Alternators Reactance for Nonlinear Loads

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Introduction

Widespread invocation of IEEE Std 519 on systems powered by generators, together with increased use of equipment that draws harmonic currents, mean that the impedance of emergency or standby power sources has become more important. Particularly for data centers and other facilities strongly dependent on data processing equipment, electronic loads may be more than half of the total load. If the harmonic contribution of these loads is not accounted for in the overall design, the emergency or standby generators may need to be oversized so much that they are not practical or economical.

Sources of Harmonic Current

In an office or industrial setting, the largest sources of harmonic currents are electronic equipment using rectifiers to transform the three-phase power to DC. For data processing equipment, these loads are usually UPS systems, and for industrial facilities, they will probably be variable-speed drives. In any case, three types of rectifier are common:

Six- and twelve-pulse rectifier

A six-diode bridge rectifier fed from the line-to-line AC voltage (we are only considering three-phase systems) will draw six pulses of current per cycle, two from each phase. Because this current is pulsed, it causes harmonics of the line frequency to appear in the current waveform. These harmonic currents interact with the impedance of the generator to produce harmonic voltages that may cause problems for other equipment connected to the same line. By using a transformer with a dual winding on the input, feeding two rectifiers, the current drawn by the rectifiers may be spread out so as to have lower harmonic current. This is called a twelve-pulse rectifier. A typical six-pulse rectifier draws about 30% total harmonic current, mostly fifth and seventh harmonics. A twelve-pulse rectifier draws about 11% harmonic current, mostly 11^{th} and 13^{th} harmonics [1].

Because these rectifiers draw high harmonic currents, filters are often added to bypass these currents and make the input current more sinusoidal. The large capacitors used in these filters cause the input power factor to be leading, which can cause problems with generator stability.

Active front end rectifier

By using an inverter similar to the output inverter as a rectifier, with some small filters, the input current waveform can be shaped to be a nearly perfect sine wave with approximately unity power factor. This type of rectifier does not usually cause any harmonic or power factor problems to the generator.

Harmonic Loading Effects

Harmonic currents drawn by nonlinear loads interact with the system impedance to induce harmonic voltages on the power line. These harmonic voltages may cause misoperation of electronic equipment, overheating of transformers, motors, and switchgear, and noise on analog signals such as telephone lines among other problems [1]. Because the generator is small by comparison with the generation capacity of the utility, it has a much higher impedance, so any harmonic currents cause much larger harmonic voltages than they would operating on utility power. Loads connected line-to-line do not draw any current from the neutral. They only have line-to-line harmonics, and if they are balanced, none that are multiples of three. The impedance seen by these harmonics at the generator is the negative-sequence reactance or X2, because they "rotate" at a different rate than the fundamental current in the same way that negative-sequence currents do. This impedance is sometimes not found on the generator data sheet, but the subtransient reactance X"d is usually a fair approximation for machines with a fully-connected damper cage.

Single-phase loads connected from line to neutral (possibly including large numbers of computers with single-phase power supplies) may also draw high third-harmonic currents. Third-harmonic currents and multiples have the same phase angle on all three phases. These currents add together in the neutral and may cause heating of the neutral if it is not sized correctly. The important impedances for third harmonic are the stator leakage reactance and the zero-sequence reactance. If a three-phase UPS or delta-wye transformer is connected between the generator and load, the generator will be isolated from these third-harmonic currents, and they should not be considered for generator selection.

Apart from the problems caused by the negative-sequence harmonic voltages to other connected equipment, they can cause additional generator heating, mainly in the rotor. Third-harmonic currents do not couple to the rotor very much, so do not cause extra heating in the rotor. A generator with fully-connected copper damper windings should normally not need to be derated more than about 10% to account for the extra heating.

Harmonic Mitigation

Equipment manufacturers and consultants have proposed various remedies for harmonic voltage problems. Following is a table showing some typical suggestions:

Source	Recommended practice	Reference
Caterpillar	Six-pulse: 1.6x oversize, twelve-pulse: 1.4x oversize	3
Liebert	Six-pulse: 1.6x oversize, twelve-pulse: 1.4x oversize	4
Cummins	Guidelines and calculations given, 2-5x UPS capacity stated as "conventional wisdom"	5
Cummins	X"d 12% maximum given as a typical requirement	6
GE	X"d 8-12% for a "good" generator	7
AMPS	As low as 3.3% maximum X"d for six-pulse, table given	8
Stamford Newage	X"d = 12% taken as typical but graphs and tables given	9
Lane Coburn Assoc	X"d 12% maximum	10

The practice of requiring a specific oversizing factor for the generator for harmonic loading should be discouraged. The harmonic impedance is the most important factor in sizing a generator for nonlinear loads, and it does not correlate directly with generator size. If the increase in rating causes a jump in frame size, the impedance may actually increase. Even in the same frame size, an increase in stack length is not a guarantee that impedance will decrease proportionally, since turns, pitch, and number of slots play a significant role in impedance.

The maximum amount of reactance that should be specified in the generator varies depending on many factors such as:

1. How much of the load is UPS or other harmonic generating equipment.
2. How much harmonic current is produced by each UPS or other device.
3. How much voltage total harmonic distortion (THD) can be tolerated
4. How many generators can be online at any given time.
5. Presence of any other power sources.
6. Presence of harmonic filters or capacitors on the power system.
7. Transformer connections in the power system (by arranging to have some transformers connected delta-wye and some wye-wye, a considerable amount of fifth- and seventh-harmonic current cancellation occurs).

A full system harmonic analysis is usually advisable to determine the actual reactance requirement. Using a rule of thumb such as 12% maximum X”d risks either wasting money on an excessively oversize generator, or failure of the system to meet harmonic requirements. A very rough calculation can be performed to get an idea of the order of magnitude of impedance required. The formula is:

$$THD = 0.01379 X_2 \mathrm{P}$$

where THD is the percent total harmonic voltage distortion, X_2 is negative-sequence impedance (%), and P_H is the percent of load that consists of rectifiers. This assumes typical six-pulse load [2]. For twelve-pulse the distortion is one half of the amount calculated. No account of the generator harmonics is taken, so they need to be added. No account is taken of transformer or cabling impedances, or the effect of filters or other system loads. Figure 1 is a nomograph that may be used to estimate the distortion according to the above formula.

Per IEC-60034-4, reactances of a synchronous machine are normally declared in the data sheet with a tolerance of ±15%. Given six-pulse load, it will be evident that exceeding 25% nonlinear load will require *maximum* X2 less than 15% (nominal less than 12.75%). Especially for larger generators, 15% is a low value for X2, and to achieve this as a guaranteed maximum will require special design along with a significant increase in size and cost. Guaranteed values of X2 less than 10% may not be practical, since the increased size or inertia may make it impossible to couple the generator to the engine. The system designer needs to investigate other techniques for reducing harmonics instead of requiring the generator to do the job by itself. These might include:

1. Specifying that electronic equipment loading the system have reduced harmonic current, by using higher pulse number rectifiers or active rectification, or by adding filters to these loads.
2. Adding system-wide passive or active filtering to reduce harmonic voltages.
3. Adding phase-shifting transformers to some part of the nonlinear load to effect harmonic cancellation with a fully-loaded system, or using a six-phase generator to achieve the same effect.

Conclusions

The practice of requiring a fixed value of generator reactance as a panacea for any sort of nonlinear load is misguided and will likely lead to failure of the system to meet requirements, unnecessary expense of a greatly oversized generator, or both. A system-wide harmonic study followed by careful consideration of all available means of harmonic mitigation is the correct solution to this problem. For preliminary quotation as much information as possible should be obtained from the user, then reasonable assumptions should be made and clearly stated in the quotation.

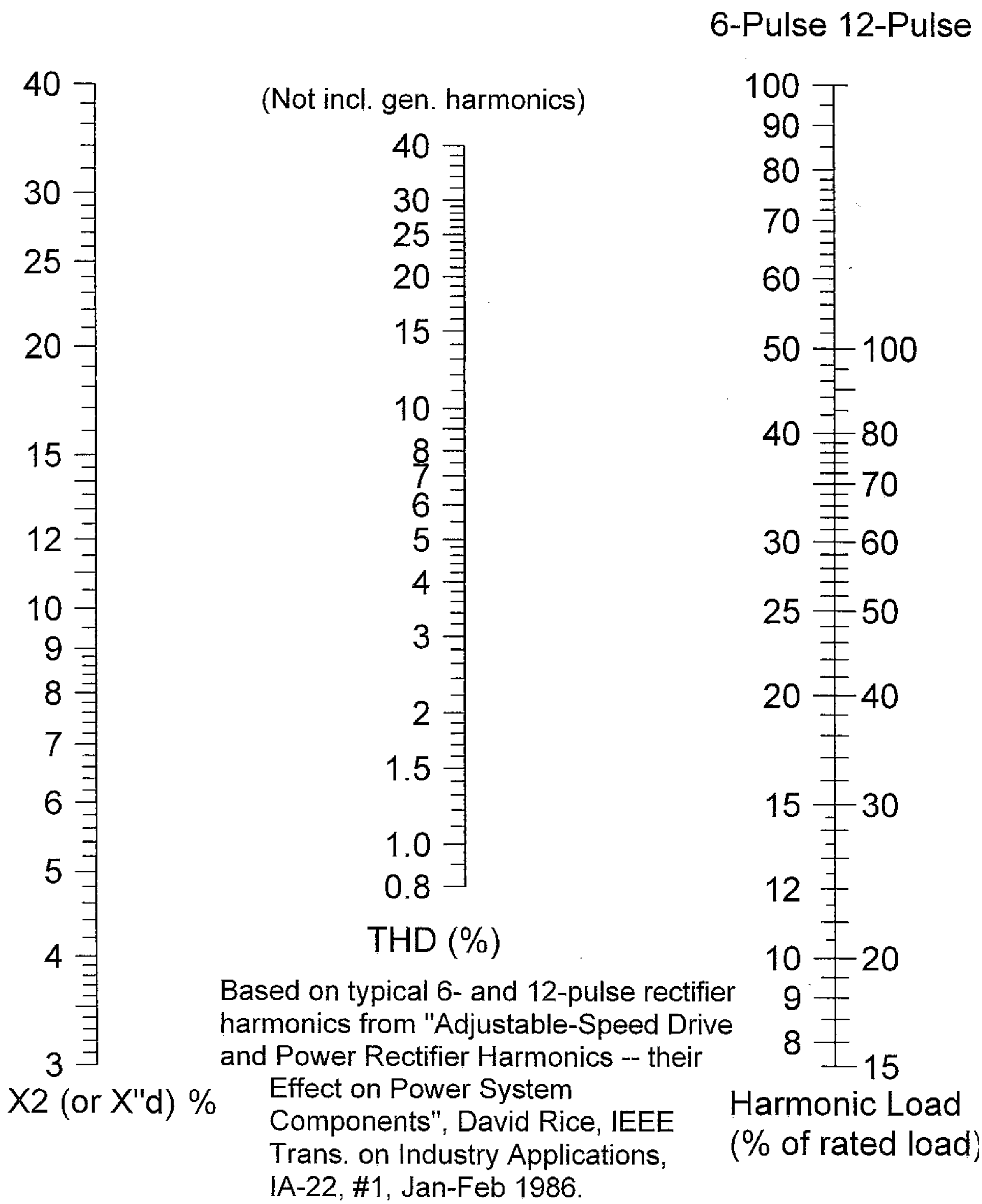

Figure 1. Nomogram for harmonic load calculation.

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