Magstrom white paper

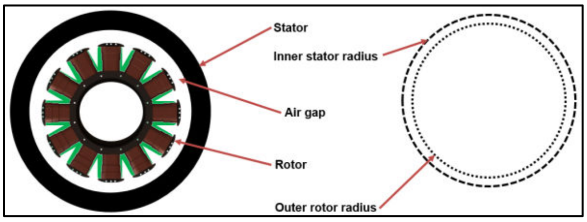
What is airgap irregularity & magnetic unbalance

From a mechanical perspective, airgap shape variations are not problematic unless the rotor and stator come into contact. However, since the airgap length determines the magnetic flux density between the rotor and stator, which in turn determines the magnetic forces and losses in the electrical machine, they can give rise to concern.

Electrical machines and airgaps

Electrical machines are utilized to convert mechanical energy into electrical energy and vice versa. However, the strong magnetic fields between the rotor and the stator, required for the function of the machine, also creates large forces between the two components. Typically, electromagnets on the rotor are pulled by electromagnets on the stator. The magnetic field in the airgap between the rotor and stator is supposed to be rotationally symmetric.

Ideally, both the rotor and stator should be represented by circles that are not only perfect in shape but also concentric in nature, i.e. that share the same center (although a salient pole rotor means that its outer radius is *not* a perfect circle).



The physical distance between the rotor and stator, together with material properties and current in the rotor and stator windings determine the magnetic field strength locally. The local variation in magnetic field strength in turn can cause the amplitude of oscillating forces to increase as well as induce extra losses.

In practice, a machine in operation will never be perfectly circular; there is always some form of airgap irregularity. Some of these irregularities are due to irregularities in the shape of the stator or non-concentricity between stator and rotor ("static eccentricities"), and some are due to irregularities in the shape of the rotor or radial movement of the rotor as it spins ("dynamic eccentricities").

It is important to distinguish between these two types of airgap irregularities since they produce fundamentally different behavior of the excitation forces.

- A machine with *static eccentricity* has a magnetic flux density in the airgap that is not uniform in space, but which does not change in time. Such an eccentricity gives rise to static forces between rotor and stator, which do not lead to vibrations (on their own) but do lead to reduced lifetime of the machine.
- A machine with *dynamic eccentricity* on the other hand has a magnetic flux density in the airgap that is not uniform either in space or time. Such an eccentricity creates forces that are time dependent (varying in time) which typically result in vibrations.

To make matters worse, the two types of eccentricity normally coexist in electric machines and interact.

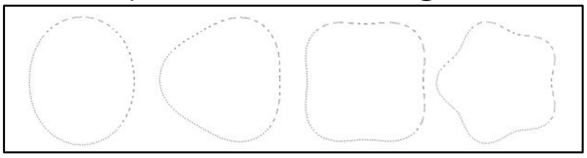
The link between airgap irregularity and vibrations is a complicated issue and depends on the design and actual airgap variations in the relevant machine. Therefore, it is hard to make general statements about airgap irregularities, forces, and the resulting vibrations.

If the rotor has a shape deviation in combination with some special shape deviation on the stator, it can cause a time varying, dynamic, *total* force between the rotor and stator. A dynamic force may give rise to vibration. It is therefore very important to know which type of airgap variation the unit has, for both the rotor and stator, if one fully wants to understand the issues.

As an example, an oval rotor concentrically located inside a perfectly round stator does not exhibit any constant- nor time-varying net force. However, an oval rotor which is not concentric with a perfectly round stator produces both a strong static, as well as an oscillating, net force with a frequency double that of the rotational speed. Further, the rotor poles experience a cyclic force on top of the large time-independent magnetic attraction force towards the stator. The symmetry of the rotor and stator shape are clearly very important to understand what forces the system will exhibit.

The origin of the shape deviations in the rotor or stator could have many possible causes. For instance, these deviations could be caused by machining tolerances in the manufacturing process, the installation process, thermal expansion, bearing positioning, foundation movement, to name only a few.

It is important that the rotor and stator are concentric, otherwise the machine has the lowest order airgap deviation in the airgap: eccentricity. The rotor and/or stator can additionally have shape deviations in terms of increasing order of deviations: they could be eccentric, oval, triangular, rectangular, pentagonal, hexagonal, and so on, or even display any combination of these shapes, as shown in the figure below.



Different shape deviations that both the rotor and or stator can have. The shape can also be any combination of any of the deviations. From left to right – oval, triangular, square, pentagonal.

The higher the order of the shape deviation, the less pronounced it normally is in terms of distance or % of the airgap length. The shape deviations can also change dynamically with temperature and as the rotor spins, but typically, the shape deviations change slowly with time.

There are international standards that address the acceptable levels of shape variations in hydropower generators, such as ISO 20816-2018, and recommend certain maximum levels of different shape variations that should not be exceeded. However, these standards are not binding, and it is up to the buyer of the generators to accept what levels they think are suitable.

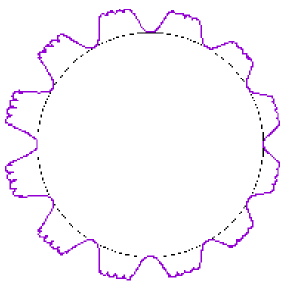
In hydropower units, which are typically mounted with a vertical rotational shaft and where the static eccentricity is the main source of concern, the acceptance level of the static eccentricity can be as low as 4%, although acceptance levels of 10% are more common for older units. For some hydropower generator designs, substantially higher values are considered acceptable, notably old bulb turbines.

The acceptance level of 4% for some hydropower generators is driven by the manufacturer's capability to produce machines with that low value, and the knowledge that low eccentricities produce low bearing forces, and that the unit can operate safely at that level. Safe operation means that the rotor will not touch the inside of the stator at any time.

Relation between airgap variations, forces, and vibrational frequencies

It is important to note that even for a machine with ideal rotor and stator shape, all points on the stator experience a *local* force that oscillates with the pole passing frequency (two times the electrical frequency). Put simply, because the rotor has strong electromagnets, and the stator is made from magnetic material, as the rotor spins and passes a local point on the stator, there is an attraction force between the electromagnet on the rotor and the magnetic material on the stator.

These local forces will affect the machine *locally*, but as a whole, the machine will not experience any oscillating *net* force between the rotor and stator. For each oscillating force at any given point, there is an identical oscillating force 180 mechanical degrees apart and these two forces will sum to zero in a machine without shape irregularities. The magnetic field can be likened to a negative pressure that affects all magnetic parts of the design. However, the pressure can also be summed to a total force. A non-zero net total force originates from shape irregularities, predominantly eccentricity.

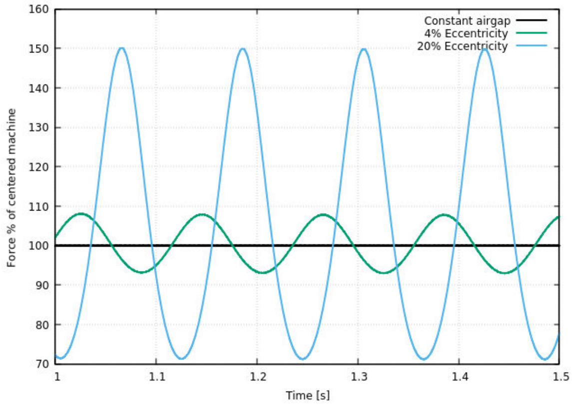


The magnetic pressure acting between the rotor and stator for a 12-pole eccentric machine. The small airgap is at 180° which is where the attraction force is the largest. Force densities shown at one instant for the spinning rotor.

The magnetic force acts on both the rotor and stator parts. Indeed, it is the magnetic coupling in the airgap that transfers the forces between the rotor and stator. This implies that if the rotor is oscillating, for instance from a bending motion of the shaft, then the stator will experience an oscillating force with the same frequency. This effect is usually referred to as unbalanced magnetic pull ("UMP"). The UMP can be constant in time and space, and/or have time varying parts which can also change direction as a function of time.

The force density, i.e. the magnetic pressure that is exerted in the airgap, is predominantly acting radially. There is also a tangential component, which depends mainly on the loading of the machine. The magnetic forces in the airgap are always attractive, e.g. the rotor is attracted to the stator, and the stator is attracted to the rotor, locally.

It is known from the hydropower industry that some airgap irregularities, such as a static eccentricity does not necessarily lead to a recorded increase in stator vibrations as observed via the use of a vibration monitoring system[1]. However, such static forces will increase the risk of fatigue in the system from other oscillating forces. In addition to this, the static force leads to time-varying local forces on the rotor poles, as shown in the figure below.



Radial magnetic force exerted on one pole in a 12 pole hydropower generator for a perfectly centered, circular rotor and stator (black) and for a perfectly circular with 4% (green) and 20% (blue) eccentric stator/rotor respectively.

[1] **M. Nässelqvist, R. Gustavsson, and J.-O. Aidanpää,** **"***A methodology for protective vibration monitoring of hydropower units based on the mechanical properties",* J. of Dynamic systems, Measurement, and Control **135**, 041007 (Jul 2013)); M. Nässelqvist, **"***Vibration management in the hydropower industry", Conf. on Vibrations in nuclear applications* (Nov 2018).