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Simulation of the effect of voltage transients on an induction motor with ATP/EMTP

José Gonçalves[1], José Baptista[1], Luís Neves[2,3] and Filipe Tadeu Oliveira[2,3]

[1] Department of Engineering, University of Trás-os-Montes and Alto Douro
5001-801 Vila Real, Apartado 1013, Portugal
Phone: +351 259 350 000, e-mail: jagoncalves@gmail.com

[2] Department of Electrical Engineering, School of Technology and Management, Polytechnic Institute of Leiria
Campus 2 – Morro do Lena – Alto do Vieiro, 2411-901 Leiria, Apartado 4163, Portugal
Phone: +351 244 820 300, e-mails: lneves@estg.ipleiria.pt, ftadeu@estg.ipleiria.pt

[3] Institute for Systems and Computers Engineering at Coimbra
Rua Antero de Quental, Nº199, 3000 - 033 Coimbra, Portugal

Abstract. The present study aims at understanding the behaviour of the induction motor when subject to different kinds of disturbances. The intention was to broaden the study of some disturbances by using a transient simulation software, ATP/EMTP, and comparing results with laboratory measurements. Obtained simulation results approached very closely the laboratory measurements, with small differences probably due to the model simplifying assumptions and uncertainties associated to the model parameter estimation process. However, although this theoretical model presents a response very similar to the actual model, improvements could be made by better modelling of the mechanical load, and by using different kinds of dynamic loads. Also, the use of more accurate laboratory equipment, and namely, programmable power supplies could lead to more accurate comparisons and better learning.

Key words

Power quality, Induction electric machines, Transient behaviour simulation.

1. Introduction

Presently, electricity is one of the fundamental pillars of modern society, widely used by the industrial and tertiary sectors. Due to its own nature, it cannot be stored in large quantities, so its production must be adjusted to consumption at all times. The integration of the production, transmission and distribution systems of the electric grid is therefore decisive to ensure both security of supply (continuity of service) and a number of technical specifications that constitute what may be named as power quality.

Power quality is a relatively recent concept, on which a number of normative acts have been published in recent years. Most of the national normative is composed by European and International Norms, transcribed or adapted to national norms. International/European norm IEC/EN 50160 defines a number of parameters to be observed in electrical networks, setting limits to some of the disturbances that affect the power supply to costumers.

Also, a very significant part of electric loads are electric motors, particularly induction motors. The present work will concentrate on the effects of some power quality disturbances on these machines, both in terms of behaviour and lifetime reduction. It should be highlighted that approximately 80% of all industrial motors are induction machines.

Disturbances effects can be divided into short-term effects (incorrect behaviour of a device, or set of devices) and long-term effects, such as overheating, insulation deterioration and lifetime reduction. Most disturbances studied have both short-term and long-term effects. This paper aims to determine the response of an induction machine, particularly in terms of speed, torque, heating, mechanical vibrations, efficiency, etc.

A number of simulation tools have been developed in the last few years, especially for steady-state simulations. Few algorithms are able to accurately determine the response of a system to a transient; one of these algorithms is EMTP/ATP, which is used in this work. ATPdraw software is here used as an input data interface to the EMTP/ATP engine, allowing the implementation of the model and the application of power quality disturbances and subsequent analysis of the effects. Whenever possible, simulation results were validated by adequate laboratory experiments and conclusions derived.

2. Modelling

In order to accomplish this work, a model of an electric machine and load with a mechanical load was created using the ATPdraw interface software for the ATP/EMTP engine. A number of parameters necessary for this model were obtained through laboratory tests of a 1,1 kW squirrel-cage induction machine, according to IEE std. 112 [5] and inserted in the software, adapting the UM3 universal machine model (Fig. 1).

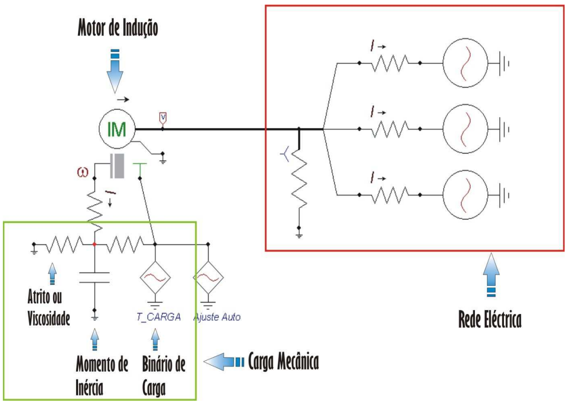


Fig 1. ATP/EMTP model for the induction machine and load

Mechanical load parameters, such as moment of inertia and load torque were added based on their electric equivalent.

Upon completion of the model, adequate validation tests were performed, comparing performances obtained through simulation with actual measurements. Although these tests are beyond the scope of the present papers, results fully validated the model.

3. Simulation of disturbances using ATP/EMTP

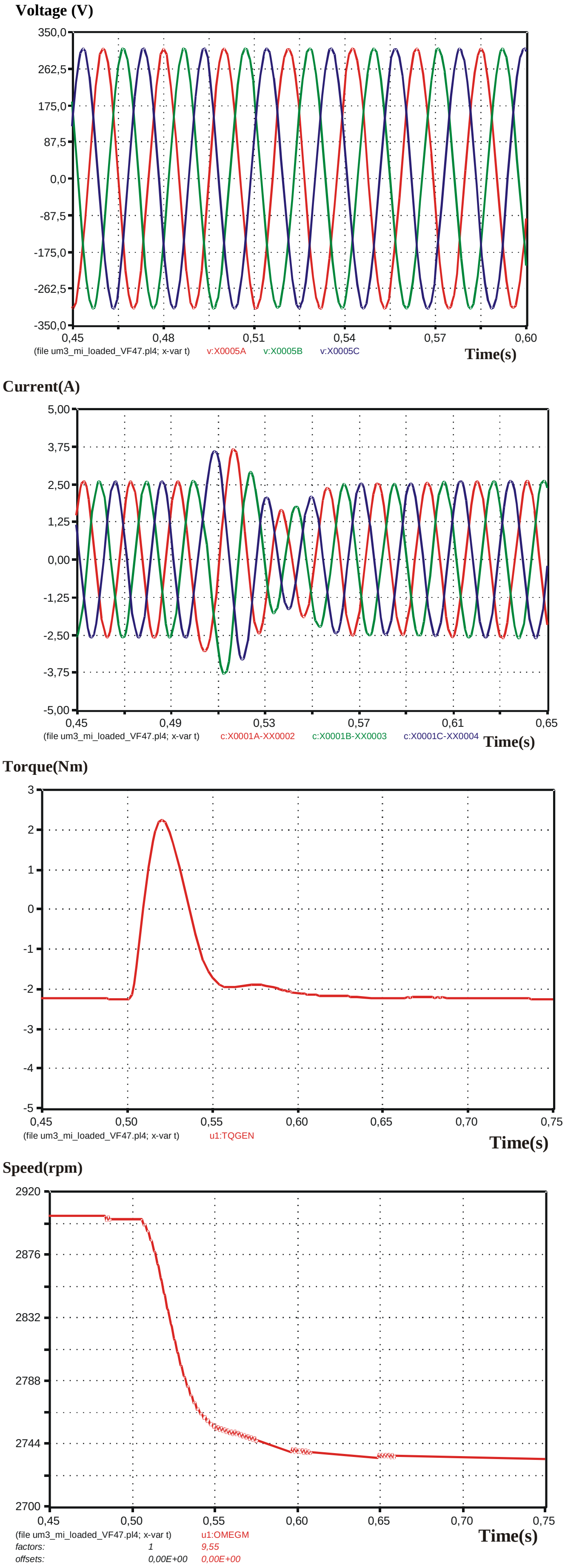
In order to estimate the effect of several power supply disturbances on the behaviour of the electric machine and its load, a number of scenarios was created and the simulation run.

On each scenario a constant mechanical load of 2 Nm was considered, and disturbances were introduced at t=0,5s. Initial slip was simulated at 10%, in order to quickly stabilize the set, since inrush characteristics were not object of study at this instance.

Selected results are presented in the following sub-sections.

A. Frequency variation (F=47 Hz)

For this scenario, the frequency, initially established as 50 Hz, was switched to 47 Hz at t=0,5s. Results are shown below:



Figs. 2A to 2D. Voltage, current , torque and rotating speed response for frequency variation - 47 Hz

Results confirm that, after a short transient, speed stabilizes at a lower value, whereas torque, after a transient, stabilizes around the same value. There is also a slight current peak, which is different for each of the phases.

Table I shows the results for more instances of the simulation, with data retrieved from the charts:

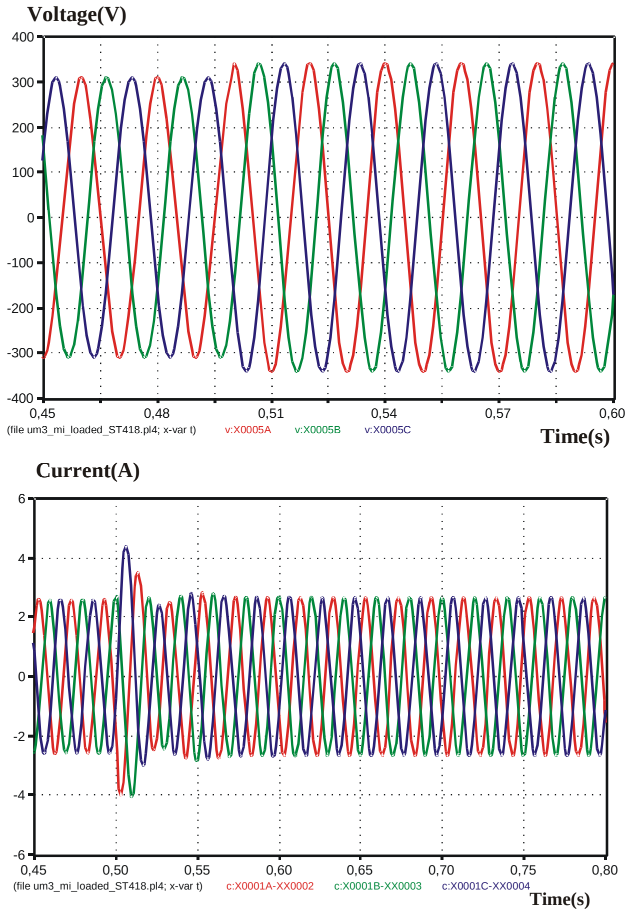
TABLE I. – Frequency variation – simulation results

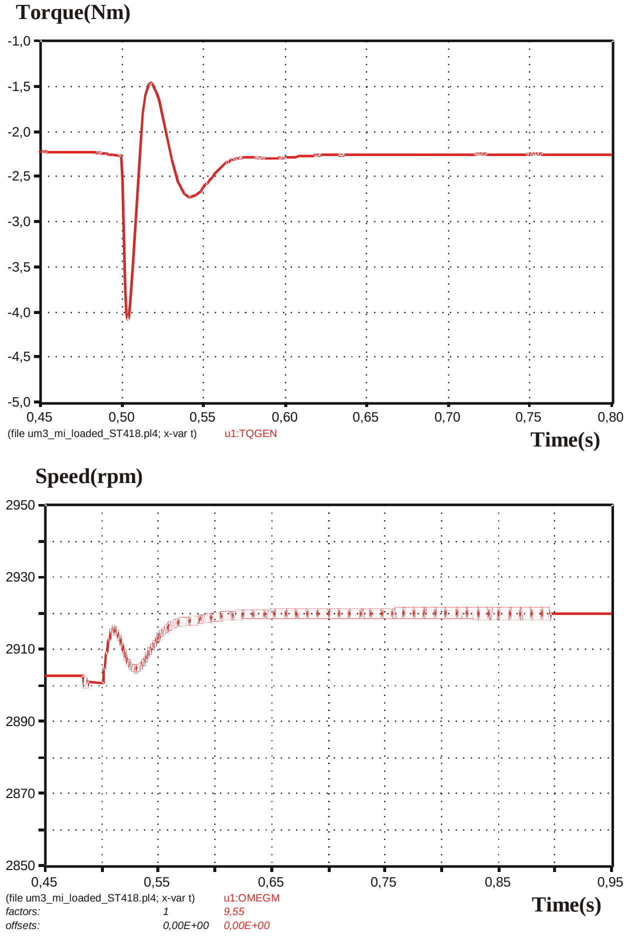
	50Hz	40Hz		47Hz		57,5Hz		60Hz	
	Stable	Stable	Peak	Stable	Peak	Stable	Peak	Stable	Peak
U [V]	309,8	310,0	-	310,0	-	309,9	-	310,0	-
I [A]	2,61	2,81	-11,5	2,63	-3,8	2,64	-8,32	2,66	-10,07
T [Nm]	-2,27	-2,22	18,8	-2,27	2,25	-2,29	-7,6	-2,3	-7,95
Vel. [rpm]	2902	2339	2244	2733	-	3315	-	3452	-

Results of simulation with both lower and higher frequencies show values consistent with those obtained for the 47 Hz test, with speed strongly dependent on frequency and torque mostly invariant after a small transient.

B. *Voltage surges/Overvoltages*

For this scenario a number of surges and overvoltages were simulated; the main results for a 10% overvoltage are shown below:





Figs. 3A to 3D. Voltage, current , torque and rotating speed response for a 3-phase 10% overvoltage

As depicted in figures 3A to 3D, the current stabilizes on a higher value, after a short transient. This may represent a slight overcurrent, which can cause long-term consequences such as lifetime reduction.

The torque presents a transient, but then stabilizes around the same value as before, due to the nature of the load. Speed, on the other hand, is increased due to the fact that the mechanical power is increased, and load torque is maintained.

Table II summarizes results obtained for further simulations:

TABLE II. – Overvoltages – simulation results

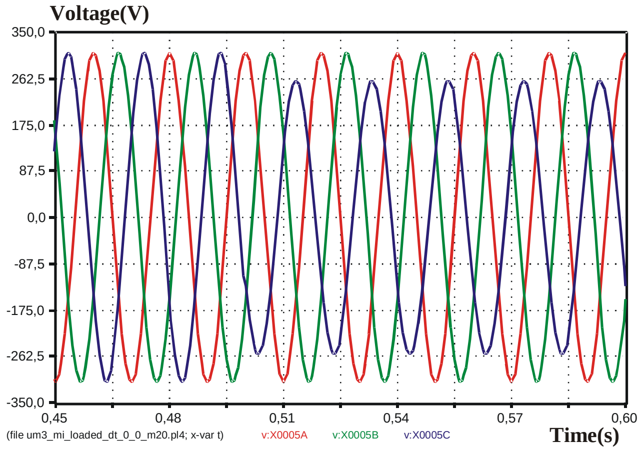
Surge	**380V**	**418V**		**437V**	
	Stable	**Stable**	**Peak**	**Stable**	**Peak**
I [A]	2,61	2,67	4,43	2,72	5,33
T [Nm]	-2,27	-2,26	-4,1	2,25	-5
Vel.[rpm]	2902	2920	2916	2928	2922

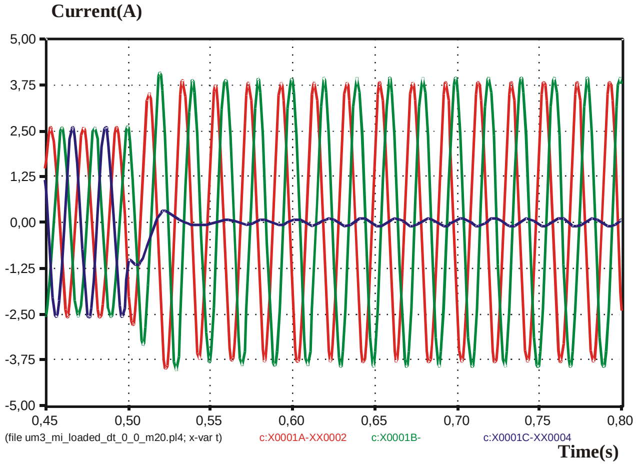
As the voltage is increased, so is the speed, although the synchronous speed (3000 rpm for 50 Hz, 2 poles) is not reached, due to the intrinsic characteristics of the induction machine.

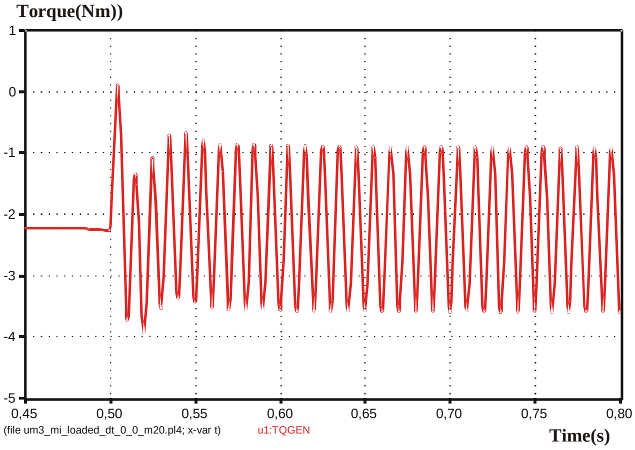
C. Voltage unbalance

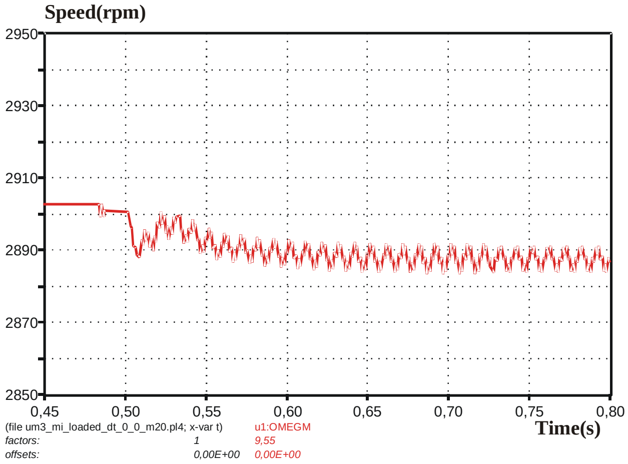
In most situations, unbalance is actually caused by the load itself, or by its connection. However, network voltage unbalance can also occur.

For this simulation, a one-phase (T,-20%) unbalance was introduced and the following figures depict the results:









Figs. 4A to 4D. Voltage, current , torque and rotating speed response for a 20% voltage unbalance

It is patent that the voltage unbalanced is "amplified" in the currents, showing a strong impact on the phase with 20% lower voltage, with a very low current. In the other two phases, demanded current is higher than beforethe disturbance.

The torque is also severely affected, turning into a pulsating torque centred around the previously stable torque. This, associated with the consequent fluctuations of speed, can be have serious consequences in terms of vibrations, noise, wear of mechanical components and lifetime reduction.

Table III summarizes the results for other trials:

TABLE III. – Unbalance – simulation results

		Stable			Scenario 1			Scenario 2		
		R	S	T	R	S	T	R	S	T
Voltage unbalance		0%	0%	0%	0%	0%	-10%	20%	-10%	-10%
U [V]		310	310	310	310	310	282	372	282	282
I [A]		2,6	2,61	2,61	3,26	3,32	1,21	7,07	0,65	0,65
T [Nm]	Stable	-2,27			-2,25			-2,25		
	ΔT	0			1,5			5,05		
Speed [rpm]	Stable	2902			2895			2897		
	Δrpm	0			5			13		
		Scenario 3			Scenario 4			Scenario 5		
		R	S	T	R	S	T	R	S	T
Voltage Unbalance		0%	0%	-20%	0%	-10%	-10%	0%	-20%	-20%
U [V]		310	310	258	310	282	282	310	258	258
I [A]		3,82	3,95	0,11	3,99	1,94	1,87	5,16	1,47	1,27
T [Nm]	Stable	-2,28			-2,3			-2,28		
	ΔT	2,69			1,46			2,5		
Speed [rpm]	Stable	2885			2888			2875		
	Δrpm	7			5			8		

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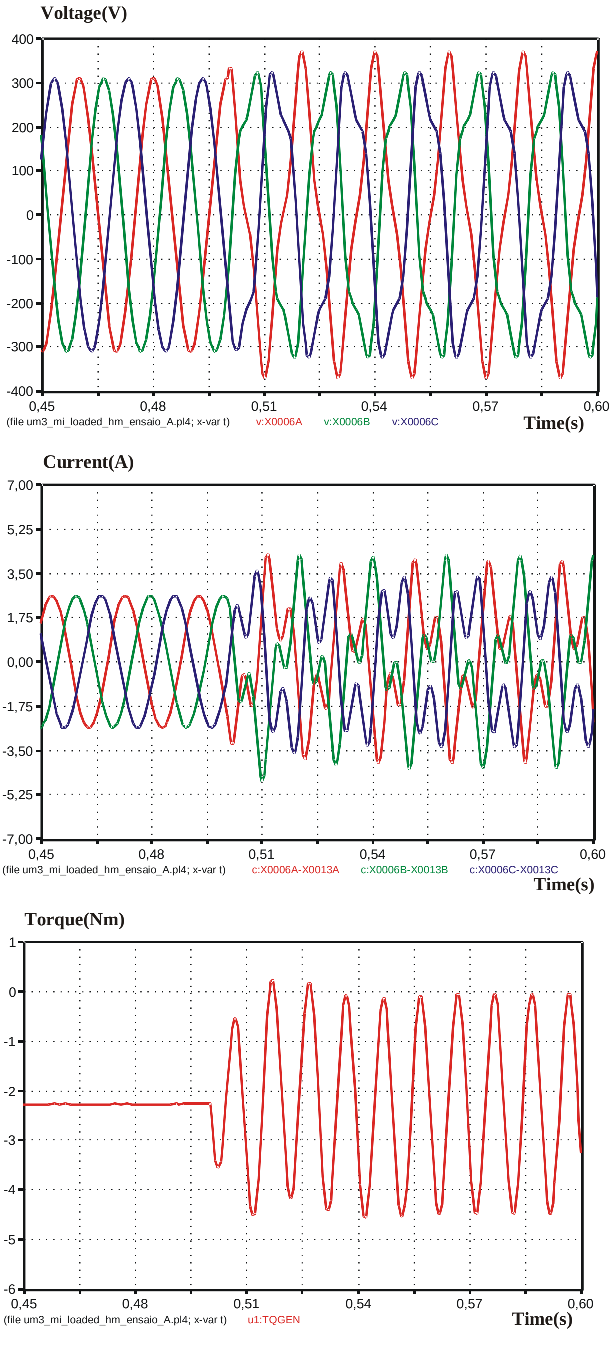
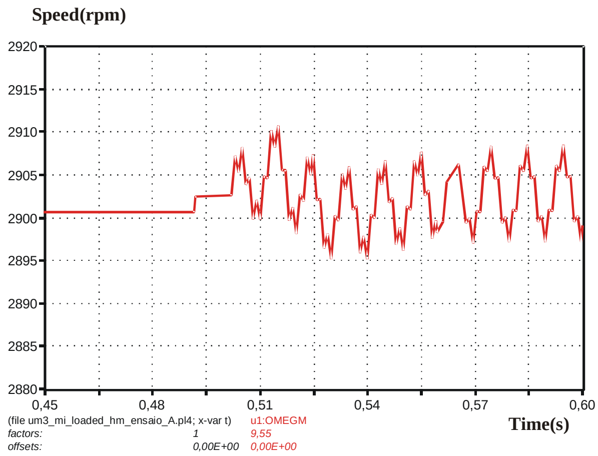
From table III one can conclude that, before a voltage unbalance, the motor produces a pulsating torque, with both electrical and mechanical consequences, whice are more severe for bigger unbalances. In most of the scenarios tested, the nominal current of the motor is exceeded.

Also, it is possible to conclude that mechanical effects depend most on the magnitude of the unbalance, whereas electrical effects are more affected by the number of phases unbalanced.

C. Harmonics

For this simulation, a scenario with a 20% 3rd harmonic was selected:





Figs. 5A to 5D. Voltage, current , torque and rotating speed response for a 20% 3rd harmonic

It is visible that the introduction of a single harmonic(3rd) causes the torque and the speed to pulsate. It is also clear that, although pulsating, the torque maintains its mean value, whereas the speed mean value changes slightly.

Table IV summarizes the results for other trials:

TABLE IV. – Harmonics – simulation results

Scenario		**Average**	**Variation**	
			Range	**Ampl. Δ**
Stable	**Torque**	-2,27	-	-
	Speed	2902	-	-
Scenario A – 3.º H=20%	**Torque**	-2,26	[-0,04;-4,46]	4,42
	Speed	2903	[2903;2897]	6
Scenario B – 5.º H=20%	**Torque**	-2,25	[-0,87;-3,63]	2,76
	Speed	2902	[2903;2900]	3
Scenario C – 3.º H=20% ; 5.º H=10%	**Torque**	-2,26	[-0,07;-5,05]	4,98
	Speed	2903	[2903;2897]	6
Scenario D – 3.º H=20% ; 5.º H=15% ; 7.º H=10%	**Torque**	-2,26	[-0,03;-5,73]	5,7
	Speed	2903	[2906;2897]	9
Scenario E – 5.º H=20% ; 7.º H=10%	**Torque**	-2,25	[-0,63;-4,06]	3,43
	Speed	2901	[2905;2900]	5
Scenario F – 5.º H=10% ; 7.º H=5% ; 19.º H=3% ; 23.º H=3%	**Torque**	-2,25	[-1,43;-3,14]	1,71
	Speed	2902	[2903;2899]	4
Scenario G – 3.º H=20% ; 5.º H=10% ; 7.º H=5% ; 19.º H=3% ; 21.º H=3% ; 23.º H=3%	**Torque**	-2,26	[-0,25;-5,15]	4,9
	Speed	2903	[2908;2897]	11
Scenario H – 5 Hz = 3% ; 10 Hz = 5% ; 15 Hz = 3%	**Torque**	-2,26	[4,29;-7,82]	12,11
	Speed	2889	[2916;2842]	74

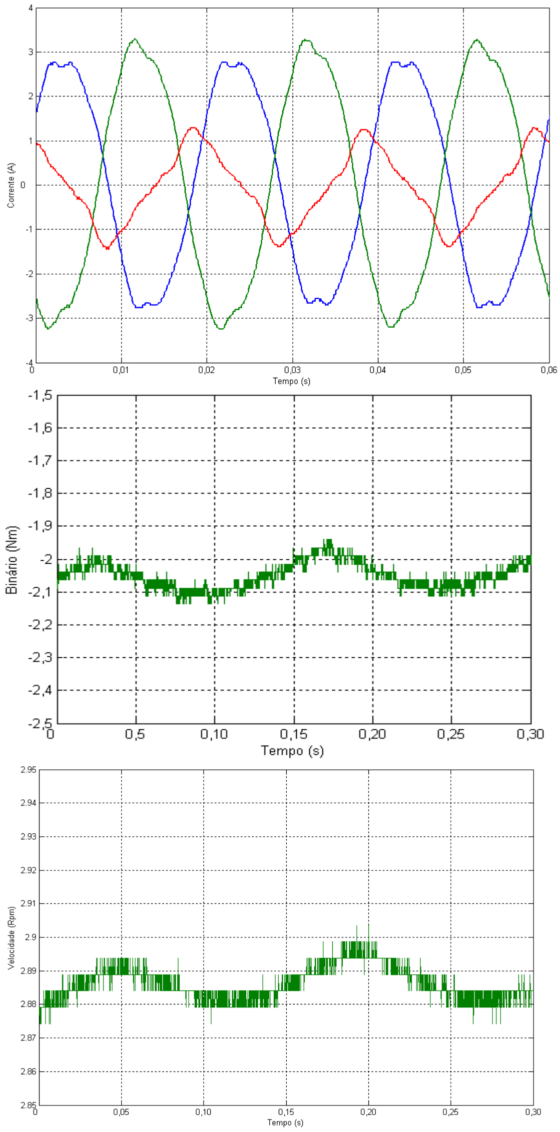
The values in table IV further show and reinforce the previous remarks, and confirms that in every case harmonic introduction caused pulsating torque and speed Also, higher current levels represent higher losses, and consequently heating and lower lifetime for the motor.

One indirect remark on the subject is that the Total Harmonic Distortion (THD) is not a particularly useful index where losses and other effects are considered.

4. Comparison with results from laboratory trials

The machine model had already been fully tested and validated through laboratory trials in what concerts steady-state behaviour. At this point, a comparison between simulation results and lab results for the disturbances considered was performed.

Although a full comparative analysis is beyond the scope of this paper, it can be stated that laboratory trials confirm the machine behaviour predicted by simulation, with some differences in value that do not change the main conclusions.



Figs. 6A to 6C. Current , torque and rotating speed response for a 20% voltage unbalance

In order to obtain laboratory measurements of the simulated quantities, a set of an induction machine, an electromagnetic brake and an active programmable power source were assembled. The induction machine used was the same taken as a reference for the simulation, and the brake has reference-purpose torque and speed sensors. The power source is a California Instruments three-phase, 15kVA fully wave-programmable power source.

As an example, figs. 6A to 6C depict the actual measured response of a laboratory set of electric motor+ electromagnetic load set to simulate a mechanical load, and can be compared with figures 4B to 4D.

Although the waveforms are similar, the difference in obtained values for torque is evident. Apart from questions like precision, the most likely reason for the discrepancies is the fact that an electromagnetic brake was used to emulate a mechanical load.

Despite the fact that a mechanical load and an adequately set electromagnetic brake have a similar behaviour in steady-state, before transients the brake has a more “damped” response, even when the internal PID controller is inactive and the brake control is in open-loop.

Another source for differences between results obtained is saturation. Even vey detailed electromagnetic transient models of electric machines are often less accurate when near the saturation part of the magnetization curve.

5. Conclusions and Outlook

The present work enabled the authors to verify the behaviour of a standard induction motor before a number of common electric disturbances.

The increasing level of power quality disturbances can have considerable effects on the behaviour of electric machines, their loads and the lifetime of both, with the respective financial consequences. Incorrect behaviour of some equipments and increased losses are also consequences of poor power quality.

In spite of the discrepancies found between some of the obtained values, the behaviour trend of the machine, as obtained through simulation, was confirmed by the laboratory tests performed. Also, results are consistent with the mainstream references on this subject.

The developed model provided an adequate basis for the study of these disturbances, applied to a standard mechanical load. Future enhancements of the model should be able to accommodate more detailed, complex mechanical loads, as well as a more accurate measurement system

In order to further study and compare the lab results with those obtained through simulation, actual mechanical loads should be considered, and their parameters very accurately determined.

Future work can also include a wider range of electric machines, disturbances, and more precise measuring instruments, specially for mechanical torque.

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