waukesha	WI	53188	(262) 549-2904	www.waukeshaengine.com
East Penn Mfg. Co. Inc.	Deka Road	Lyon Station	PA	19536	(610) 682-6361	www.svensson.com/public/c000354.html
Elliott Energy Systems, Inc.	2901 S.E. Monroe Street	Stuart	FL	34997	(561) 219-9449	www.elliott-turbo.com/
GE Distributed Power Systems	1 River Road, Bldg 59E-1	Schenectady	NY	12345	(800) 443-3278	www.gepower.com
GENERAC Power Systems, Inc.	Hwy. 59	Waukesha	WI	53186	(262) 968-2561	www.generac.com/corporate/index.cfm
Honeywell Power Systems	8725 Pan American Freeway	Albuquerque	NM	87113	(505) 798-6031	www.honeywell.com/
Honeywell Power Systems	2525 W. 190th Street	Torrance	CA	90504	(310) 512-4178	www.honeywell.com
Kohler Co.	N7650 County Trunk	Sheboygan	WI	53083	(920) 459-1651	kohlerco.com/powersystems/generators/home.html
M-C Power Corporation	8040 S. Madison Street	Burr Ridge	IL	60521	(630) 986-8040	apollo.osti.gov/html/fe/mcpwr.html

Company	Address	City	St	Zip	Phone	URL
McDermott Technology	PO Box 11165	Lynchburg	VA	24506	804-522-6743	www.mcdermott.com
Modular Cogeneration Corporation	10209 Menlo Avenue	Silver Springs	MD			none found
Mosaic	1700 S. Mount Prospect Road	Des Plaines	IL	60018	(847) 768-0842	none found
Northern Power Systems	182 Mad River Park	Waitsfield	VT	05673	(802) 496-2955	www.northernpower.com
Power Works (Ingersal Rand)	32 Exeter St	Portsmouth	NH	3801	(603) 512-1724	www.powerworks.com
Siemens Westinghouse Power Corp.	4400 Alafaya Trail, MC 381	Orlando	FL	32826	(407) 281-2500	www.siemens.com
Solar Turbines, Inc.	P.O. Box 85376 2200 Pacific Highway	San Diego	CA	92186	(858) 694-6000	www.cat.com/products/solarturbines/solarmain/solarmain.html
SONAT Power Systems, Inc.	P.O. Box 2563	Birmingham	AL	35202	(205) 327-2340	www.sonat.com/home/sps/product5.htm
Trigen Energy Corp.	650 S. Clinton Avenue	Trenton	NJ	08611	(609) 396-1892	www.trigen.com
Trigen Energy Corp.	One Water Street	White Plaines	NY	10601	(914) 286-6691	www.trigen.com

Data Sheets for Caterpillar Generators

See following:

Caterpillar™ Power Module



Features:

- Rating: 1825 kWe Prime Power, 2000 kWe standby, 480V, 60 Hz
- 3516B electronic engine for reduced emissions
- 825 frame brushless, permanent magnet excited SR4B synchronous generator with 2/3 pitch
- 75 dBA sound pressure level at a distance of 15 meters (50 ft)
- 1250 gallon UL listed double wall fuel tank allows 10 hours of operation at 100% load
- Fuel transfer system for pumping fuel from external auxiliary fuel tanks
- Fueling options: diesel only or diesel/natural gas
- Utility paralleling 600V class switchgear
- Capable of automatic or manual paralleling with a utility power source as a load management system, with provisions for standby operation feeding an isolated electrical load network
- Remote communications capability is included that allows user to remotely monitor, start and stop the unit

Accessories:

- Generator step-up transformers allow connections to the following electrical distribution systems: 2400V, 4160V, 12,470V, 13,200V, 13,800V and 14,400V
- Standard interconnecting cable between generator and step-up transformer
- 1100-gallon external auxiliary fuel tanks
- 8200-gallon refueling trailers

Manufactured by Caterpillar and offered by:

Williams Distributed Power Services
P.O. Box 3102
Tulsa, OK 74101
Phone: 1-800-WILLIAMS
Fax: (918) 573-0828

© 1999 The Williams Companies, Inc.

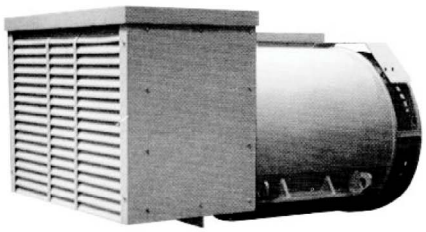
CATERPILLAR®

SR4 Generators

800 Frame

50 Hz 1000-2250 kV•A 1500 rpm
60 Hz 1000-2250 kW 1800 rpm

50 Hz 500-2000 kV•A 1000 rpm
60 Hz 500-2000 kW 1200 rpm



CATERPILLAR ENGINE FACILITIES ISO 9001 CERTIFIED

CATERPILLAR® SR4 GENERATOR

Type . . . . . Brushless, revolving field, solid-state automatic voltage regulator
Construction . . . . . Single bearing, two bearing close coupled – 808 and 809 frame 4 pole) three phase, wye connected
Insulation . . . . . Class H
Enclosure . . . . . Drip proof IP 22, guarded
Alignment . . . . . Caterpillar pilot shaft
Overspeed capability 150%
Waveform . . . . . Less than 5% deviation
Paralleling capability . . . . . Standard with adjustable voltage droop
Voltage regulator . . . . . 3-phase sensing with Volts-per-Hertz response
Voltage regulation . . . . . Less than ± 1%
Voltage gain . . . . . Adjustable to compensate for engine speed droop and line loss
TIF . . . . . Less than 50
THD . . . . . Less than 5%
Number of leads 6

STANDARD FEATURES

All metal components are plated or painted
Anticondensation heaters
Built-in paralleling capability with adjustable voltage droop
Class H rotor and stator insulation
4-Pole Terminal Strip for convenient customer load connection
Improved transient response with a standard V/Hz regulator
Optimum winding pitch for minimum total harmonic distortion
Performance and design matched to Caterpillar engines
Radio frequency noise suppression better than industry standards
Six leads for differential protection
Standard voltages: 380V, 480V, & 600V (1800 rpm 805-807 frame only) @ 60 Hz; 380V, 400V, 415V, 500V @ 50 Hz
Standards: meets or exceeds the requirements of IEC 34-1, NEMA MG 1-22, BS4999, BS5000, VDE0530, UTE5100, CSA22.2, ISO8528-3
Superior construction and testing
Telephone influence factor (TIF) of less than 50
VR3 automatic voltage regulator with 3-phase sensing
Wet, layer wound rotors individually tested to 125% overspeed; prototypes to 150% @ 170°C for two hours
Windings coated with a fungus-resistant resin

OPTIONAL FEATURES

Coastal/harsh environment form wound version
Bearing temperature detectors – 100Ω Pt or 10Ω Cu RTD
Custom voltages
Extra dips and bakes of insulating resins
Manual voltage control
Permanent magnet excitation*
RFI filter – 82/499/EEC, VDE 875/10.84 A2 Level N, BS800 standards, and MIL-STD-461B (conducted, radiated, and susceptibility)
Stator temperature detectors – Type J [Iron - (Constantan) thermocouples or surface mount RTDs (l00Ω Pt or 10Ω Cu)]
2/3 stator winding pitch
VR3F for enhanced transient response and block loading

CATERPILLAR®

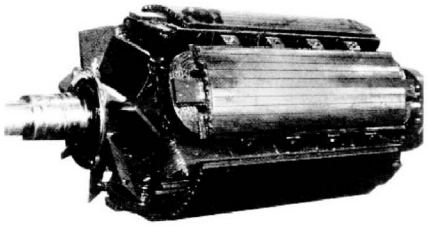
SR4 GENERATORS – 800 FRAME

OPTIONAL FEATURES (CONT.)

*** Optional Permanent Magnet Excited Generator:**
Eliminates the need for series boost
Field forcing for 10 seconds for generator protection
Improved performance with non-linear loads
Marine certified by ABS, LR, DNV, BV, and others
Permanent magnet exciter provides power isolation to VR3 regulator
Permanent magnet provides circuit current sustaining for 300% rated current for 10 seconds
Preferred in marine and petroleum applications
Radio frequency noise suppression exceeds industry standards MIL-STD-461, 82/449/EEC, VDE875/10.84
Stator thermocouples installed as standard – J type

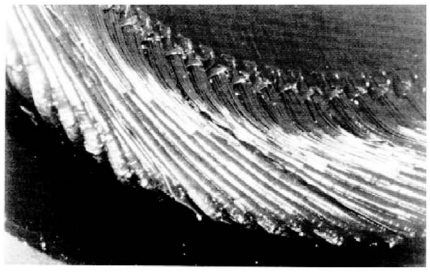
ROTOR CONSTRUCTION

The main rotor uses a precision "wet" layer wound process, with epoxy painted on the bare rotor and on each layer. This ensures bonding of all the wire layers together, bonding of the coils to the rotor laminations, and a sealed insulation system. The rotor epoxy is then oven-cured.
The exciter rotor is machine wound and receives two dips and bakes of a fungus-resisting resin.
Numerically controlled turning and grinding machines produce rotor shafts with close repeatable tolerances. Grade-8 bolts are used wherever joints are subject to induced stresses.
A complete coating of red sealer is applied to protect the rotors and shaft from moisture corrosion.
All rotor designs are prototype tested to 150% overspeed at 170° C for two hours without any movement of material. Every production rotor is dynamically balanced in two planes to within 0.025 mm peak-to-peak amplitude and run at 125% overspeed before assembly into the stator.



MAIN STATOR CONSTRUCTION

Stator coil pitch, coil distribution, and skew are designed to produce optimum waveform and minimum total harmonic content.
Stator slots are insulated by slot liners and coil separators. Slot liners, coil separators, and top sticks provide a minimum of 20 mm (4/5 in) distance from the coil to ground. The thickness of liners, separators, and phase sheets provides protection between phases and ground.
Low voltage stator windings are given a 3000 volt "high pot" test (150% of the NEMA and IEC requirements for 480 volt generators) before the insulation is applied. The stators are then given two dips and bakes of epoxy resin before being given a final 2000 volt "high pot" test.



SR4 GENERATORS – 800 FRAME

CATERPILLAR®

	50 Hz 1500 rpm					60 Hz 1800 rpm				
Frame	805	806	807	808	809	805	806	807	808	809
Voltage	400	400	400	400	400	480	480	480	480	480
Ratings										
Standby	130° C Rise					130° C Rise				
kV•A	1400	1500	1750	2000	2250	1750	1875	2188	2500	2812
kW	1120	1200	1400	1600	1800	1400	1500	1750	2000	2250
Prime	105° C Rise					105° C Rise				
kV•A	1275	1360	1600	1825	2050	1594	1700	2000	2281	2562
kW	1020	1088	1280	1460	1640	1275	1360	1600	1825	2050
Eff* (%)	95.2	95.5	95.6	95.4	95.8	95.5	95.8	95.8	95.7	96.0
Reactances* (per unit)										
Subtransient-Direct Axis X"d	0.16322	0.14278	0.12314	0.12040	0.10996	0.17002	0.14873	0.12827	0.12542	0.11454
Subtransient Quadrature Axis X"q	0.18997	0.16995	0.14999	0.13043	0.12045	0.19789	0.17703	0.15624	0.13587	0.12547
Transient Saturated X'd	0.21724	0.19796	0.17284	0.21746	0.19444	0.22630	0.20621	0.18004	0.22652	0.20255
Synchronous Direct Axis Xd	2.62384	2.66162	2.42393	2.94127	2.60783	2.73317	2.77252	2.52492	3.06382	2.71649
Synchronous Quadrature Axis Xq	1.22238	1.23150	1.11903	1.40477	1.24718	1.27331	1.28282	1.16565	1.46330	1.29915
Negative Sequence X2	0.17660	0.15636	0.13656	0.12542	0.11521	0.18396	0.16288	0.14225	0.13064	0.12001
Zero Sequence Xo	0.04270	0.03281	0.06525	0.03858	0.02393	0.04448	0.03418	0.06797	0.04018	0.02493
Time Constants* (seconds)										
Open Circuit Transient Direct Axis T'do	3.81252	4.22776	4.45075	4.69513	5.38377	3.81252	4.22776	4.45075	4.69513	5.38377
Short Circuit Transient Direct Axis T'd	0.31566	0.31445	0.31737	0.34712	0.40142	0.31566	0.31445	0.31737	0.34712	0.40142
Open Circuit Subtransient Direct Axis T"do	0.01419	0.01365	0.01355	0.01316	0.01363	0.01419	0.01365	0.01355	0.01316	0.01363
Short Circuit Subtransient Direct Axis T"d	0.00325	0.00308	0.00280	0.00263	0.00210	0.00271	0.00257	0.00234	0.00219	0.00175
Open Circuit Subtransient Quad Axis T"qo	0.01267	0.01264	0.01313	0.01178	0.01257	0.01267	0.01264	0.01313	0.01178	0.01257
Short Circuit Subtransient Quad Axis T"q	0.00015	0.00011	0.00008	0.00007	0.00004	0.00013	0.00010	0.00007	0.00006	0.00004
Armature Ta	0.03395	0.03346	0.03202	0.02615	0.03010	0.03395	0.03346	0.03202	0.02615	0.03010

* Note: All efficiency, reactance, and time constant values are for standby ratings.

CATERPILLAR®

SR4 GENERATORS – 800 FRAME

	50 Hz 1000 rpm				60 Hz 1200 rpm			
Frame	806	807	809	815	806	807	809	815
Voltage	400	400	400	400	480	480	480	480
Ratings								
Standby	130° C Rise				130° C Rise			
kV•A	950	1150	1300	2000	1218	1437	1562	2500
kW	760	920	1040	1600	975	1150	1250	2000
Prime	105° C Rise				105° C Rise			
kV•A	875	1045	1169	1825	1125	1306	1375	2281
kW	700	836	935	1460	900	1045	1100	1825
Eff* (%)	94.2	94.5	95.1	95.8	94.4	94.8	95.4	96.2
Reactances* (per unit)								
Subtransient-Direct Axis X"d	0.18494	0.15825	0.13574	0.18483	0.19815	0.16484	0.13307	0.19253
Subtransient Quadrature Axis X"q	0.17548	0.15233	0.13254	0.18310	0.18801	0.15867	0.12994	0.19073
Transient Saturated X'd	0.28694	0.24148	0.22038	0.28376	0.30744	0.25155	0.21606	0.29559
Synchronous Direct Axis Xd	2.04803	1.71775	1.71884	2.10181	2.19432	1.78932	1.68514	2.18938
Synchronous Quadrature Axis Xq	1.12643	0.94571	0.93823	1.15516	1.20689	0.98512	0.91983	1.20329
Negative Sequence X2	0.18021	0.15529	0.13414	0.18396	0.19308	0.16176	0.13151	0.19163
Zero Sequence Xo	0.07075	0.04435	0.03275	0.05491	0.07580	0.04620	0.03211	0.05720
Time Constants* (seconds)								
Open Circuit Transient Direct Axis T'do	2.83951	2.89041	3.19222	3.53415	2.83951	2.89041	3.19222	3.35415
Short Circuit Transient Direct Axis T'd	0.39784	0.40634	0.40930	0.47714	0.39784	0.40634	0.40930	0.47714
Open Circuit Subtransient Direct Axis T"do	0.01525	0.01604	0.01544	0.02057	0.01525	0.01604	0.01544	0.02057
Short Circuit Subtransient Direct Axis T"d	0.00275	0.00240	0.00203	0.00157	0.00230	0.00201	0.00169	0.00131
Open Circuit Subtransient Quad Axis T"qo	0.00816	0.00915	0.00951	0.01707	0.00816	0.00915	0.00951	0.01707
Short Circuit Subtransient Quad Axis T"q	0.00015	0.00012	0.00007	0.00007	0.00013	0.00010	0.00006	0.00006
Armature Ta	0.03172	0.02830	0.02861	0.04486	0.03172	0.02830	0.02861	0.04486

* Note: All efficiency, reactance, and time constant values are for prime ratings.

Materials and specifications are subject to change without notice. The International System of Units (SI) is used in this publication.

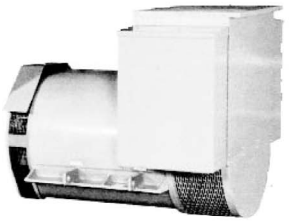
LEHX4254 (6-94) ©1994 Caterpillar Printed in U.S.A.

CATERPILLAR®

SR4B Generators

690 Continuous

50 Hz 500-1375 kV•A 1500 rpm
60 Hz 500-1360 kW 1800 rpm



CATERPILLAR ENGINE FACILITIES ISO 9001 CERTIFIED

CATERPILLAR® SR4B GENERATOR

Type	Brushless, revolving field, solid-state automatic voltage regulator
Construction	Single bearing, two bearing three phase, wye connected
Insulation	Class H
Enclosure	Drip proof IP 22, guarded
Alignment	Caterpillar pilot shaft
Overspeed capability	150%
Waveform	Less than 5% deviation
Paralleling capability	Standard with adjustable voltage droop
Voltage regulator	3-phase sensing with Volts-per-Hertz response
Voltage regulation	Less than ±1%
Voltage gain	Adjustable to compensate for engine speed droop and line loss
TIF	Less than 50
THD	Less than 5%
Number of leads	6

STANDARD FEATURES

General

Class H insulation (rotor, stator, and leads)
Improved efficiency
Motor starting capability in excess of 1.9 SkVA per continuous kW
Improved wire & terminal identification ensuring reliable connections
New compact size – reduction in length
Performance and design matched to Caterpillar engines
Radio frequency noise suppression better than industry standards
Six leads standard for differential protection
Standards: meets or exceeds the requirements of IEC 34-1, NEMA MG 1-22, BS4999, BS5000, VDE0530, UTE5100, CSA22.2, ISO8528-3
Superior construction and testing

Mechanical

Full cage construction
Six-hole power bus bars for convenient customer load connection
Terminal box with DIN rail mounted terminal blocks
Wet, layer wound rotors individually tested to 125% of rated speed; prototypes to 150% @ 170° C for two hours

Stator

Anticondensation heaters standard
Optimum winding pitch for minimum total harmonic distortion
Standard voltages: 380V, 480V, & 600V @ 60 Hz; 380V, 400V, 415V, & 500V @ 50 Hz
Vacuum impregnation insulation system
Windings coated with a fungus resistant resin

Excitation System

Built-in paralleling capability with adjustable voltage droop and sensing isolation transformers standard
Improved transient response with a standard V/Hz regulator
Permanent magnet excitation system standard:
- eliminates the need for series boost
- improved performance with non-linear loads
- marine certified by ABS, LR, DNV, BV, and others
- preferred in marine applications
- provides power isolation to VR3 regulator
- radio frequency noise suppression exceeds industry standards
  - MIL-STD-461
  - 82/449/EEC
  - VDE 875/10.84
- short circuit current sustaining to 300% rated current for 10 seconds

VR3 automatic voltage regulator with three phase sensing

CATERPILLAR®

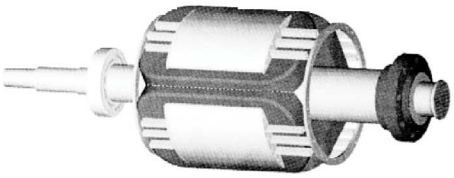
SR4B GENERATORS – 690 CONTINUOUS

OPTIONAL FEATURES

2/3 stator winding pitch
Air filter
Bearing temperature detectors – 100Ω Pt or 10Ω Cu
Custom voltages
Digital voltage regulator for superior transient response, block loading, generator protection, and flexibility
Manual voltage control
Oversized, generator mounted circuit breaker box (1009 H x 685 W x 406 D mm)
RFI filter – 82/499/EEC, VDE 875/10.84 A2 Level N, BS800 standards, and MIL-STD-461B (conducted, radiated, and susceptibility)
Stator temperature detectors – Type J (Iron-Constantan) thermocouples or embedded RTDs (100Ω Pt or 10Ω Cu)
Terminal box extension with:
separate compartment for control devices
modular design allowing RH or LH mount
optimized for use with or without circuit breakers
dimensions are 1009 H x 685 W x 304 D mm
VR3F for enhanced transient response and block loading

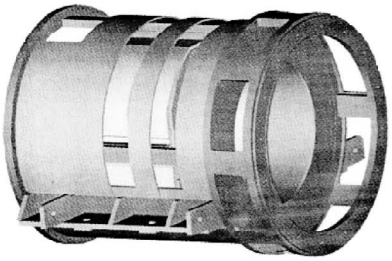
ROTOR CONSTRUCTION

The main rotor uses a precision "wet" layer wound process, with epoxy painted on the bare rotor and on each layer. This ensures bonding of all the wire layers together, bonding of the coils to the rotor laminations, and a sealed insulation system. The rotor epoxy is then oven-cured.
The exciter rotor is machine wound and receives two dips and bakes of a fungus-resisting resin.
Numerically controlled turning and grinding machines produce rotor shafts with close repeatable tolerances. Grade-8 bolts are used wherever joints are subject to induced stresses.
A complete coating of red sealer is applied to protect the rotors and shaft from moisture corrosion.
All rotor designs are prototype tested to 150% of rated speed at 170° C for two hours without any movement of material. Every production rotor is dynamically balanced in two planes to within 0.025 mm peak-to-peak amplitude and run at 125% of rated speed before assembly into the stator.



MAIN STATOR CONSTRUCTION

New square lamination stator design
Stator coil pitch, coil distribution, and skew are designed to produce optimum waveform and minimum total harmonic content.
Stator slots are insulated by slot liners and coil separators. Slot liners, coil separators, and top sticks provide a minimum of 25 mm (1 in) distance from the coil to ground. The thickness of liners, separators, and phase sheets provides superior protection between phases and ground.
Low voltage stator windings are given a 3000 volt "high pot" test (150% of the NEMA and IEC requirements for 480 volt generators) before the insulation is applied. The stators are then given a vacuum impregnation treatment of polyester material followed by an application of epoxy resin. This sealed stator is then given a final 2000 volt "high pot" test.



SR4B GENERATORS – 690 CONTINUOUS

CATERPILLAR®

	60 Hz 1800 rpm						
Frame	690	691	692	693	695	696	697
Voltage	480	480	480	480	480	480	480
Ratings							
105° C Rise							
kV•A	906	1025	1138	1250	1419	1594	1700
kW	725	820	910	1000	1135	1275	1360
Eff (%)	94.1	94.7	94.7	95.3	95.4	95.7	95.9
Reactances (per unit)							
Subtransient-Direct Axis X"d	0.18512	0.21097	0.17926	0.17081	0.17457	0.17639	0.19217
Subtransient Quadrature Axis X"q	0.21162	0.24418	0.21207	0.20571	0.21045	0.21516	0.23783
Transient Saturated X'd	0.24934	0.28559	0.25588	0.24485	0.24495	0.24851	0.26938
Synchronous Direct Axis Xd	3.09157	3.59410	3.53995	3.39278	3.31530	3.40882	3.65632
Synchronous Quadrature Axis Xq	1.54364	1.79356	1.75518	1.68283	1.65168	1.69743	1.82044
Negative Sequence X2	0.19837	0.22758	0.19566	0.18826	0.19251	0.19577	0.21500
Zero Sequence Xo	0.04576	0.09639	0.03343	0.06974	0.08917	0.00500	0.00501
Time Constants (seconds)							
Open Circuit Transient Direct Axis T'do	3.25945	3.35810	3.64902	3.72354	4.04882	4.17199	4.01441
Short Circuit Transient Direct Axis T'd	0.26288	0.26684	0.26376	0.26872	0.29915	0.30414	0.29576
Open Circuit Subtransient Direct Axis T"do	0.01215	0.01219	0.01137	0.01122	0.01250	0.01256	0.01216
Short Circuit Subtransient Direct Axis T"d	0.00177	0.00172	0.00165	0.00152	0.00136	0.00128	0.00123
Open Circuit Subtransient Quad Axis T"qo	0.01150	0.01178	0.01132	0.01154	0.01310	0.01345	0.01329
Short Circuit Subtransient Quad Axis T"q	0.00011	0.00011	0.00009	0.00008	0.00007	0.00006	0.00007
Armature Ta	0.02543	0.03332	0.02744	0.03301	0.03738	0.04107	0.04758

CATERPILLAR®

SR4B GENERATORS – 690 CONTINUOUS

	50 Hz 1500 rpm						
Frame	690	691	692	693	695	696	697
Voltage	400	400	400	400	400	400	400
Ratings							
105° C Rise							
kV•A	725	820	910	1000	1150	1250	1375
kW	580	656	728	800	920	1000	1100
Eff (%)	93.8	94.4	94.4	95.0	95.1	95.5	95.8
Reactances (per unit)							
Subtransient-Direct Axis X"d	0.17771	0.20253	0.17209	0.16397	0.16980	0.16933	0.17721
Subtransient Quadrature Axis X"q	0.20315	0.23441	0.20358	0.19748	0.20470	0.20655	0.22153
Transient Saturated X'd	0.23937	0.27417	0.24564	0.23506	0.23826	0.23857	0.25318
Synchronous Direct Axis Xd	2.96790	3.45034	3.39835	3.25707	3.22475	3.27247	3.53624
Synchronous Quadrature Axis Xq	1.48190	1.72181	1.68497	1.61551	1.60657	1.62953	1.75603
Negative Sequence X2	0.19043	0.21847	0.18784	0.18073	0.18725	0.18794	0.22642
Zero Sequence Xo	0.04393	0.09253	0.03527	0.06695	0.08673	0.00480	0.19937
Time Constants (seconds)							
Open Circuit Transient Direct Axis T'do	3.25945	3.35810	3.64902	3.72354	4.04882	4.17199	4.01089
Short Circuit Transient Direct Axis T'd	0.26288	0.26684	0.27066	0.26872	0.29915	0.30414	0.28716
Open Circuit Subtransient Direct Axis T"do	0.01215	0.01219	0.01189	0.01122	0.01250	0.01256	0.01155
Short Circuit Subtransient Direct Axis T"d	0.00212	0.00178	0.00198	0.00182	0.00163	0.00153	0.00148
Open Circuit Subtransient Quad Axis T"qo	0.01150	0.01768	0.01177	0.01154	0.01310	0.01345	0.01276
Short Circuit Subtransient Quad Axis T"q	0.00012	0.00013	0.00014	0.00009	0.00008	0.00007	0.00008
Armature Ta	0.02543	0.03332	0.02953	0.03301	0.03738	0.04107	0.04440

Materials and specifications are subject to change without notice.

The International System of Units (SI) is used in this publication.

LEHX4474 (12-94)

©1994 Caterpillar

Printed in U.S.A.

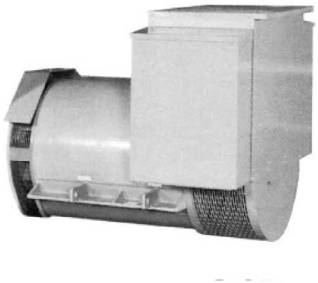
CATERPILLAR®

SR4B Generators

440-450 Standby/Prime

Standby Power 50 Hz 175-400 kV•A 1500 rpm
60 Hz 175-400 kW 1800 rpm

Prime Power 50 Hz 150-365 kV•A 1500 rpm
60 Hz 160-365 kW 1800 rpm



CATERPILLAR ENGINE FACILITIES ISO 9001 CERTIFIED

CATERPILLAR® SR4B GENERATOR

Type . . . . . Brushless, revolving field, solid-state automatic voltage regulator
Construction. . . . . Single bearing, three phase, wye connected
Insulation . . . . . Class H
Enclosure . . . . . Drip proof IP 22, guarded
Alignment. . . . . Caterpillar pilot shaft
Overspeed capability 150%
Waveform. . . . . Less than 5% deviation
Paralleling capability . . . Standard with adjustable voltage droop
Voltage regulator . . . . . 3-phase sensing with Volts-per-Hertz response
Voltage regulation. . . . . Less than ± 1%
Voltage gain . . . . . Adjustable to compensate for engine speed droop and line loss
TIF. . . . . Less than 50
THD. . . . . Less than 5%
Number of leads 12

STANDARD FEATURES

General
Class H insulation (rotor, stator, and leads)
Improved efficiency
Motor starting capability in excess of 2.1 SkVA per continuous kW Prime Power (PP)
Performance and design matched to Caterpillar engines
Radio frequency noise suppression better than industry standards
Twelve leads standard for differential protection
Standards: meets or exceeds the requirements of IEC 34-1, NEMA MG 1-22, BS4999, BS5000, VDE0530, UTE5100, CSA22.2, ISO8528-3
Superior construction and testing

Mechanical
Wet, layer wound rotors individually tested to 125% of rated speed; prototypes to 150% @ 170° C for two hours

Stator
Optimum winding pitch for minimum total harmonic distortion
Standard voltages: 208V*, 380V*, 480V, & 600V* @ 60 Hz; 400V @ 50 Hz
Windings coated with a fungus resistant resin

Excitation System
Adjustable voltage droop and paralleling capability
Improved transient response with a standard V/Hz regulator
Self excited
VR3 automatic voltage regulator with three-phase sensing

* Four-lead generators

CATERPILLAR®

SR4B GENERATORS – 440-450 STANDBY/PRIME

OPTIONAL FEATURES

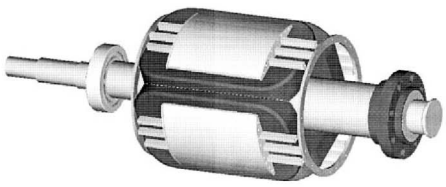
2/3 stator winding pitch
Bearing temperature detectors – 100Ω Pt or 10Ω Cu
Custom voltages
Manual voltage control
Generator mounted circuit breaker box
Paralleling kit with sensing and power isolation transformers
RFI filter – 82/499/EEC, 89/336/EEC, German VDE 875/10.84 A2 Level N, British BS800 standards, MIL-STD-461B and MIL-STD-461C (conducted, radiated, and susceptibility)
Stator temperature detectors – Type J (iron-constantan) thermocouples
Separate compartment for low voltage wiring connections
Terminal box extension with modular design allowing RH or LH mount optimized for use with or without circuit breakers
VR3F for enhanced transient response and block loading

ROTOR CONSTRUCTION

The main rotor uses a precision "wet" layer wound process, with epoxy painted on the bare rotor and on each layer. This ensures bonding of all the wire layers together, bonding of the coils to the rotor laminations, and a sealed insulation system. The rotor epoxy is then oven-cured.
The exciter rotor is machine wound and receives two dips and bakes of a fungus-resisting resin.
Numerically controlled turning and grinding machines produce rotor shafts with close repeatable tolerances. Grade-8 bolts are used wherever joints are subject to induced stresses.
A complete coating of red sealer is applied to protect the rotors and shaft from moisture corrosion.
All rotor designs are prototype tested to 150% of rated speed at 170° C for two hours without any movement of material. Every production rotor is dynamically balanced in two planes to within 0.025 mm peak-to-peak amplitude and run at 125% of rated speed before assembly into the stator.

MAIN STATOR CONSTRUCTION

New square lamination stator design
Stator coil pitch, coil distribution, and skew are designed to produce optimum waveform and minimum total harmonic content.
Stator slots are insulated by slot liners and coil separators. Slot liners, coil separators, and top sticks provide a minimum of 25 mm (1 in) distance from the coil to ground. The thickness of liners, separators, and phase sheets provides superior protection between phases and ground.
Low voltage stator windings are given a 3000 volt "high pot" test (150% of the NEMA and IEC requirements for 480 volt generators) before the insulation is applied. The stators are then given a vacuum impregnation treatment of polyester material followed by an application of epoxy resin. This sealed stator is then given a final 2000 volt "high pot" test.





CATERPILLAR®

SR4B GENERATORS – 440-450 STANDBY/PRIME

	50 Hz 1500 rpm – Standby							
Frame	443	444	445	446	447	448	449	450
Voltage	400	400	400	400	400	400	400	400
Ratings								
130° C Rise								
kV•A	175	200	225	250	275	300	350	400
kW	140	160	180	200	220	240	280	320
Eff (%)	90.2	91.0	91.5	91.0	91.4	92.3	92.7	93.3
Reactances (per unit)								
Subtransient-Direct Axis X"d	0.17250	0.16991	0.16095	0.16470	0.16638	0.14425	0.15429	0.16049
Subtransient Quadrature Axis X"q	0.18904	0.18889	0.18150	0.18739	0.19111	0.16823	0.18214	0.19176
Transient Saturated X'd	0.27311	0.27279	0.26201	0.27045	0.27574	0.24262	0.26259	0.27636
Synchronous Direct Axis Xd	2.72549	2.77295	2.71072	2.82860	2.91648	2.61143	2.86493	3.05477
Synchronous Quadrature Axis Xq	1.60555	1.63199	1.59398	1.66241	1.71313	1.53266	1.68038	1.79064
Negative Sequence X2	0.18077	0.17940	0.17123	0.17604	0.17875	0.15624	0.16821	0.17612
Zero Sequence Xo	0.05149	0.04196	0.05134	0.05361	0.05532	0.04959	0.05446	0.05812
Time Constants (seconds)								
Open Circuit Transient Direct Axis T'do	1.33008	1.40984	1.49384	1.54984	1.61144	1.71633	1.80584	1.90009
Short Circuit Transient Direct Axis T'd	0.13328	0.13869	0.14439	0.14818	0.15235	0.15946	0.16552	0.17189
Open Circuit Subtransient Direct Axis T"do	0.00778	0.00781	0.00783	0.00785	0.00786	0.00789	0.00791	0.00793
Short Circuit Subtransient Direct Axis T"d	0.00325	0.00306	0.00285	0.00272	0.00257	0.00230	0.00209	0.00187
Open Circuit Subtransient Quad Axis T"qo	0.00709	0.00731	0.00755	0.00770	0.00787	0.00814	0.00837	0.00861
Short Circuit Subtransient Quad Axis T"q	0.00043	0.00038	0.00032	0.00031	0.00028	0.00021	0.00020	0.00017
Armature Ta	0.01722	0.01976	0.02063	0.01780	0.01889	0.02001	0.02198	0.02501

SR4B GENERATORS – 440-450 STANDBY/PRIME

CATERPILLAR®

	60 Hz 1800 rpm – Standby						
Frame	443	444	445	446	448	449	450
Voltage	480	480	480	480	480	480	480
Ratings							
130° C Rise							
kV•A	219	250	288	312	375	437	500
kW	175	200	230	250	300	350	400
Eff (%)	91.1	91.9	92.3	91.8	92.9	93.3	93.8
Reactances (per unit)							
Subtransient-Direct Axis X"d	0.17968	0.17699	0.17139	0.17156	0.15026	0.16072	0.16718
Subtransient Quadrature Axis X"q	0.19692	0.19676	0.19326	0.19520	0.17524	0.18973	0.19975
Transient Saturated X'd	0.28449	0.28415	0.27899	0.28172	0.25273	0.27353	0.28787
Synchronous Direct Axis Xd	2.83906	2.88849	2.88642	2.94646	2.72023	2.98430	3.18205
Synchronous Quadrature Axis Xq	1.67245	1.69999	1.69729	1.73167	1.59652	1.75039	1.86525
Negative Sequence X2	0.18830	0.18688	0.18232	0.18338	0.16275	0.17522	0.18346
Zero Sequence Xo	0.05363	0.05464	0.05467	0.05585	0.05166	0.05673	0.06054
Time Constants (seconds)							
Open Circuit Transient Direct Axis T'do	1.33008	1.40984	1.49684	1.54984	1.71633	1.80584	1.90009
Short Circuit Transient Direct Axis T'd	0.13328	0.13869	0.14439	0.14818	0.15946	0.16552	0.17189
Open Circuit Subtransient Direct Axis T"do	0.00778	0.00781	0.00783	0.00785	0.00789	0.00791	0.00793
Short Circuit Subtransient Direct Axis T"d	0.00272	0.00255	0.00238	0.00227	0.00192	0.00175	0.00156
Open Circuit Subtransient Quad Axis T"qo	0.00709	0.00731	0.00755	0.00770	0.00814	0.00837	0.00861
Short Circuit Subtransient Quad Axis T"q	0.00037	0.00033	0.00029	0.00026	0.00018	0.00017	0.00015
Armature Ta	0.01722	0.01976	0.02063	0.01780	0.02001	0.02198	0.02501

	50 Hz 1500 rpm – Prime						
Frame	443	445	446	447	448	449	450
Voltage	400	400	400	400	400	400	400
Ratings							
130° C Rise							
kV•A	150	205	225	250	275	320	365
kW	120	164	182	200	220	256	292
Eff (%)	90.9	91.8	91.4	91.8	92.5	93.0	93.6
Reactances (per unit)							
Subtransient-Direct Axis X"d	0.14785	0.14665	0.14823	0.15126	0.13223	0.14106	0.14645
Subtransient Quadrature Axis X"q	0.16204	0.16536	0.16865	0.17374	0.15421	0.16653	0.17498
Transient Saturated X'd	0.23409	0.23872	0.24340	0.25068	0.22240	0.24008	0.25217
Synchronous Direct Axis Xd	2.33614	0.46977	2.54574	2.65135	2.39381	0.61936	2.78748
Synchronous Quadrature Axis Xq	1.37619	1.45229	1.49617	1.55739	1.40494	1.53634	1.63396
Negative Sequence X2	0.15494	0.15601	0.15844	0.16250	1.14322	0.15380	0.16071
Zero Sequence Xo	0.04413	0.04678	0.04825	0.05029	0.04546	0.04979	0.05303
Time Constants (seconds)							
Open Circuit Transient Direct Axis T'do	1.33008	1.49384	1.54984	1.61144	1.71633	1.80584	1.90009
Short Circuit Transient Direct Axis T'd	0.13328	0.14439	0.14818	0.15235	0.15946	0.16552	0.17189
Open Circuit Subtransient Direct Axis T"do	0.00778	0.00783	0.00785	0.00786	0.00789	0.00791	0.00793
Short Circuit Subtransient Direct Axis T"d	0.00322	0.00283	0.00270	0.00256	0.00229	0.00208	0.00186
Open Circuit Subtransient Quad Axis T"qo	0.00709	0.00755	0.00770	0.00787	0.00814	0.00837	0.00861
Short Circuit Subtransient Quad Axis T"q	0.00037	0.00029	0.00027	0.00026	0.00019	0.00018	0.00016
Armature Ta	0.01722	0.02063	0.01780	0.01889	0.02001	0.02198	0.02501

SR4B GENERATORS – 440-450 STANDBY/PRIME

CATERPILLAR®

	60 Hz 1800 rpm – Prime					
Frame	443	445	446	448	449	450
Voltage	480	480	480	480	480	480
Ratings						
130° C Rise						
kV•A	200	263	281	344	400	456
kW	160	210	225	275	320	365
Eff (%)	91.5	92.5	92.1	93.0	93.5	94.0
Reactances (per unit)						
Subtransient-Direct Axis X"d	0.16428	0.15649	0.15440	0.13774	0.14694	0.15255
Subtransient Quadrature Axis X"q	0.18004	0.17646	0.17568	0.16064	0.17347	0.18227
Transient Saturated X'd	0.26010	0.25473	0.25354	0.23167	0.25009	0.26268
Synchronous Direct Axis Xd	2.59571	2.63543	2.65181	2.49355	2.72850	2.90362
Synchronous Quadrature Axis Xq	1.52910	1.54970	1.55851	1.46348	1.60036	1.70204
Negative Sequence X2	0.17216	0.16647	0.16504	0.14919	0.16020	0.16741
Zero Sequence Xo	0.04903	0.04992	0.05026	0.04735	0.05186	0.05524
Time Constants (seconds)						
Open Circuit Transient Direct Axis T'do	1.33008	1.49384	1.54984	1.71633	1.80584	1.90009
Short Circuit Transient Direct Axis T'd	0.13328	0.14439	0.14818	0.15946	0.16552	0.17189
Open Circuit Subtransient Direct Axis T"do	0.00778	0.00783	0.00785	0.00789	0.00791	0.00793
Short Circuit Subtransient Direct Axis T"d	0.00270	0.00237	0.00226	0.00191	0.00174	0.00155
Open Circuit Subtransient Quad Axis T"qo	0.00709	0.00755	0.00770	0.00814	0.00837	0.00861
Short Circuit Subtransient Quad Axis T"q	0.00034	0.00025	0.00024	0.00017	0.00015	0.00014
Armature Ta	0.01722	0.02063	0.01780	0.02001	0.02198	0.02501

Materials and specifications are subject to change without notice. The International System of Units (SI) is used in this publication.

LEHX6429 © 1996 Caterpillar Inc. Printed in U.S.A.
All rights reserved.

CATERPILLAR®

SR4 HV Generators

60 Hz/500-2000 kW
1800 rpm
12 470/13 200/
13 800 Volts



CATERPILLAR® SR4 HV GENERATOR

Type ..... Brushless, revolving field
Drive configuration .. Two bearing close coupled
Connection ..... 3-phase, wye
Insulation ..... Class F
Enclosure ..... IP23 open drip proof guarded
Overspeed capability 125%
Waveform ..... Less than 5% deviation
Number of leads 6
Voltage regulator ..... 3-phase sensing with Volts-per-Hertz response
Paralleling capability ..... Standard with cross current compensation
Voltage regulation ..... Less than ± 0.5%
THD ..... Less than 5%
TIF ..... Less than 5%

STANDARD FEATURES

General
Class F Vacuum Pressure Impregnated (VPI) insulation on stator, rotor, exciter, and leads
High efficiency
Excellent motor starting capabilities
Performance and design matched to Caterpillar engines
Rewindable on-site: B stage insulation technology
Space heater: 120/240 Volts, single phase, 2 kW
Cross-current compensation CT (for parallel operation) mounted and wired in generator terminal box
Standards: Meets or exceeds the requirements of IEC 34-1, NEMA MG 1-22, BS4999, ISO8528-3, IEEE 43, CSA C22.2-100, EGSA 101P

Mechanical
Terminal box: fabricated construction, modular design allowing RH or LH cable entry, sized to accommodate 4 CTs, DIN rail mounted terminal blocks, and meets IP44 protection level
Bearings: anti-friction, bracket mounted, regreasable exciter end bearing insulated to eliminate circulating currents through shaft and one (1) 100 ohm platinum RTD installed in each bearing

Rotor
Salient pole type, fully laminated
Insulation: Class F, VPI
Encapsulation by one-part epoxy system

Stator
Form wound
MICA between turns
MICA between conductor and ground
Insulation: Class F, VPI
Encapsulation by two-part epoxy system
Fabricated bar and plate steel construction
Optimum winding pitch
Two (2) 100 ohm platinum RTDs installed per phase

Excitation System
Brushless exciter
Permanent Magnet (PM) generator
Solid state automatic voltage regulator KCR-760

OPTIONAL FEATURES

Differential current transformers
2V/Hz automatic voltage regulator KCR-760
Digital excitation control system
VAR/power factor controller
RFI suppression to meet MIL Standard 461
Minimum/Maximum excitation limiter
Automatic/Manual control
Diode Fault Detector (DFD)
Motor Operated Potentiometer (MOP)
Thermostat for automatic control of space heater
Air inlet filter
LH extension box to allow LH cable entry

3-phase, 60 Hz, 1800 rpm, 12 470 Volts

kW	910	1000	1000	1100	1135	1250	1360	1500	1600	1750	1825	2000	2050	2250	2275	2500	2750	3000
kV•A	1138	1250	1250	1375	1419	1563	1700	1875	2000	2188	2281	2500	2563	2813	2844	3125	3438	3750
Generator Frame	2516	2516	2516	2516	2519	2519	2524	2524	2528	2528	2530	2530	2532	2532	2919	2919	2924	2924
Arrgt. Number	143-5330	143-5330	139-0320	139-0320	139-0318	139-0318	139-0316	139-0316	139-0314	139-0314	139-0312	139-0312	143-5328	143-5328	139-0310	139-0310	143-5326	143-5326
Temp. Rise (°C)	105	130	105	130	105	130	105	130	105	130	105	130	105	130	105	130	105	130
Power Factor	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Pitch	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7222	0.7222	0.7222	0.7222
Total Weight	4608	4608	4764	4764	5169	5169	5793	5793	6229	6229	6479	6479	6479	6479	8305	8305	9263	9263
Rotor Weight	1096	1096	1151	1151	1296	1296	1518	1518	1673	1673	1762	1762	1762	1762	2373	2373	2727	2727
Efficiency (%) 25% load	88.9	89.6	89.6	90.3	90.3	91.0	91.1	91.8	91.9	92.5	92.5	93.0	92.5	93.0	90.1	90.8	91.0	91.6
Efficiency (%) 50% load	93.0	93.3	93.5	93.8	94.1	94.4	94.7	95.0	95.1	95.3	95.4	95.6	95.3	95.5	94.0	94.4	94.6	94.9
Efficiency (%) 75% load	94.0	94.1	94.5	94.6	95.1	95.2	95.6	95.8	95.9	96.0	96.1	96.2	95.9	96.0	95.1	95.2	95.6	95.7
Efficiency (%) 100% load	94.1	94.0	94.7	94.6	95.3	95.3	95.9	95.9	96.1	96.1	96.2	96.2	96.0	96.0	95.4	95.4	95.9	95.9
X"d Subtransient Direct Axis	0.2642	0.2904	0.2612	0.2873	0.2303	0.2536	0.2012	0.2219	0.2012	0.22	0.2074	0.2273	0.233	0.2557	0.2545	0.2796	0.2092	0.2283
X"q Subtransient Quadrature Axis	0.2633	0.2893	0.2562	0.2818	0.2263	0.2492	0.1995	0.2201	0.2016	0.2205	0.2085	0.2285	0.2343	0.2571	0.2611	0.2869	0.2196	0.2396
X'd Transient Saturated	0.2841	0.3122	0.2808	0.3089	0.2519	0.2774	0.2269	0.2502	0.2289	0.2504	0.2377	0.2605	0.267	0.2931	0.2868	0.3151	0.2446	0.2668
Xd Synchronous Direct Axis	1.5594	1.7137	1.5801	1.7381	1.4887	1.6395	1.4307	1.5779	1.4708	1.6087	1.5487	1.6972	1.7396	1.9094	1.7828	1.9591	1.604	1.7498
Xq Synchronous Quadrature Axis	0.9118	1.002	0.9218	1.0139	0.8645	0.9521	0.8259	0.9109	0.8481	0.9276	0.892	0.9775	1.002	1.0997	1.069	1.1747	0.9577	1.0447
X2 Negative Sequence	0.2638	0.2898	0.2587	0.2845	0.2283	0.2514	0.2003	0.221	0.2014	0.2203	0.208	0.2279	0.2336	0.2564	0.2578	0.2833	0.2144	0.2339
X0 Zero Sequence	0.108	0.1187	0.1078	0.1185	0.0987	0.1087	0.091	0.1004	0.0929	0.1016	0.0971	0.1064	0.109	0.1197	0.0693	0.0761	0.0595	0.0649
T'do Open Circuit Transient Direct Axis	2.9892	2.9892	3.0602	3.0602	3.2141	3.2141	3.3896	3.3896	3.7116	3.7116	3.5433	3.5433	3.7603	3.7603	4.5999	4.5999	4.8878	4.8878
T'd Short Circuit Transient Direct Axis	0.5447	0.5447	0.5439	0.5439	0.5439	0.5439	0.5376	0.5376	0.5777	0.5777	0.5439	0.5439	0.5772	0.5772	0.7399	0.7399	0.7454	0.7454
T"do Open Circuit Subtransient Direct Axis	0.0298	0.0298	0.0306	0.0306	0.0321	0.0321	0.0338	0.0338	0.0371	0.0371	0.0354	0.0354	0.0376	0.0376	0.0459	0.0459	0.0488	0.0488
T"d Short Circuit Subtransient Direct Axis	0.0277	0.0277	0.0284	0.0284	0.0293	0.0293	0.03	0.03	0.0326	0.0326	0.0309	0.0309	0.0328	0.0328	0.0408	0.0408	0.0418	0.0418
T"qo Open Circuit Subtransient Quadrature Axis	0.0149	0.0149	0.0153	0.0153	0.016	0.016	0.0169	0.0169	0.0185	0.0185	0.0177	0.0177	0.0188	0.0188	0.0229	0.0229	0.0244	0.0244
T"q Short Circuit Subtransient Quadrature Axis	0.0034	0.0034	0.0034	0.0034	0.0033	0.0033	0.0033	0.0033	0.0035	0.0035	0.0033	0.0033	0.0035	0.0035	0.0045	0.0045	0.0046	0.0046
Ta Armature	0.0422	0.0422	0.0504	0.0504	0.0551	0.0551	0.0603	0.0603	0.0554	0.0554	0.0588	0.0588	0.0588	0.0588	0.0636	0.0636	0.0618	0.0618

3-phase, 60 Hz, 1800 rpm, 13 200 Volts

kW	910	1000	1000	1100	1135	1250	1360	1500	1600	1750	1825	2000	2050	2250	2275	2500	2750	3000
kV•A	1138	1250	1250	1375	1419	1563	1700	1875	2000	2188	2281	2500	2563	2813	2844	3125	3438	3750
Generator Frame	2516	2516	2516	2516	2519	2519	2524	2524	2528	2528	2530	2530	2532	2532	2919	2919	2924	2924
Arrgt. Number	143-5330	143-5330	139-0320	139-0320	139-0318	139-0318	139-0316	139-0316	139-0314	139-0314	139-0312	139-0312	143-5328	143-5328	139-0310	139-0310	143-5326	143-5326
Temp. Rise (°C)	105	130	105	130	105	130	105	130	105	130	105	130	105	130	105	130	105	130
Power Factor	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Pitch	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7222	0.7222	0.7222	0.7222
Total Weight	4608	4608	4764	4764	5169	5169	5793	5793	6229	6229	6479	6479	6479	6479	8305	8305	9263	9263
Rotor Weight	1096	1096	1151	1151	1296	1296	1518	1518	1673	1673	1762	1762	1762	1762	2373	2373	2727	2727
Efficiency (%) 25% load	88.4	89.2	89.2	89.9	89.8	90.5	90.6	91.4	91.5	92.1	92.1	92.6	92.1	92.6	89.8	90.6	90.7	91.3
Efficiency (%) 50% load	92.8	93.2	93.3	93.7	93.8	94.2	94.4	94.8	94.9	95.1	95.2	95.4	95.1	95.4	93.9	94.3	94.5	94.8
Efficiency (%) 75% load	93.9	94.0	94.4	94.6	95.0	95.1	95.5	95.7	95.8	95.9	96.0	96.1	95.9	96.0	95.1	95.3	95.6	95.7
Efficiency (%) 100% load	94.1	94.1	94.7	94.6	95.3	95.3	95.9	95.9	96.1	96.1	96.2	96.2	96.0	96.0	95.5	95.5	96.0	96.0
X"d Subtransient Direct Axis	0.2358	0.2591	0.2331	0.2564	0.2055	0.2263	0.1795	0.198	0.1795	0.1964	0.1851	0.2028	0.2079	0.2282	0.2271	0.2495	0.1867	0.2037
X"q Subtransient Quadrature Axis	0.235	0.2582	0.2286	0.2515	0.2019	0.2224	0.178	0.1964	0.1799	0.1968	0.1861	0.204	0.2091	0.2295	0.233	0.256	0.196	0.2138
X'd Transient Saturated	0.2536	0.2786	0.2506	0.2757	0.2248	0.2476	0.2025	0.2233	0.2043	0.2235	0.2121	0.2325	0.2383	0.2616	0.2559	0.2812	0.2183	0.2381
Xd Synchronous Direct Axis	1.3857	1.5227	1.404	1.5444	1.3249	1.4592	1.2713	1.4022	1.3072	1.4297	1.3759	1.5078	1.5455	1.6963	1.5915	1.7489	1.4102	1.5384
Xq Synchronous Quadrature Axis	0.8102	0.8903	0.819	0.9009	0.7694	0.8474	0.7339	0.8095	0.7538	0.8244	0.7924	0.8684	0.8901	0.9770	0.9543	1.0487	0.8419	0.9185
X2 Negative Sequence	0.2354	0.2587	0.2308	0.2539	0.2037	0.2244	0.1788	0.1972	0.1797	0.1966	0.1856	0.2034	0.2085	0.2288	0.23	0.2528	0.1914	0.2088
X0 Zero Sequence	0.0964	0.1059	0.0962	0.1058	0.0881	0.097	0.0812	0.0896	0.0829	0.0907	0.0866	0.0949	0.0973	0.1068	0.0618	0.0679	0.0531	0.0579
T'do Open Circuit Transient Direct Axis	2.9892	2.9892	3.0602	3.0602	3.2141	3.2141	3.3896	3.3896	3.7116	3.7116	3.5433	3.5433	3.7603	3.7603	4.5999	4.5999	4.8878	4.8878
T'd Short Circuit Transient Direct Axis	0.5470	0.5470	0.5463	0.5463	0.5454	0.5454	0.5399	0.5399	0.5801	0.5801	0.5464	0.5464	0.5798	0.5798	0.7398	0.7398	0.7567	0.7567
T"do Open Circuit Subtransient Direct Axis	0.0298	0.0298	0.0306	0.0306	0.0321	0.0321	0.0338	0.0338	0.0371	0.0371	0.0354	0.0354	0.0376	0.0376	0.0459	0.0459	0.0488	0.0488
T"d Short Circuit Subtransient Direct Axis	0.0277	0.0277	0.0284	0.0284	0.0293	0.0293	0.03	0.03	0.0326	0.0326	0.0309	0.0309	0.0328	0.0328	0.0408	0.0408	0.0418	0.0418
T"qo Open Circuit Subtransient Quadrature Axis	0.0149	0.0149	0.0153	0.0153	0.016	0.016	0.0169	0.0169	0.0185	0.0185	0.0177	0.0177	0.0188	0.0188	0.0229	0.0229	0.0244	0.0244
T"q Short Circuit Subtransient Quadrature Axis	0.0034	0.0034	0.0034	0.0034	0.0033	0.0033	0.0033	0.0033	0.0035	0.0035	0.0033	0.0033	0.0035	0.0035	0.0045	0.0045	0.0046	0.0046
Ta Armature	0.0422	0.0422	0.0504	0.0504	0.0551	0.0551	0.0603	0.0603	0.0554	0.0554	0.0588	0.0588	0.0588	0.0588	0.0636	0.0636	0.0618	0.0618

3-phase, 60 Hz, 1800 rpm, 13 800 Volts

kW	910	1000	1000	1100	1135	1250	1360	1500	1600	1750	1825	2000	2050	2250	2275	2500	2750	3000
kV•A	1138	1250	1250	1375	1419	1563	1700	1875	2000	2188	2281	2500	2563	2813	2844	3125	3438	3750
Generator Frame	2516	2516	2516	2516	2519	2519	2524	2524	2528	2528	2530	2530	2532	2532	2919	2919	2924	2924
Arrgt. Number	143-5330	143-5330	139-0320	139-0320	139-0318	139-0318	139-0316	139-0316	139-0314	139-0314	139-0312	139-0312	143-5328	143-5328	139-0310	139-0310	143-5326	143-5326
Temp. Rise (°C)	105	130	105	130	105	130	105	130	105	130	105	130	105	130	105	130	105	130
Power Factor	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Pitch	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7619	0.7222	0.7222	0.7222	0.7222
Total Weight	4608	4608	4764	4764	5169	5169	5793	5793	6229	6229	6479	6479	6479	6479	8305	8305	9263	9263
Rotor Weight	1096	1096	1151	1151	1296	1296	1518	1518	1673	1673	1762	1762	1762	1762	2373	2373	2727	2727
Efficiency (%) 25% load	88.0	88.9	88.7	89.5	89.4	90.1	90.2	91.0	91.1	91.7	91.6	92.2	91.7	92.3	89.6	90.3	90.4	91.0
Efficiency (%) 50% load	92.6	93.0	93.1	93.5	93.6	94.0	94.2	94.6	94.7	94.9	95.0	95.2	95.0	95.2	93.8	94.2	94.4	94.7
Efficiency (%) 75% load	93.8	94.0	94.3	94.5	94.8	95.0	95.4	95.6	95.7	95.8	95.9	96.0	95.8	95.9	95.1	95.3	95.5	95.7
Efficiency (%) 100% load	94.1	94.0	94.6	94.6	95.2	95.3	95.8	95.9	96.0	96.0	96.2	96.2	96.0	96.0	95.5	95.6	96.0	96.0
X"d Subtransient Direct Axis	0.2157	0.2371	0.2132	0.2346	0.188	0.2071	0.1643	0.1812	0.1643	0.1797	0.1693	0.1856	0.1902	0.2088	0.2078	0.2283	0.1708	0.1864
X"q Subtransient Quadrature Axis	0.215	0.2362	0.2092	0.2301	0.1848	0.2035	0.1629	0.1797	0.1646	0.1801	0.1703	0.1866	0.1913	0.2099	0.2132	0.2343	0.1793	0.1956
X'd Transient Saturated	0.232	0.2549	0.2293	0.2522	0.2057	0.2265	0.1853	0.2043	0.1869	0.2044	0.1941	0.2127	0.218	0.2393	0.2341	0.2573	0.1997	0.2179
Xd Synchronous Direct Axis	1.2609	1.3857	1.2776	1.4053	1.2055	1.3277	1.1595	1.2789	1.1922	1.304	1.2548	1.3751	1.4095	1.5470	1.4374	1.5796	1.249	1.3625
Xq Synchronous Quadrature Axis	0.7373	0.8102	0.7453	0.8198	0.7001	0.771	0.6694	0.7383	0.6875	0.7519	0.7227	0.792	0.8118	0.8910	0.8619	0.9472	0.7457	0.8135
X2 Negative Sequence	0.2154	0.2367	0.2112	0.2323	0.1864	0.2053	0.1636	0.1804	0.1644	0.1799	0.1698	0.1861	0.1907	0.2094	0.2105	0.2313	0.1751	0.1910
X0 Zero Sequence	0.0882	0.0969	0.088	0.0968	0.0806	0.0887	0.0743	0.082	0.0759	0.083	0.0792	0.0868	0.089	0.0977	0.0565	0.0621	0.0486	0.0530
T'do Open Circuit Transient Direct Axis	2.9892	2.9892	3.0602	3.0602	3.2141	3.2141	3.3896	3.3896	3.7116	3.7116	3.5433	3.5433	3.7603	3.7603	4.5999	4.5999	4.8878	4.8878
T'd Short Circuit Transient Direct Axis	0.5500	0.5500	0.5493	0.5493	0.5484	0.5484	0.5416	0.5416	0.582	0.582	0.5481	0.5481	0.5817	0.5817	0.7494	0.7494	0.7817	0.7817
T"do Open Circuit Subtransient Direct Axis	0.0298	0.0298	0.0306	0.0306	0.0321	0.0321	0.0338	0.0338	0.0371	0.0371	0.0354	0.0354	0.0376	0.0376	0.0459	0.0459	0.0488	0.0488
T"d Short Circuit Subtransient Direct Axis	0.0277	0.0277	0.0284	0.0284	0.0293	0.0293	0.03	0.03	0.0326	0.0326	0.0309	0.0309	0.0328	0.0328	0.0408	0.0408	0.0418	0.0418
T"qo Open Circuit Subtransient Quadrature Axis	0.0149	0.0149	0.0153	0.0153	0.016	0.016	0.0169	0.0169	0.0185	0.0185	0.0177	0.0177	0.0188	0.0188	0.0229	0.0229	0.0244	0.0244
T"q Short Circuit Subtransient Quadrature Axis	0.0034	0.0034	0.0034	0.0034	0.0033	0.0033	0.0033	0.0033	0.0035	0.0035	0.0033	0.0033	0.0035	0.0035	0.0045	0.0045	0.0046	0.0046
Ta Armature	0.0422	0.0422	0.0504	0.0504	0.0551	0.0551	0.0603	0.0603	0.0554	0.0554	0.0588	0.0588	0.0588	0.0588	0.0636	0.0636	0.0618	0.0618

SR4 HV GENERATORS

CATERPILLAR®

MAIN STATOR CONSTRUCTION

The stator frame has fabricated bar and plate steel construction. It is machined to tolerance to provide alignment with the rotor. Non-oriented, silicon steel laminations with core plated insulation on both sides are used to reduce core loss and temperature rise in the machine, and to improve efficiency. The stacked laminations are skewed to reduce harmonic distortion caused by the slots, and held under pressure with clamping plates without welding on the laminations.

Winding overhang on the stator is insulated between phases. Surge ropes are used to support the winding overhang. The windings are braced to withstand single phase and three phase fault conditions.

All insulation materials used in the stator have a minimum temperature rating of 155° C (Class F) per IEEE Std 1. The coils are of a formed coil construction. Turn-to-turn testing is performed on all stator windings prior to impregnation.

The complete stator is processed in a Vacuum Pressure Impregnation (VPI) chamber. Encapsulation of the stator is accomplished with a two-part epoxy system. The epoxy resin is held within a groundwall tape made of woven glass fabric with mica paper, which has 16 – 25% resin and 450 – 600 Volts/mil of electrical strength. The proper stoichiometric balance of the epoxy resin and hardener is accomplished during the VPI cycle. To ensure thorough penetration of resin into the windings, the vacuum pressure cycle is below 2000 microns, and the air pressure cycle is greater than 90 psi. A high-potential test is conducted on the stator after impregnation per IEEE Std 115.



ROTOR CONSTRUCTION

The rotor is fully laminated, salient pole type. Low resistance amortisseur bars are inserted through slots in the field poles and brazed/welded to a continuous shorting ring to complete the damping circuit. Cooling fans are an integral part of the rotor assembly. The rotor has accessible provisions for bolt-on balancing weights.

All insulation materials used in the rotor have a minimum temperature rating of 155° C (Class F) per IEEE Std 1. The poles are of a layer wound construction.

The complete winding and rotor pole assembly is processed in a Vacuum Pressure Impregnation (VPI) chamber. Encapsulation of this assembly is accomplished with a thixotropic, single component epoxy resin. To ensure thorough penetration of resin into the windings, the vacuum pressure cycle is below 2000 microns, and the air pressure cycle is greater than 90 psi. A high-potential test is conducted on the rotor after impregnation per IEEE Std 115.

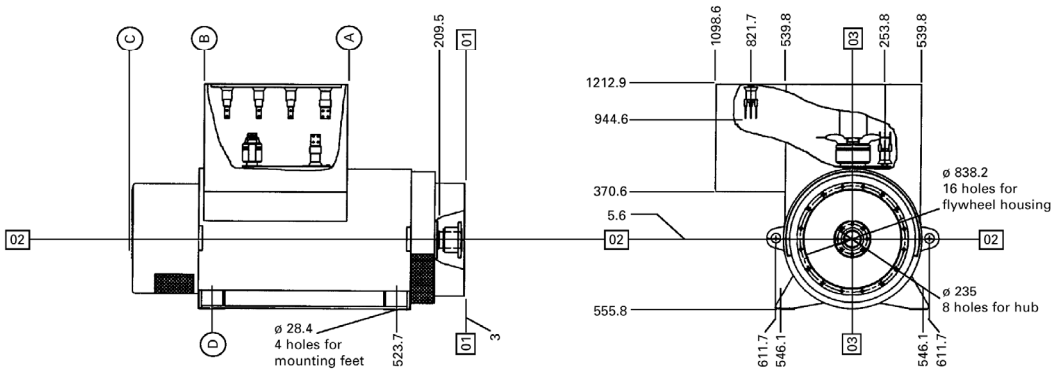
The alternator is capable of withstanding, without adverse effects, overspeed of 125% of synchronous speed for the duration of one minute. The rotor is dynamically balanced. The vibration displacement does not exceed 0.0508 mm peak to peak.



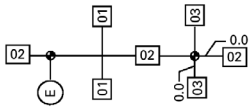
CATERPILLAR®

SR4 HV GENERATORS

2500 SR4 HV GENERATOR



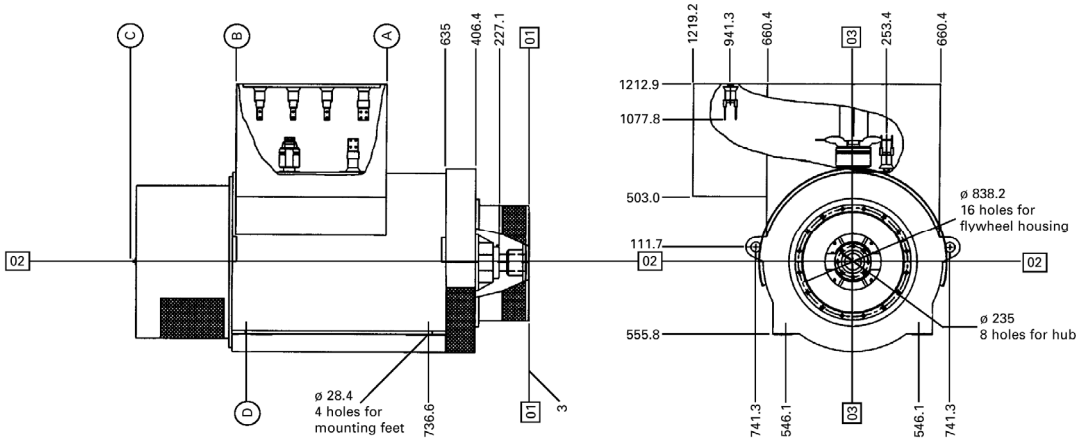
LEFT VIEW FRONT VIEW



(AS DEFINED BY ENGINE)
DETAIL OF CENTER OF GRAVITY
SCALE: NONE

Frame	Weight	A	B	C	D	E
2532	14333	930.1	2073.1	2841.6	2003.3	1209.5
2530	14168	930.1	2073.1	2841.6	2003.3	1209.5
2528	13574	879.3	2002.3	2590.8	1946.1	1184.1
2524	12672	828.5	1971.5	2540.0	1895.3	1140.0
2521	11700	726.9	1869.9	2348.4	1800.1	1095.2
2519	11275	676.1	1819.1	2387.6	1742.9	1076.5
2516	10483	676.1	1819.1	2387.6	1742.9	1035.1
2515	10100	676.1	1819.1	2387.6	1742.9	1019.0

2900 SR4 HV GENERATOR



LEFT VIEW FRONT VIEW

Frame	Weight	A	B	C	D	E
2919	8273	1042.9	2185.9	2971.8	2108.2	1309.9
2924	9227	1093.7	2236.7	3022.6	2159.0	1371.6

Materials and specifications are subject to change without notice.
The International System of Units (SI) is used in this publication.

LEHX8234
Printed in U.S.A.
Supersedes LEHX7207

© 1998 Caterpillar Inc.
All rights reserved.

B
TYPES OF NONLINEAR LOADS

Commercial Nonlinear Load Characteristics

Most harmonic currents in commercial systems are caused by nonlinear loads, that is, loads that draw currents whose frequencies differ from the frequency of the source. Many electronic devices are nonlinear loads because they use solid-state rectifiers at their inputs and filter capacitors after the rectifiers. An example of this type of circuit is a personal computer power supply, as shown in Figure B-1.

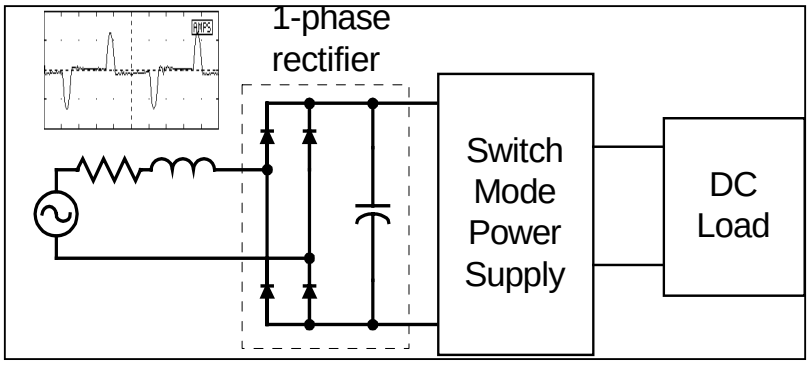


Figure B-1
PC Power Supply Circuit Diagram

When the AC line voltage is higher than the voltage across the filter capacitor, (solid state rectifiers draw current in pulses). This pulsed current is very rich in harmonics, as seen in Figure B-2. The harmonic spectrum plot shows the presence of odd harmonics, with relatively large magnitudes at the lower frequencies. As the frequency increases, the magnitudes decrease.

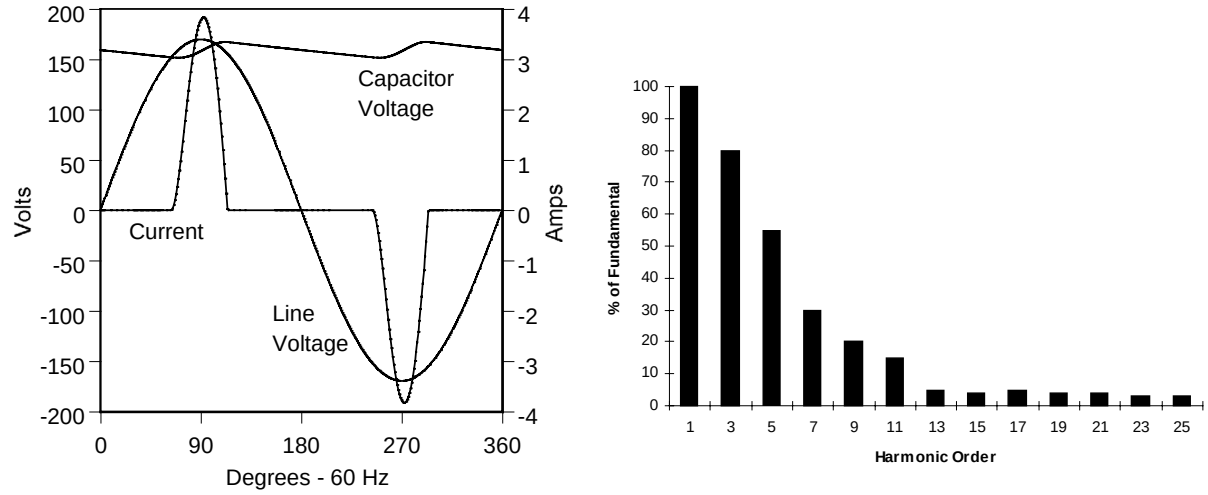


Figure B-2
PC Power Supply Current and Spectrum

The PC power supply is only one of many possible harmonic producers in the 120-volt range. Other loads that inject harmonic currents include office equipment for communications, printing and copying and lighting (high-efficiency electronic ballasts.) Nonlinear loads in the 480 V range include adjustable-speed drives (ASDs) for HVAC, large computers, uninterruptible power supplies, and 277-V lighting.

Harmonic currents are not produced by the source; rather, the nonlinear load causes harmonic currents. As these nonlinear loads become more and more prevalent, the effect on the power system becomes more pronounced. Because the harmonic currents are a result of the nature of the loads, it is appropriate to consider the load to be a source of harmonic current. As harmonic components are injected back into the power system, they cause voltage drops (at the corresponding frequencies) across the cable and source impedance upstream, which creates voltage distortion in the power system. As can be seen in Figure B-3, voltage distortion is worse at points closer to the load. Voltage distortion is a direct function of the current harmonic component magnitudes and the impedance in the system (cables and transformers).

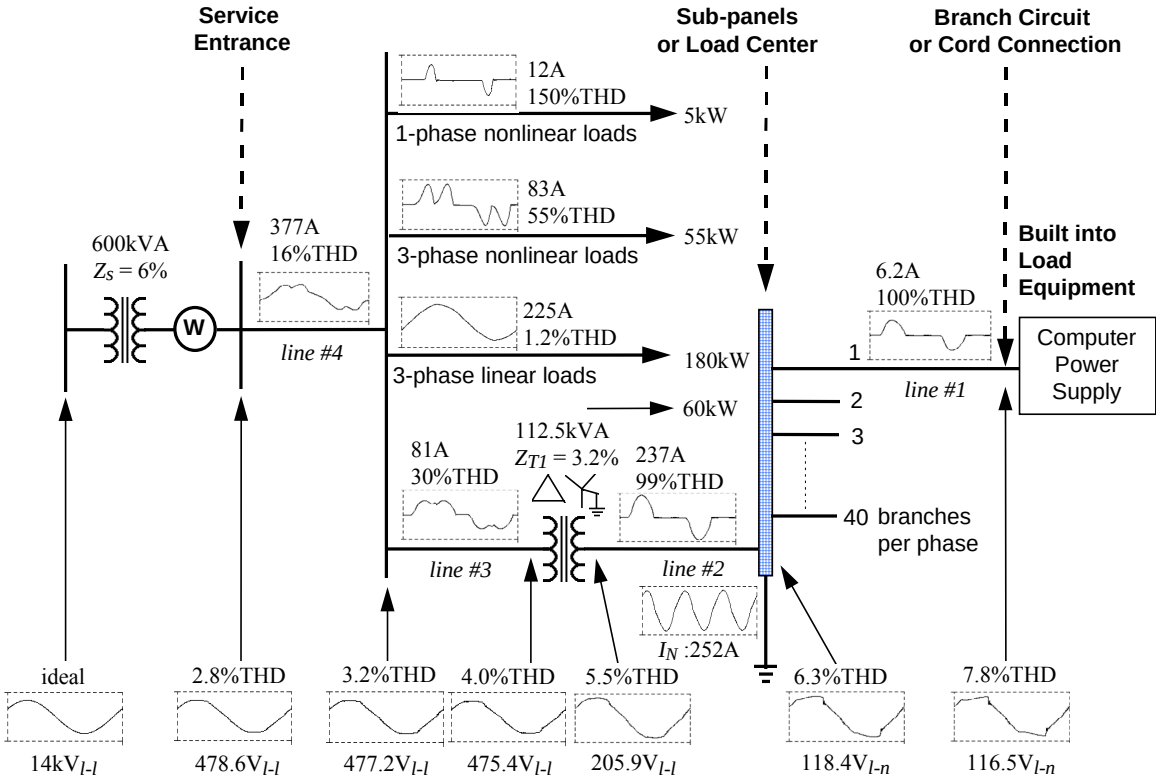


Figure B-3
Commercial Building Distribution System

Figure B-3 shows the wiring system of a typical commercial office building and its voltage and current profiles under mixed linear and nonlinear loads. The most significant harmonic producers in this system are the switch mode power supplies (SMPS) used in personal computers.

Line Segment #1 is a 20 A branch circuit feeding single-phase computer loads. The total harmonic distortion (THD) of each branch circuit current is about 100%. The current THD on Line Segment #2 is similar, at 99%. Line Segment #2 is a three-phase feed from the delta-wye transformer secondary. The loads on different phases share the neutral, which carries a significant amount of third harmonic current. The third harmonic current, along with other harmonics that are multiples of three times the fundamental, are known as triplen harmonics. These triplen harmonics do not cancel, but rather add in the neutral. This results in a neutral current larger than the phase current. As long as the loading is balanced, the triplens cannot show up on the primary line current of the Δ-Y transformer, and so the current THD is reduced to 30% at the primary. For an unbalanced system, the triplen harmonics will not be completely canceled and will show up on the primary line current.

Line Segment #4 has a current THD of 16%. This current represents the combination of all the building loads, both linear and nonlinear. The reduction in THD occurs mostly as a result of the domination of the linear loads. The three-phase linear loads totaling 225A tends to swamp out the nonlinear contribution, thereby reducing the THD on the service entrance feeder.

The distorted current on each line segment interacts with the line inductance, causing voltage distortions. Figure B-3 also shows the waveforms, THD and associated rms values of the voltages and currents in the system. The voltage at the input of the single-phase SMPS load has the highest THD at 7.8%. It also presents a flat-topping of the waveshape, which is a reflection of the rectifier output capacitor voltage. With a typical SMPS design of 5% ripple voltage of the dc-link capacitor, this flat-topping of the voltage waveshape is commonly seen in all electronic loads.

The adjustable speed drives do not represent a large load in this facility, but they do inject a large percentage of harmonic content per kW load. As seen in Figure B-3, this current is dominated by the 5^{th} and 7^{th} harmonics, which can increase the rms value of current as well as excite resonant conditions in the system, if they exist.

In the model shown in Figure B-3, the upstream system voltages are gradually smoothed by other types of loads, especially linear loads. At the service entrance of the modeled system, the voltage THD is reduced to 2.8%. Note that the source voltage is assumed as ideal, with a 6% equivalent impedance that combines the 600-kVA transformer and the upstream source impedance.

Industrial Nonlinear Load Characteristics

The nonlinear loads prevalent in industrial systems are typically adjustable-speed drives and heating systems that use rectifiers at their inputs. All these devices use a similar topology, that is, a rectifier, a dc bus, and an inverter to control output voltage and frequency. Figure B-4 shows the typical topology for a voltage-source AC drive. Figure B-4 also shows the input line current and harmonic spectrum.

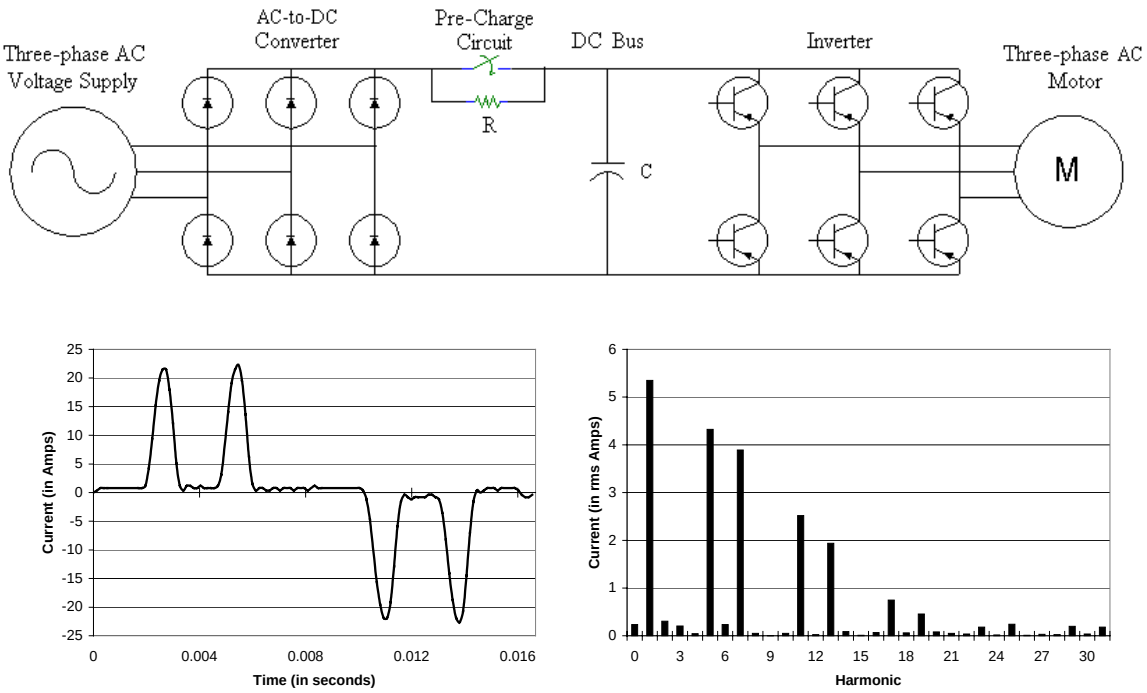


Figure B-4
Typical AC Drive Topology, Input Current, and Spectrum

The heating applications may use a controlled rectifier with phase-controlled thyristors (usually SCRs) instead of diodes. The line current will still be somewhat distorted, but also with some reactive power requirement due to the phase shift induced between line voltage and line current. The topology shown in Figure B-5 is for a DC motor drive, which has a similar front end using a controlled rectifier. The typical DC drive topology is shown in Figure B-5 along with its harmonic spectrum.

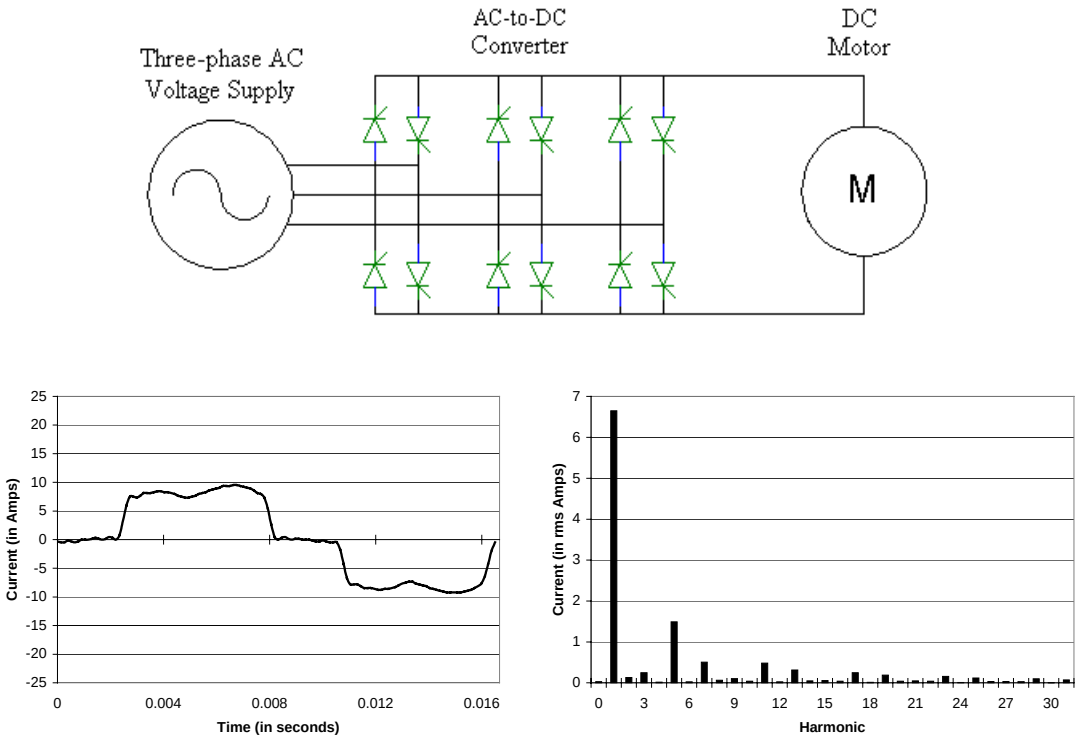


Figure B-5
DC Drive Input Current and Spectrum

Another topology for heating applications involves the use of semiconverters for half-wave rectification. While these semiconverters are very popular, they have an interesting side-effect. They produce even-order harmonics. Even-order harmonics are caused by nonlinear loads that destroy the y-axis symmetry of the current waveform. Typically, current waveforms possess the symmetry in question, and the even-order harmonic terms in the harmonic spectrum all have zero coefficients. However, if the waveform is not symmetrical about the y-axis, then there will be some non-zero even-order harmonic terms. The semiconverter shown in Figure B-6 uses a half-wave rectifier. The rectification is accomplished with three diodes and three phase-controlled SCRs. Figure B-6 also shows the voltage and current waveforms and spectra associated with them.

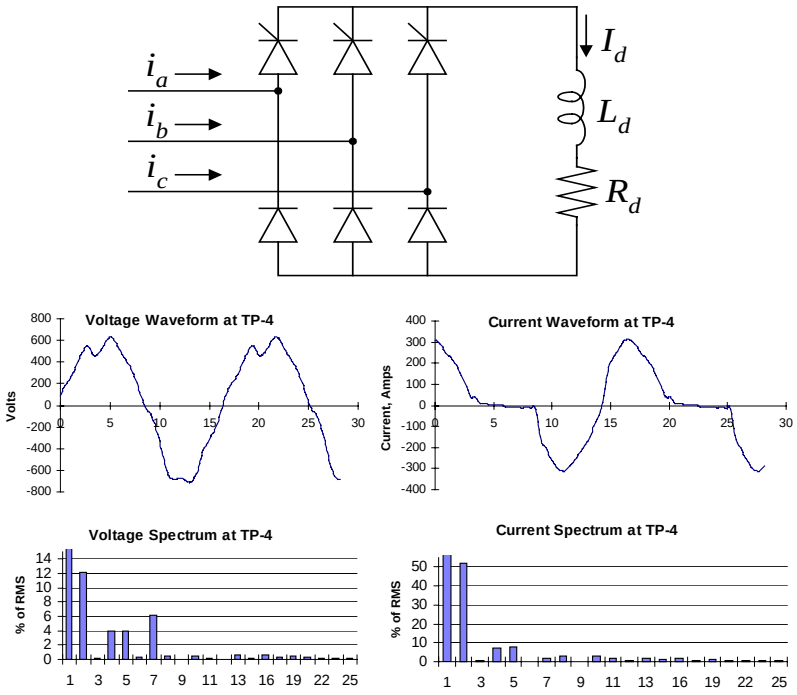


Figure B-6
Semiconverter with Voltage and Current Waveforms and Spectra

It is easy to see the large second and fourth harmonic components. It should also be noted that there is no DC component. With a 50% second harmonic current component, the voltage distortion is nearly 12% at the second harmonic. This condition can be treated similarly to odd harmonics, but care must be taken to avoid resonances at the even harmonics also, whereas that would not normally be a consideration.

Other loads, such as arc furnaces, cycloconverters and power line carrier communication systems, can cause distortion at frequencies that are not integer multiples of the power frequency. These are known as interharmonics. These may occur anywhere in the spectrum between the integer harmonics, causing further distortion of the waveform. Problems caused by interharmonics include many of the same ones that integer harmonics cause, such as transformer and cable heating, possible multiple zero crossings, and telephone interference, as well as light flicker. Filter design must take interharmonics into consideration, since there may be more frequencies to deal with and more possibilities of resonance.

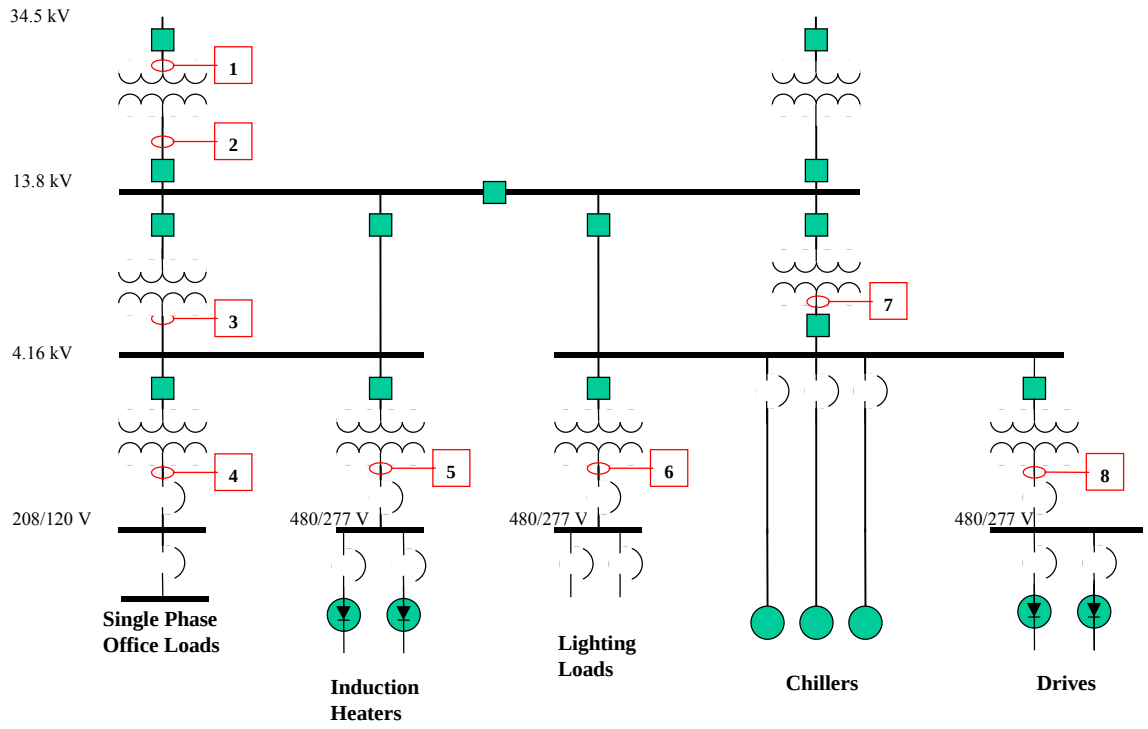


Figure B-7
Simplified One-line Diagram of Industrial Plant

Figure B-7 is a simplified one-line diagram of the distribution system in an industrial plant. In a harmonic study for an industrial customer, the first step is to decide where to take measurements. From IEEE Std. 519-1992, the voltage distortion limits should be applied at the PCC (point of common coupling), Point 1 in Figure B-7. Point 2 can be used, but the results should be reflected to the high side of that transformer to ensure that the limits are applied at the point where other customers could be connected.

Point 3 is at the 4160 V bus feeding offices and induction heaters (Bus 3), while Point 7 is at the 4160-V bus for lighting, chillers, and drives (Bus 7). These points also will be used to refer to the current, such that feeder Point 3 will refer to Feeder 3, Point 7 to Feeder 7, and so forth. Busses 3 and 7 can be considered intermediate busses, since they are not at the PCC. They are not the first panel upstream of the loads, with the exception of the chillers. Some vendors use adjustable-speed drives on their compressors and pumps. However, in the case shown in Figure B-7, it is assumed that the chillers are using motors across the line with no speed control, so there will be no harmonic distortion issues with these loads. These linear loads will, however, provide some dilution of the nonlinear currents injected into Bus 7. If the vendor is using ASDs on the chiller motors, the load will be nonlinear and must be considered for harmonic injection.

Bus 4 is at the 208/120-V secondary of a delta-wye transformer feeding office loads. This type of panel was analyzed in the previous section on commercial office buildings. There is a significant probability of heavy current distortion in the feeders from this panel as well as a high level of neutral current flowing at the third harmonic. The transformer feeding Bus 4 will experience

extra heating as a result of these currents, and the voltage at Bus 4 may be distorted by the harmonic current components injected into the bus by the single-phase nonlinear office loads. On a plant-wide scale, however, this effect is usually a much smaller issue than the effect of three-phase nonlinear loads. In industrial plants, the loading is dominated by three-phase devices. Thus in Figure B-7, the induction heaters and the adjustable-speed drives represent the dominant nonlinear three-phase loads, while the chillers represent a large linear three-phase load.

At Bus 5, the current will be the sum of the induction heater currents. While there may be some cancellation between the individual heaters, there will still be some significant distortion in this current. The current in the feeders from Bus 5 to the heaters will have the most distortion, since there is no chance for cancellation. The voltage at the heater terminals may be somewhat distorted, as the individual distorted heater currents flow through the feeder impedances. The voltage at Bus 5 is distorted by the sum of the heater currents flowing through the transformer impedance, causing voltage drops at the predominant frequencies in the current. The Bus 5 voltage distortion is less than that at the heater terminals, due to the current cancellation effect. So, as usual, the major issues at Bus 5 are *conductor heating, transformer heating and voltage distortion*. In addition, since the heaters use phase-controlled rectifiers, there will be some induced phase shift, which causes a reactive power requirement. This will lead to power factor correction requirements, and the possibility of resonant conditions due to the addition of power factor correction capacitor banks.

At Bus 6, the current is the sum of all the lighting loads. Modern electronic ballasts and fixtures for HID or HPS lights will draw nonlinear currents, but ANSI C82.11-1993 limits electronic ballast current harmonics to less than 32%. Therefore, any voltage distortion at Bus 6 is limited in the same fashion. There should not be any major issues at Bus 6 regarding conductor heating, transformer heating, neutral heating, or voltage distortion.

Bus 8 will be examined before Bus 7, since the loads on Bus 8 will affect Bus 7. At Bus 8, the adjustable-speed drives are voltage-source AC types and will likely have the most pronounced impact on voltage and current distortion in the entire plant. First of all, the individual feeders to the drives may experience current distortion levels as high as 150% THD. In addition, there is usually not much cancellation of these currents at Bus 8 because the front end of these drives are passive diode rectifiers and all the significant harmonic components of current are displaced from the line voltage by the same amount. Thus the dominant harmonics, 5^{th} and 7^{th} will be in phase and simply add at Bus 8. The feeder to Bus 8 will then have the same distortion levels as the individual feeders. The voltage at Bus 8 will be distorted by the current interaction with the transformer impedance, resulting in a voltage THD at Bus 8 higher than anywhere in the plant (besides the drive terminals themselves). Any other loads to be connected to this bus must be examined for sensitivity to harmonics before connection. So, again, the major issues at Bus 8 are *conductor heating, transformer heating and voltage distortion.* However, in this case the adjustable speed drives have passive diode front ends, and therefore have a displacement power factor of unity. Therefore, there will be no reactive power requirement for these loads.

At Bus 7, the chiller motor loads do not inject any harmonic components into the bus. As these chillers present a significant load to the bus, they tend to dilute the THD in the current upstream. How much dilution is a direct function of the ratio of chiller (linear) load to drive and lighting

(nonlinear) load. Therefore, the current distortion in the feeder to Bus 7 will be less than that to Bus 8, and the voltage distortion caused on Bus 7 will be less than on Bus 8.

Other possible problems stem from system resonance conditions. Even though the distortion at the PCC may be within limits, power factor may be poor and require improvement. Installation of power factor correction capacitors can often result in a parallel resonance condition with the system inductance. Current components at or near the resonant frequency may be amplified significantly. The bus voltage can be severely distorted as a result, to the point of exceeding IEEE 519 limits. Therefore, the addition of series tuning reactors for the power-factor correction capacitor banks may be required. The reactors shift the resonance point of the system away from the predominant frequencies, which can significantly improve the bus voltage distortion.

Target:
Customer Power Conditioning Solutions

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

© 2001 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. ELECTRIFY THE WORLD is a service mark of the Electric Power Research Institute, Inc.

Printed on recycled paper in the United States of America

1006489

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com