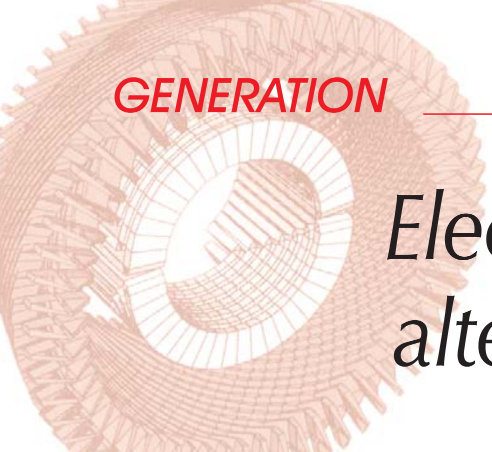

Electrical signature analysis and alternator condition monitoring

by Mike Rycroft, EE Publishers

Rotating electrical machines are at the core of most generation networks. As machines are designed to tighter margins there is a growing need, for the sake of reliability, to monitor their behaviour and performance. Electrical signature analysis is proving valuable on wide range of plant, increasingly on wind turbines and hydro plant.

Vibration analysis (VA) as means of detecting failure of mechanical parts of electrical machines is a well-established technique. VA can be extended to detect certain electrical faults as well, but for accurate electrical condition detection, electrical testing is required. Accelerometers applied to mechanical components of the drive train are traditionally used for condition monitoring but require their own data acquisition system and analysis software.

In contrast, the electrical current and voltage are continuously available and can be used for condition monitoring. Electric signature analysis makes use of the abnormal variations in output voltage and current to detect faults and failures.

Faults in alternators result from mechanical as well as electrical problems. Mechanical problems can in many cases affect the electrical output of the alternator, and the electrical components become transducers for mechanical faults. Analysis of the output waveform can detect and identify mechanical problems, without the need for additional equipment.

Electrical signature analysis

Electrical signature analysis (ESA) is the term used for the evaluation of voltage and current signals of electric machines [2]. More commonly applied to motor analysis, ESA can equally be applied to alternators and generators. ESA consists of a set of methods and techniques that monitor the condition of the machine by identifying patterns and deviations in the voltage and current. It involves the processing and analysis of voltage and current signals acquired from the alternators under both operating and off-line conditions. The technique may be applied continuously or on a periodic basis. In the case of alternators, it is primarily based on the voltage signature and the frequency spectrum of voltage under both load and open circuit conditions.

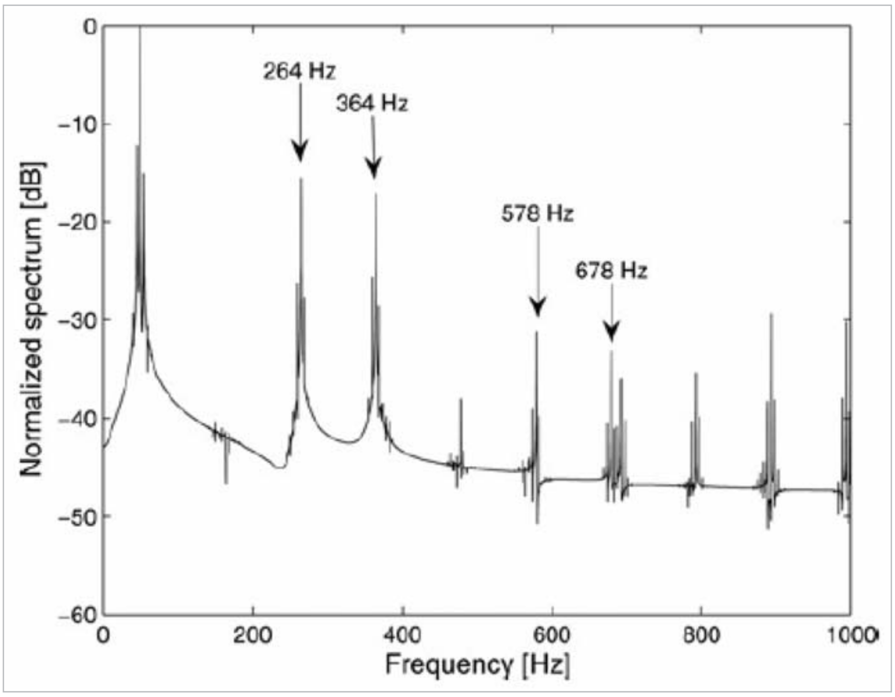

Fig. 1: Frequency spectrum of a healthy alternator [6].

An alternator, even in healthy condition, does not produce a "clean" output frequency spectrum, but one which contains frequency components in addition to the fundamental. The pattern of the output is correlated with the deviation of the operating conditions of the equipment from the ideal state, and in the case of a machine with problems can be used to diagnose the state of health of the machine. Typical frequency spectrum of a healthy alternator is shown in Fig. 1.

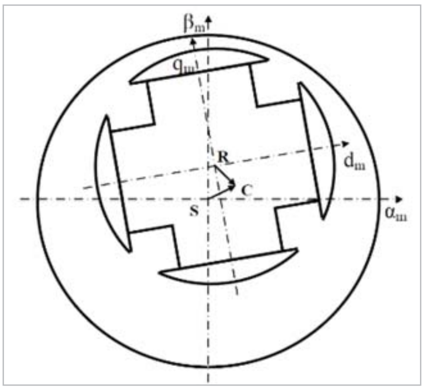

Fig. 2: Geometric representation of rotor eccentricity. (S is the stator axis of symmetry; R is the rotor axis of symmetry) [4].

Any fault that causes a periodic deviation in the electrical or mechanical conditions of an alternator or generator will cause a periodic variation in the output voltage, superimposed on the fundamental output voltage. By extracting this periodic "signature", it is possible to determine the nature and extent of the fault or problem. Through the information contained in the collected signals, extracted after adequate digital signal processing, it is possible to obtain an assessment of the operational state of the generator and turbine set. The machine acts as a transducer for mechanical faults as well as electrical, allowing the electrical signals (voltage and/or current) to carry information on mechanical problems. This electrical fault signature may be caused by many things.

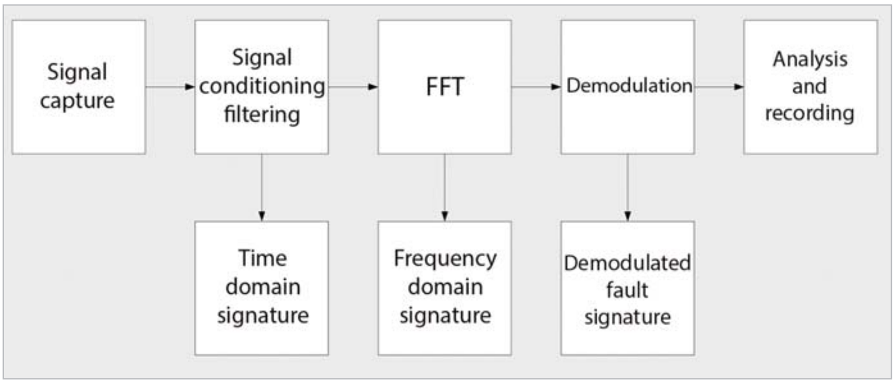

Fig. 3: ESA process.

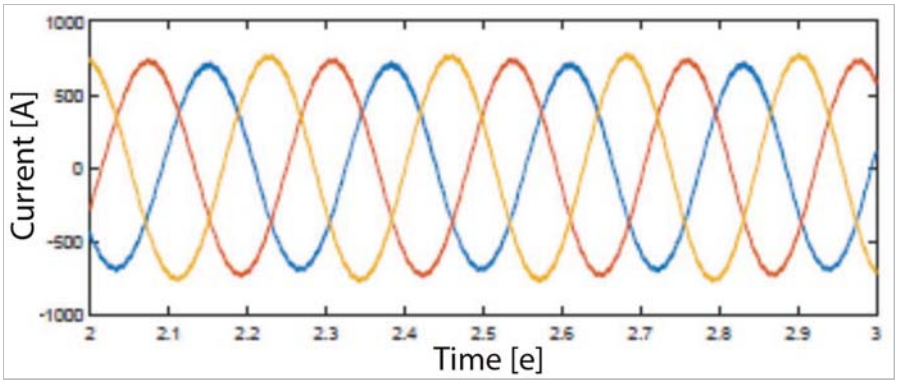

Fig. 4: Captured time domain signals [5].

Periodic speed variations in the primary drive

Typical examples include uneven wear of gear teeth in the gearbox of a wind turbine, causing speed "chatter". This uneven speed results in slight periodic changes in the voltage generated. Torque oscillations due to bearing failure can also produce periodic frequency modulation of the signal [3].

Static and dynamic rotor eccentricity

Contact between the rotor and the stator core can result in serious damage to stator and rotor windings and cores. It has been determined that about 60% of faults in electrical machines are caused by mechanical parts such as bearing, shaft and coupling [2]. Nearly 80% of these faults results in the displacement of the axis of symmetry of the rotating axis of the rotor. This illustrated in Fig. 2.

The actual air gap will be much smaller than that illustrated in Fig. 2, and any slight mechanical wear can result in significant changes in air gap. Changes in the air gap result in changes in the flux linkage between stator and rotor and in the self and mutual inductance of the rotor.

Three types of abnormal air-gap eccentricity exist: static, pure dynamic, and mixed. With no eccentricity the rotor rotates about its centre *R*, which is also the stator centre, and the airgap is constant. In the case of static eccentricity, the rotor rotates about *R*, which is displaced from *S*, and the airgap between rotor and stator varies. The position of minimal radial air gap is fixed. In the case of dynamic eccentricity, the rotor rotates around the point *S*, but the rotor is out-of-centre (*R* is not on *S*) and this causes the position of the minimal air gap to follow the turning of the rotor.

In mixed type eccentricity there is a combination of both static and dynamic eccentricity and the rotor rotates about point C. Mixed eccentricity (with both static and dynamic components) is the most general case. Both position and size of the airgap change as the rotor rotates. As the rotor recedes or approaches the stator magnetic fields, this causes a change to the voltage in the stator coils. This can be due to a number of causes, and results in a variation in the magnetic flux linkage between stator and rotor.

Stator and rotor field winding faults

These can comprise rotor damage, inter-turn fault resulting in the shorting or opening of one or more circuits of a stator phase winding, and shorts in rotor field windings in the case of synchronous machines which can cause overheating which may also result in bending of the rotor. Field winding faults cause variations in the stator and rotor magnetic fields which affect the output voltage and current waveforms.

ESA techniques

Several condition monitoring methods have been developed in order to detect mechanical faults using electrical quantities involved in alternators. Generators do not produce current, they produce voltage and thus voltage signature analysis is generally used, and not current as in motors. However, for some generators type such as doubly wound induction generators, rotor current signature analysis may be used. There are several techniques available to perform ESA on alternators.

- Machine voltage signature analysis (MVSA).
- Field current signature analysis (FCSA).

In the most common case, the voltage and current signals are captured and transformed to the frequency domain where they are analysed. Fig. 3 presents the signal acquisition, processing and analysis steps involved. For each acquired electrical signals, various parameters are computed [2]. These parameters are used for the evaluation process and for the extraction of new features:

- *Average amplitude:* The average value of the signal in the period under review.
- *RMS amplitude:* Also called effective value or mean square.
- *Minimum and maximum amplitude values:* Maximum and minimum values of amplitude in the period under review.
- *Amplitude, phase and fundamental frequency:* Value of amplitude and frequency of the fundamental component of signal.
- *Fundamental harmonics:* Multiples of the fundamental component.
- *Harmonic distortion index (HDI):* This indicates the significance of harmonic content when compared to the fundamental component of the signal.

The first stage is the capture of voltage/current time domain waveforms. These waveforms will show deviations from the perfect sinusoidal waveform, depending on the fault. Although fault signatures appear at this stage, it is difficult to analyse them, as in many cases a very low

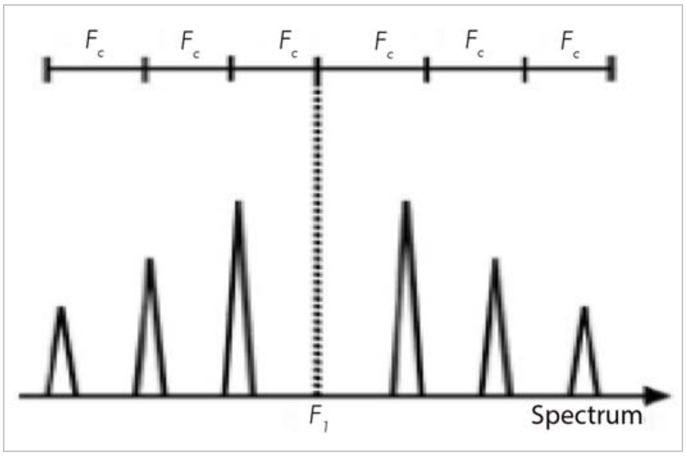

Fig. 5: Modulated simple fault [1].

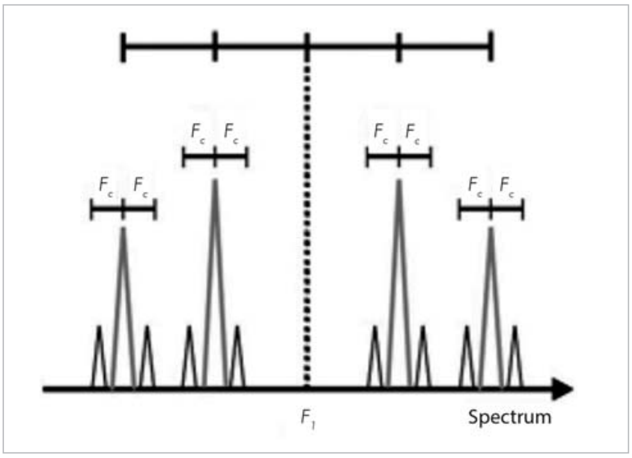

Fig. 6: Modulated complex fault [2].

level signal is present which is swamped out by the level of main the frequency (Fig. 4).

To overcome this, the frequency spectrum of the captured waveforms is derived using the fast Fourier transform (FFT). Because the fault signals are periodic, they will appear as high points in the frequency spectrum (Fig. 5). In most cases, the effect of the fault is to cause the amplitude of voltage/current to vary, which produces a frequency spectrum similar to that of an amplitude modulated RF signal, with "sidebands" around the fundamental frequency (Fig. 5). These frequencies are obtained by the following equation:

$$F = f_1 \pm k.\, f_c \qquad (1)$$

Where f_1 is the fundamental frequency, k is an integer, and f_c is the characteristic frequency of the fault. Complex faults can result in "double" modulation, with "sidebands" around the fault frequency sidebands (Fig. 6).

The fault signal level is often much lower than the fundamental frequency level, and this makes it difficult to isolate the fault signal from noise. It is possible, though, to demodulate the signal with a fundamental frequency carrier and recover the fault signal. This removes random noise from the frequency spectrum and gives a clear indication of the fault frequency. Fig. 7 shows examples of a demodulated fault signal.

Typical failure patterns

A generator does not exist on its own but consists of the alternator and drive components. Failure of drive components can also be determined from electrical signature analysis. Research has shown that the frequency of the fault signal is related to the type of fault, and the frequency of typical faults can be calculated by reference to standard formula, compiled using machine parameters such as rotational speed, number of pole pairs, slip frequency, fundamental frequency, gearbox ratio, number of rotor slots and others. For example, the characteristic frequency of stator winding faults in a DFIG alternator can be calculated from:

$$f_{st} = f_s \left[k \left(\frac{1-s}{p} \right) \pm n \right] \qquad (2)$$

where:

f_{st} is the characteristic frequency.

f_s is the fundamental frequency.

k and n are integers.

s is the slip.

p is the number of pole pairs.

More standard formulae can be obtained from the literature [5].

Machine voltage signature analysis (MVSA)

This method is used for all types of generator, and generally requires an open circuit condition, meaning that the machine must be taken off-line for recording of waveforms. The open circuit output voltage of the machine will contain periodic variations caused by faults or deviations in the machine parameters. A typical fault would be rotor eccentricity which would cause low frequency periodic variations in output voltage, similar to amplitude modulation. Fig. 8 [4] shows the difference in spectra from a healthy machine (a) and an unbalanced machine (b).

Field current signature analysis

This can be applied to both rotor and stator fields. There are several ways depending on the type of generator.

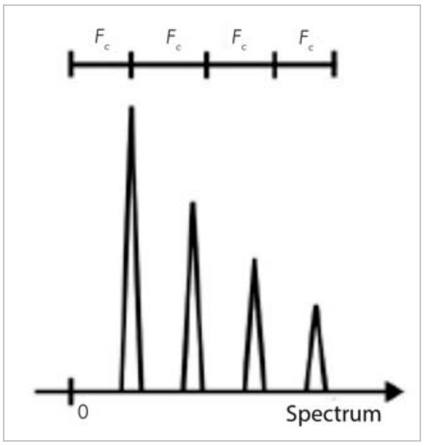

Fig. 7: Demodulated fault signals [1].

Doubly wound induction generator

This type of generator is used with wind turbines, and FCSA is proving to be increasingly useful in condition monitoring in this sector. Both rotor and stator current field current analysis are used to detect faults. A number of wind turbine faults may manifest themselves as some form of generator rotor eccentricity, including generator bearing faults, drive train misalignment, blade imbalance, pitching faults and possibly even gearbox faults [4]. Rotor eccentricity produces frequency components at odd multiples of the slip frequency (sf) e.g. 3sf and 5sf as shown in Fig. 9.

Synchronous generators

Both stator and rotor current analysis is used.

Rotor winding currents

Measurement of currents in the current flowing in the rotor of a healthy SG is DC and any AC component is indicative

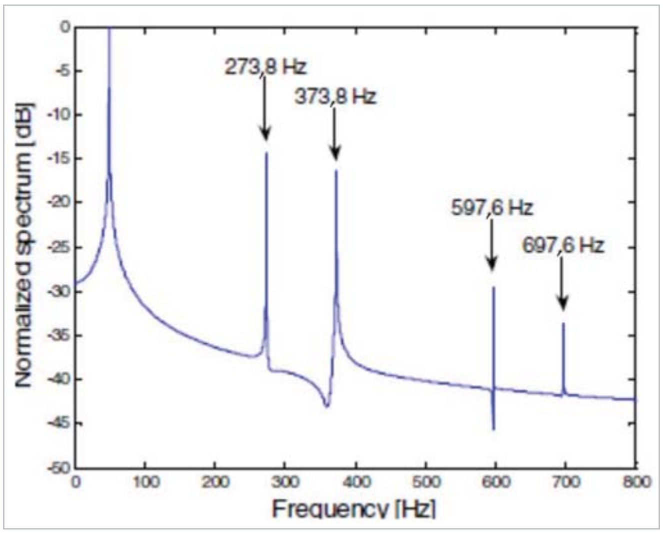

Fig. 8(a): Balanced stator and rotor windings. Balanced stator and rotor supply [6].

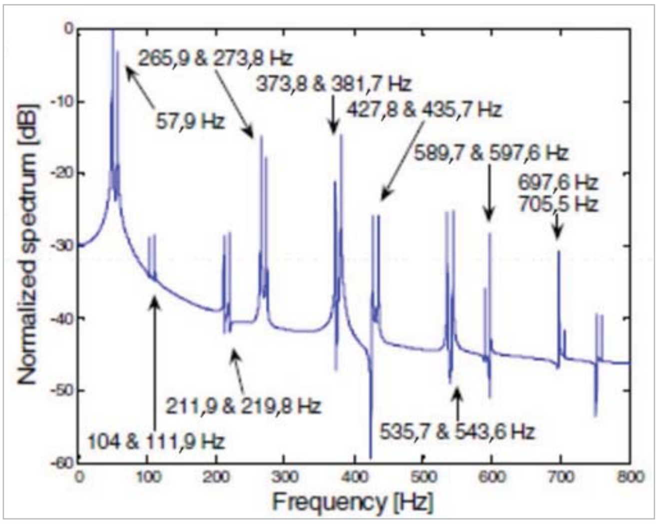

Fig. 8(b): Balanced stator and unbalanced rotor windings. Balanced stator and rotor supply [6].

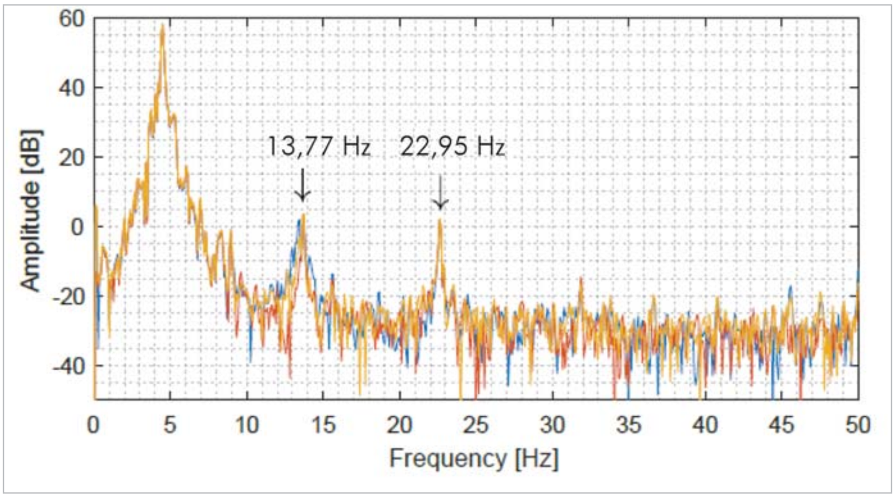

Fig. 9: FFT of rotor current [5].

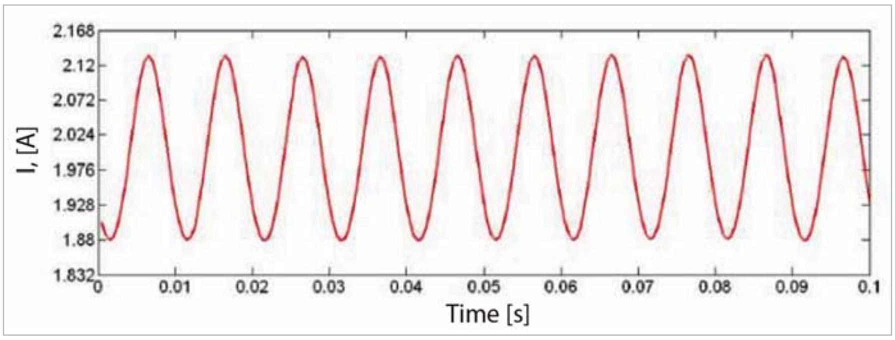

Fig. 10: Rotor current due to eccentricity [3].

of a fault. Eccentricity is a typical cause. Static eccentricity can cause a double fundamental frequency ripple in the rotor current of synchronous machines [4]. In the case of static eccentricity, the rotor winding experiences a time-varying air-gap distribution, and the rotor inductance depends on the rotor position. Any rotor pole faces a minimum and a maximum length gap through one rotor revolution: Since the rotor has $2p$ coils in series or parallel, the field circuit experiences $2p$ cycles in each round, i.e., rotor inductance changes with frequency.

$$2p \times f/p = 2f \qquad (3)$$

Therefore, as far as the rotor winding is supplied from a DC voltage source, a $2f$ frequency current component will be superimposed to the rotor DC current. The MMF produced by this AC component is g.

Permanent magnet generators (PMG)

In PMGs there is no rotor excitation and hence no rotor current, so signature analysis can only be performed on the stator current. Results are similar to synchronous alternator analysis.

Predictive maintenance

ESA can be used as a predictive maintenance tool by establishing the baseline or start-up voltage/current signatures as a reference and comparing the change of signature profile with time. It is also possible to establish reference "warning" levels that indicate that action is needed, as well as predictive decay rate algorithms which can give advance warning of potential problems.

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