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Operating an electric motor in saturation – mechanical vibrations and other effects

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Abstract. This paper addresses some of the effects of running an electric motor near and in the saturation zone of the electromagnetic hysteresis curve, namely mechanical effects such as mechanical vibrations and rotation speed apart from the classic electrical and thermal effects. Mechanical vibrations are intrinsically characteristic of rotating machines, and other turbomachine characteristics, such as rotor unbalance, non-linearity and shaft variable stiffness can introduce severe disturbances in the operation of the machine. Rotation speed is also affected by electric parameters, when the mechanical machine is connect to an electric machine, meaning both the electric machine type and the process by which it is driven affects both the value of speed and its constancy.

Key words

Induction machines, harmonics, hysteresis, saturation, mechanical vibrations.

1. Introduction

It is well known that most electric motors, namely induction machines, are designed to operate in the linear portion of the hysteresis curve, and therefore the machine working parameters are selected and the magnetic materials used are so calculated.

Traditional operation of electric machines, without variable speed drives and other solid-state converters, meant that a well-designed and run machine would rarely operate in electromagnetic saturation. However, modern equipments used to control induction machines, including those using standard voltage-frequency control techniques, mean that the saturation zone is reached much more often.

The work presented in this paper is an attempt to assess effects of this operation mode, other than the classic electrical and thermal effects, which include increased stator current and losses, which cause added heating, and overall lower lifetime of the machine.

The token was to observe if also mechanical vibrations and rotation speed were significantly influenced, or rather if in the saturation zone those effects are somewhat "filtered".

2. Laboratory equipment

In order to study the influence of the electric supply to the motor on the overall behaviour of a mechanical load, a specially designed, dimensioned and built one-stage inertia flexible rotor (OSIFRO) set was used. This provided a simple mechanical load with a well-fitted (and well-known) dynamic model with which to work. Fig. 1 shows a view of the OSIFRO model:

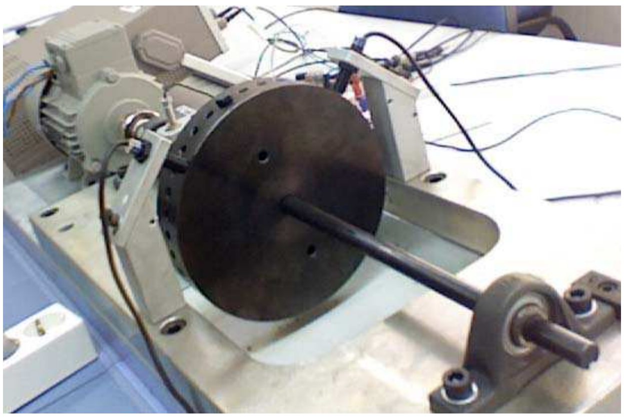

Fig. 1. A view of the OSIFRO

To drive the OSIFRO, a 0,37 kW squirrel-cage induction machine was connected using a three-phase input/output, 15 kVA programmable AC power source from California Instruments, which in this instance provided perfect voltage sine waves of a range of amplitudes and frequencies.

The OSIFRO mechanical load is constituted by a flexible, non-linear (keyed) rotor with a cylindrical inertia. This mechanical load is intrinsically slightly unbalanced, and adequate correction masses can be added to balance the rotor.

This work required a number of electrical and mechanical quantities to be measured. In order to acquire and accommodate the several quantities to be measured, a PC-based, high-precision data acquisition card was used, along with voltage and current active probes, accelerometers, proximity inductive sensors and a keyphasor.

3. Experimental tests and results

In order to study the behaviour of the mechanical load connected to the induction motor, a number of trials were devised and performed, and the main results are presented in this section.

For the sake of comparability, all tests were performed under similar and coherent conditions, and cover the operating frequency range of the mechanical machine excluding the main harmonic resonance, due the strain that such trials would cause on the shaft and bearings of the machine.

A. *Mechanical frequency near 20 Hz (under the main harmonic resonance; pure sine voltage waveform*

For the first set of trials, the machine was operated at a speed near 20 Hz (mechanical speed, which correspond to 1200 rpm), which lies under the main resonance, around 25 Hz. To reach this speed four different adjustments were made, which will be repeated for the other sets of trials:

1) *Voltage control with standard frequency sine wave.*

   Voltage was regulated to reach the chosen mechanical speed, using a 50 Hz 'pure' sine wave.

2) *Voltage-Frequency control on the verge of saturation (slightly under the saturation point)*

   Voltage and frequency were adjusted in order to obtain the set mechanical speed while nearing the saturation point.

3) *Voltage-Frequency control on the verge of saturation (slightly over the saturation point)*

   Voltage is slightly increased in comparison to the previous set of conditions, whilst maintaining the frequency, in order to enter the saturation zone only slightly.

4) *Working in saturation*

   Voltage is increased whilst maintaining the frequency parameters, in order to have the electric machine clearly working in saturation.

Tables I and II sum up the main quantities set and measured for this first set of trials:

Tables I.and II – Main adjustments and measured quantities for the first set of trials

Conditions	Frequency [Hz]	Voltage [V]	Current [A]	Power [W]
1	50	25,5	0,578	12
2	41	60,0	0,633	13
3	41	70,0	0,745	16
4	41	130,0	2,730	92

Conditions	Vibration amplitude	Std. Dev	Average speed [Hz]	Std. Dev
1	9,1645	0,0186	20,6088	0,0047
2	9,0596	0,0190	20,1871	0,0680
3	9,1982	0,01	20,2598	0,0426
4	9,2258	0,0128	20,4002	0,0210

Figures 2 and 3 depict a time plot of the measurements performed in this set of trials, for conditions 2 and 4 (in blue, the keyphasor signal; in red and green, the components for the vibrations amplitude, in cyan and violet, respectively, the supply voltage and stator current (one phase)). Here, mechanical vibrations are measured as an Euclidean distance to two fixed points in orthogonal directions.

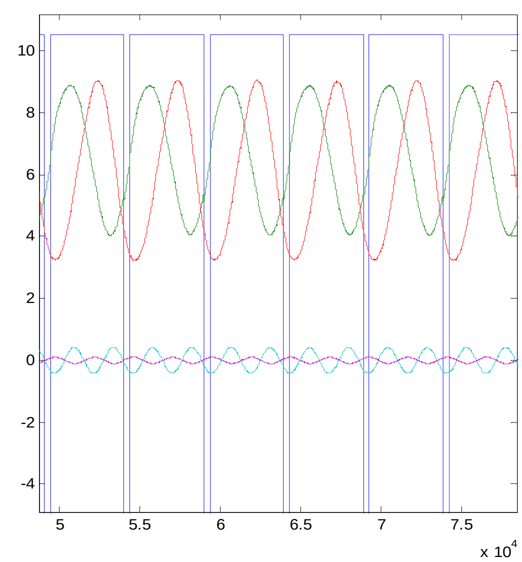

Fig. 2. Time plot of keyphasor, shaft distances, voltage and current signals measured under conditions 2.

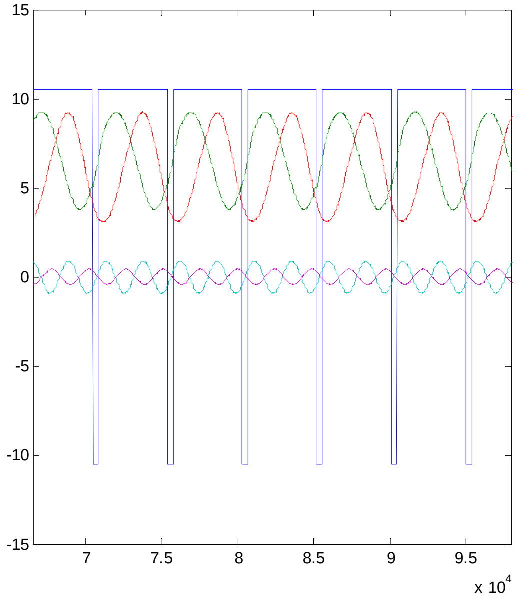

Fig. 3. Time plot of keyphasor, shaft distances, voltage and current signals measured under conditions 4.

From the observation of the figures, as well as from reading the comparative results from the table, it is patent that little difference occurs both in the amplitude of mechanical vibrations and rotation speed due to saturation; as widely expected, most significant is the increase in the current and power consumed, due to increased thermal and other losses.

B. *Mechanical frequency near 20 Hz (under the main harmonic resonance; presence of odd-numbered voltage harmonics*

The set of trials using conditions 1 to 4, as described in the previous subsection, were repeated using a 'polluted' sine waveform for the voltage, in order to study the effects of the presence of harmonics.

Tables III and IV sum up the main quantities set and measured for this second set of trials:

Tables III.and IV – Main adjustments and measured quantities for the second set of trials

Conditions	Frequency [Hz]	Voltage [V]	Current [A]	Power [W]
1	50	27	0,598	12
2	41	60	0,628	13
3	41	70	0,737	15
4	41	130	2,256	69

Conditions	Vibration amplitude	Std. Dev	Average speed [Hz]	Std. Dev
1	9,0706	0,0198	20,1629	0,0502
2	9,0980	0,0165	20,1382	0,0534
3	9,1076	0,0150	20,2281	0,0414
4	9,1371	0,0106	20,387	0,0225

Figures 4 and 5 depict a time plot of the measurements performed in this set of trials, for conditions 2 and 4 (in blue, the keyphasor signal; in red and green, the components for the vibrations amplitude, in cyan and violet, respectively, the supply voltage and stator current (one phase)).

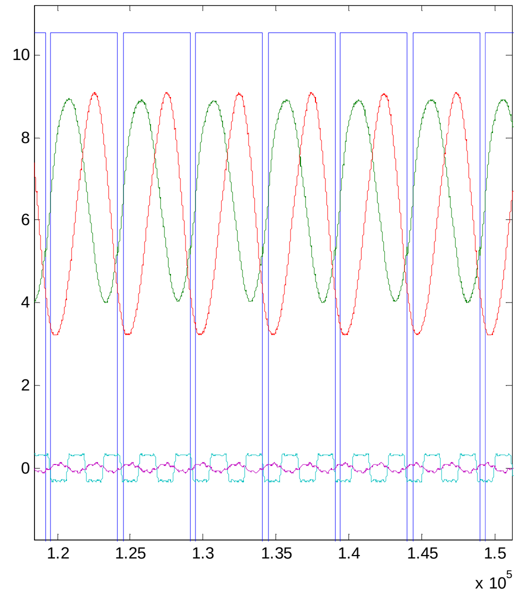

Fig. 4. Time plot of keyphasor, shaft distances, voltage and current signals measured under conditions 2.

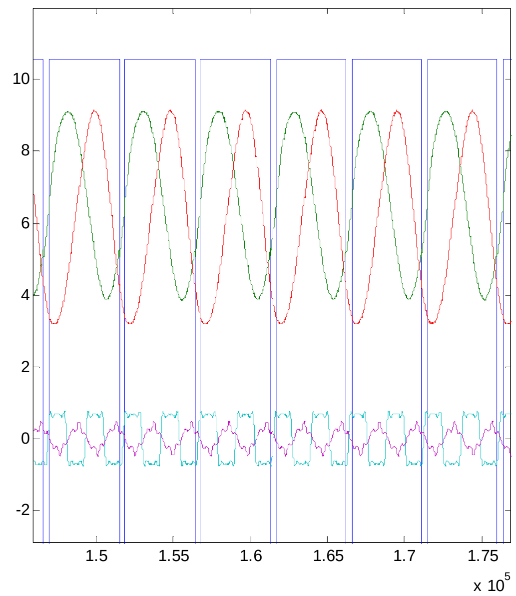

Fig. 5. Time plot of keyphasor, shaft distances, voltage and current signals measured under conditions 4.

Looking at tables III and IV, and figures 4 and 5, it is visible that the presence of harmonics does not change considerably the mechanical vibrations, although rotational speed is slightly lower than the previous set of trials.

In electrical terms, the voltage waveform, polluted with 3^{rd}, 5^{th} and 7^{th} harmonics, is 'filtered' in terms of current, leading to an unsteadier speed, which is visible under conditions 1 in both sets of trials.

The increase in consumed power is even lower in saturation than in the previous set of trials, though this has much to do with the way active power is measured in the presence of harmonics.

4. Conclusions and Outlook

A number of simple trials, some of which are presented in this paper, made it possible to analyse some of the effects of feeding an electric machine with different waveforms and frequencies.

While electrical effects of working a machine in saturation are well known, it is perhaps surprising that little or no mechanical effects are observed, apart from a small difference in the rotational speed.

The use of the saturation characteristic of electromagnetic materials, in this case, is of assistance to help in keeping mechanical speed under control, although not always as constant.

Thus, most of the results obtained here support the use of variable speed drives, or, at least, the use of a near-square waveform, in cases where the mechanical load is adjusted and speed constancy is not a very important issue.

It was also clear during the execution of these trials, that voltage-frequency control brings speed to a setpoint much faster and steadier than mere voltage control.

Future work may include a widening of these studies to further validate the conclusions drawn, as well as thermal and electromagnetic measurement of these effects.

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