Technical article

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Slot harmonics in power generation systems

Introduction

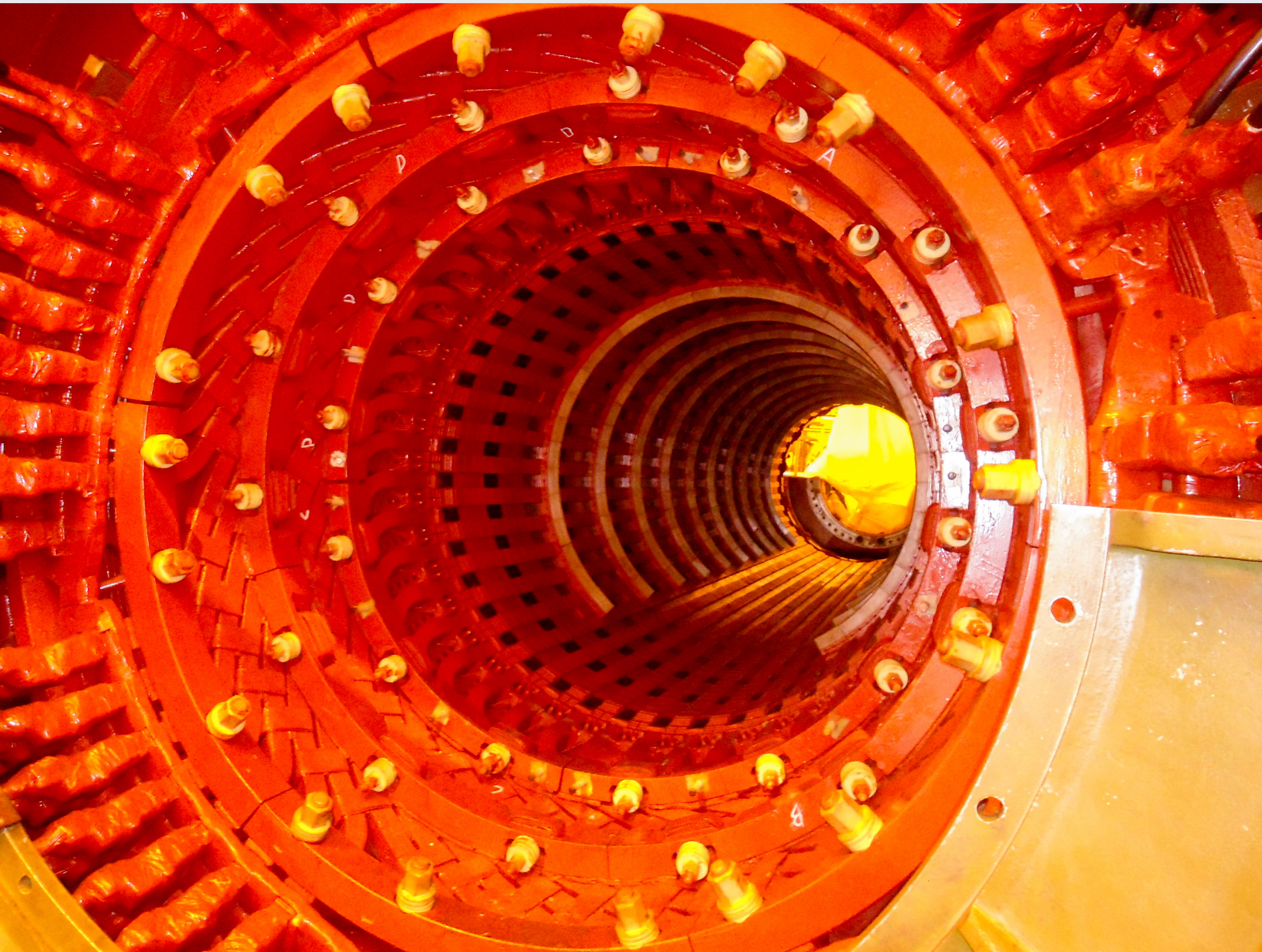
Technicians and engineers are broadly familiar with problems caused by lack of power quality and, more specifically, harmonics.
Filtration systems reduce and mitigate the actual harmonic current consumed by the receivers but, *what if the source of the power quality is the generation system?*

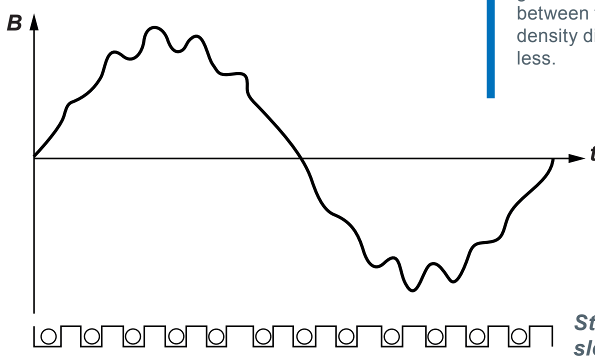
In this article we will look at slot harmonics, and a case study of resonance with these types of harmonics that are generated.

Slot harmonics

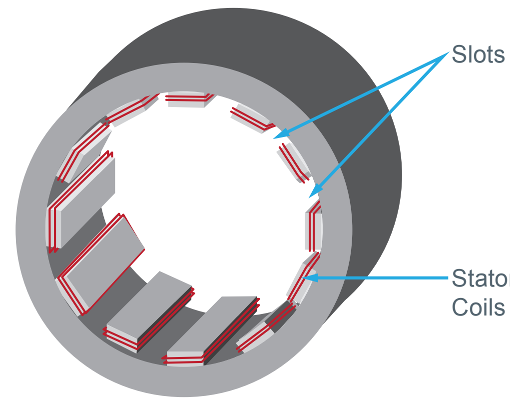
The actual construction of the stator windings of alternating current rotating electric machines can give rise to the appearance of harmonic components in voltage known as “slot harmonics”.

The existence of uniform slots around the internal part of the stator causes regular variations of reluctance and flux over the stator surface, producing distortion of the voltage wave.





The reluctance of each slot is greater than the metal surface between them, so the flux density directly over the slot is less.



Induction Motor Elements.

The existence of uniform slots around the internal part of the stator causes regular variations of reluctance and flux.

Slot harmonics occur at frequencies determined by the space between adjacent slots. The order of the components is expressed as follows:

$$v_{slot} = \frac{2 \cdot M \cdot S}{P} \pm 1$$

where:

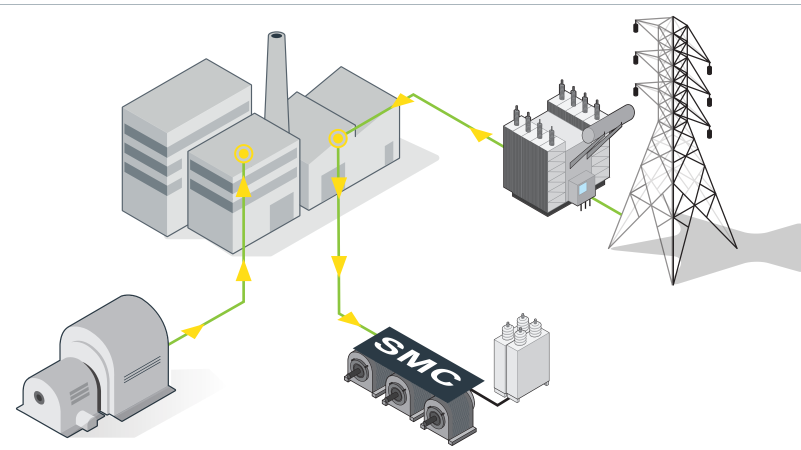
v_{slot} = order of harmonic component
S = number of stator slots
P = number of machine poles
M = whole number, normally equal to 1, with which the lowest frequency slot harmonics are produced.

The main effects of slot harmonics are:

- Induction of voltage harmonics to the electrical system, distorting the voltage wave.
- Increase in the voltage distortion rate THDU(%)
- Greater likelihood of resonance with capacitor banks
- Decrease in engine efficiency (lower torque, vibrations, etc.)
- Inadequate operation of sensitive electronic devices.

Slot harmonic resonance

In this case the industry in question has a dual power supply, consisting of a 6.5 MW, 4.16 kV/60 Hz generator and direct power supply from the electrical network through a 69 kV primary electrical network with a 9 MVA transformer and 4.16 kV/60 Hz secondary. The installation had a motor control system (SMC), which was compensated with a 50 kvar, 4.16 kV capacitor.



Simplified diagram of the electrical system and electrical measurements

Problems

The installation had the following problems:

- Repeated failure of the SMC motor starter.
- Tripping of the protections and degradation of the MV capacitors.
- Failures in the UPS system in low voltage.
- Damage to the electronic ballasts.
- False heating alarms in compressors, etc.

Tests

4 different tests were carried out to the motor power supply:

- Powered from the electrical network with and without a capacitor bank.
- Powered from the generator with and without a capacitor bank.

Table 1 summarises the main electrical parameters measured, showing that the variation of the harmonic components without (Fig. 1 and 2) or with (Fig. 3 and 4) a capacitor bank is practically the same, having at all times the correct levels.

Table 1

Comparison of electrical parameters at full load in a 300 H.P. engine powered from the electrical network, with and without a 50 kVAr, 4, 16 kV capacitor bank

~	50 kVAr Capacitor	Voltage (V)	Measured demand		P.F.	% THD		% voltage and current harmonics, phase 3									
								3rd		5th		7th		35th		37th	
			kW	kVAr		V	I	V	I	V	I	V	I	V	I	V	I
CFE	Out of service	4155	212	125	0.86	1.01	1.92	0.49	0.66	0.38	1.52	0.26	0.81	0.04	0.03	0.16	0.04
	Operating	4155	212	99	0.90	0.77	1.92	0.14	0.52	0.34	1.54	0.11	0.88	0.04	0.06	0.19	0.09

Fig.1

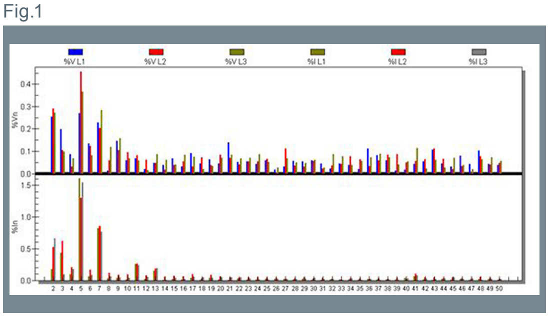


Fig.2

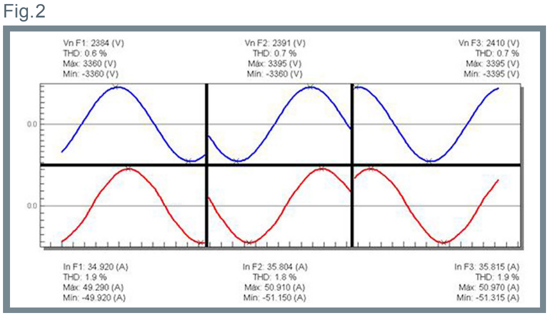


Fig.3

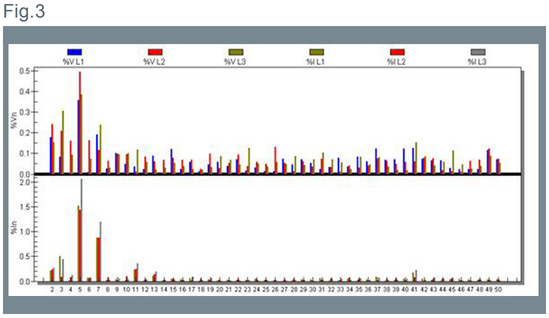
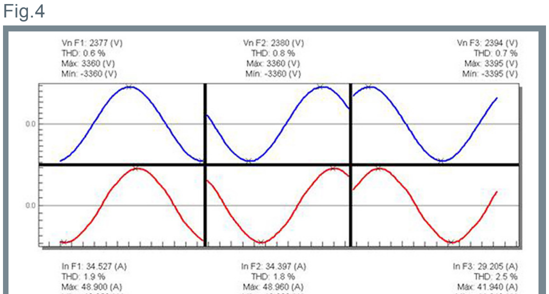


Fig.4



Customised and effective. CIRCUTOR capacitor banks (CAPACITORS) are especially manufactured according to the type of solutions needed.

Table 2 shows the performance of the system powered by the 6.5 MW generator.There is a considerable increase in the voltage distortion when the 50 kvar capacitor is connected; the increase is mainly produced in the 37th order harmonic.

Table 2

Comparison of electrical parameters at full load in a 300 H.P. engine powered by the 6.5 MW generator, with and without a 50 kVAr, 4, 16 V capacitor bank

~	50 kVAr Capacitor	Voltage (V)	Measured demand		P.F.	% THD		% voltage and current harmonics, phase 3									
								3rd		5th		7th		35th		37th	
			kW	kVAr		V	I	V	I	V	I	V	I	V	I	V	I
G 6500 kW	Out of service	4155	208	123	0.86	2.96	2.53	0.42	0.11	1.89	2.05	0.80	1.42	0.30	0.02	1.26	0.04
	Operating	4155	209	97	0.90	4.60	7.20	0.46	0.10	1.74	1.08	0.91	1.18	0.49	1.38	3.96	6.49

Fig.5

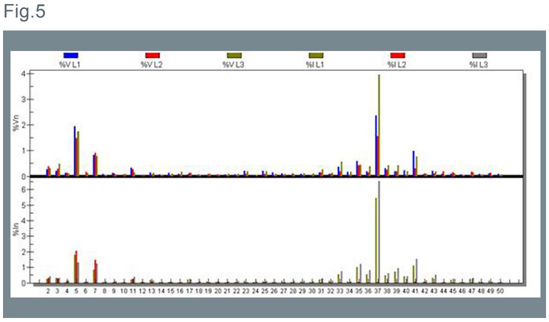


Fig.6

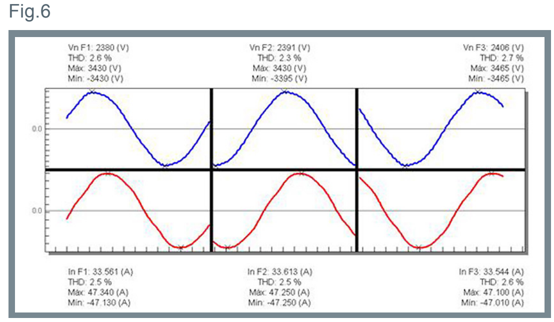


Fig.7

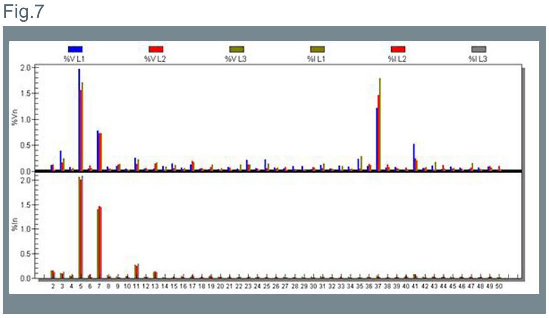
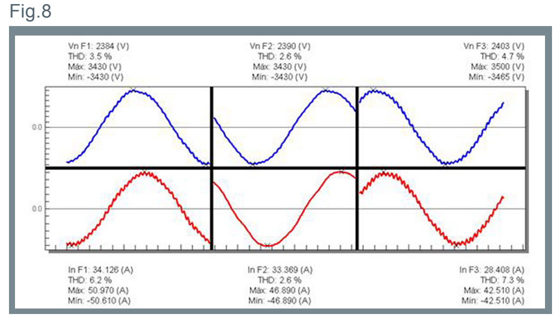
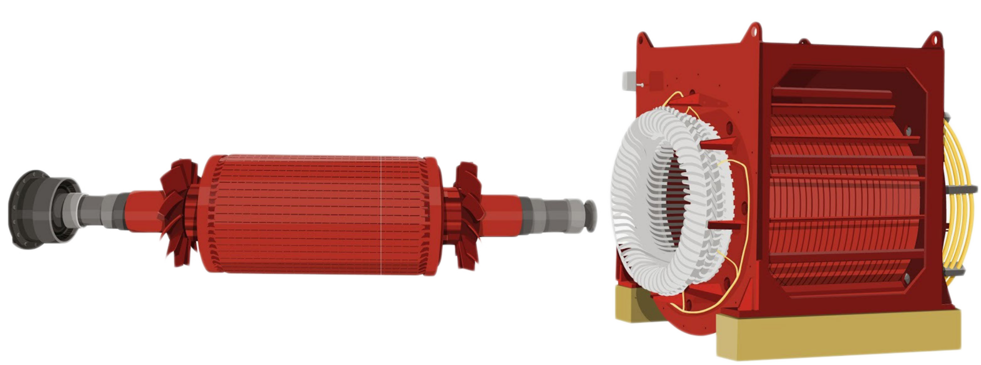


Fig.8





Detail of the rotor and the stator in a generator.

Normally in both the stator and the rotor the electrical system consists of copper conductor windings through which currents are supplied or transferred to an external circuit flow.

Source:
www.endesaeduca.com
Resources / basic concepts / Generators

As figures 6 and 7 without a capacitor and figures 5 and 8 with a capacity show, the harmonic distortion operating with the generator is greater compared to the distortion produced operating directly with the electrical network; the 5th and 37th order components have apparently negligible amplitudes (1.89% and 1.26% respectively).

With the capacitor bank operating, there is resonance in the 37th harmonic with its amplitude at high values (>3%). There were failures during the test, including the false alarm in the boiler control because of voltage distortion in all the circuits powered by the generator.

This resonance is caused by the combination of short-circuit parameters in the 4.16 kV, 71230 kVA DC bus, and the size of the capacitor, 50 kVAr. The tuning frequency is expressed as follows:

$$n = \sqrt{\frac{S_{sc}}{Q}}$$

where:

n = harmonic order of resonance

S_{sc} = Short-circuit power available in the connection point of the capacitor bank

Q = Effective power of the capacitor bank

therefore:

$$n = \sqrt{\frac{71230}{50}} = 37.74$$

Fig.9

$$v_{slot} = \frac{2 \cdot M \cdot S}{P} \pm 1 = \frac{2 \cdot 1 \cdot 72}{4} \pm 1 = 35 \text{ and } 37$$

We also saw that the generator was 4-pole and had 72 slots in its stator, so by applying the initial formula its lowest order slot harmonics are 35 and 37, coinciding with the resonance produced in the installation, and which entailed the various underlying problems. (Fig. 9)

An interesting aspect of this test was the fact that as the load dropped to 0, the distortion of the voltage wave increased, as shown in the figure with the profile of the voltage distortion rate THD(U)%.

Conclusions

In this case, the immediate measure was to leave the 50 kVAr capacitor permanently out of service, and to consider the need to use a capacitor bank with a detuned filter, detuned to 7%. However, the presence of the 37th voltage harmonic, being a generator design flaw, cannot be eliminated, meaning that in low load periods the same false alarm was produced in the boiler control. It was therefore suggested that power should be provided through an online type UPS system in order to eliminate this component from the power supply voltage.

It is becoming more essential to use compensation units with detuned filters due to the increase in applications with electronic and power electronic devices, whose effects these days cannot be discounted.

The deployment of a monitoring system enables the diagnosis, control and efficient use of electrical energy, and to help detect any anomaly in our installation.

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