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Comparative Evaluation between Theoretical Models for Three-Phase Induction Motor under Voltage Unbalance

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Abstract. This article presents the results of a comparative evaluation between representing models of three-phase induction motor (TIM) in frequency domain, time domain and by artificial neural networks obtained with laboratory tests. For this, it was studied torque and efficiency of a 1 HP motor under several situations of voltage unbalance. Considering that due to high volume of conditions involved in a study of the performance behavior of the TIM subjected to unbalances often appeal to computer simulations, it can be characterize the present study as essential to select the most appropriate tool which allows results closer to those acquired in practice.

Key words

Three-Phase Induction Motor, Voltage Unbalance, Time Domain Model, Frequency Domain Model, Artificial Neural Networks Model.

1. Introduction

Each time more research institutions, energy utilities and consumers are more concerned about power quality. This growing interest justifies the increase of the developed works about the subject. These studies, in general, aim to improve required standards for proper functioning of electrical equipment, as well as the knowledge of its behavior when supplied by improper voltage source.

Among the possible problems in the supply of electricity, it can cite the voltage unbalance. About this phenomenon, many specialists have embarked efforts regarding the influence of this phenomenon on behavior of the torque and efficiency of the motor [1]-[6]. In these publications, one of the aspects of the mentioned phenomenon that has intensified studies in the area is that numerous combinations of voltages result in the same value of factor unbalance [7]. In this case, for achieving reliable results, it is required a high number of voltage combinations to be investigated, which inhibits studies only in laboratory. To overcome this limitation, almost always computer simulations are employed. In order to not compromise the results, it is essential a careful selection of a model for representing the machine.

Based on the aforementioned considerations, the motivation for developing this work came up, which presents a comparative evaluation between the theoretical modeling commonly found in the current literature for representation of the TIM, namely:

1) Time domain model: [8]-[9];
2) Frequency domain model: [7],[9]-[11]; and
3) Artificial neural networks (ANN): [12]-[15].

Initially, this work shows the concepts related to voltage unbalance. After, the theoretical assumptions and the methodology applied in the research are presented.

Having a selection of numerous combinations of unbalanced voltages, it can be obtained the corresponding experimental and computational results. Comparing the acquired computational and experimental results, it is calculated the discrepancies resulting from use of each model. This makes possible the identification of the most appropriate model for analysis of the performance of the TIM when its voltage source is unbalanced.

2. Voltage Unbalance

Voltage unbalance is defined as any situation where voltage phasors have different magnitudes from each other, or lag angles are different from 120 electrical degrees between them or both situations [16].

In this work, the index of voltage unbalance, VUF (Voltage Unbalance Factor) is calculated by symmetrical components method. Analytically, symmetrical components are defined by the Fortescue matrix, shown in (1).

$$\begin{bmatrix} \overline{V_A} \\ \overline{V_B} \\ \overline{V_C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} \overline{V_0} \\ \overline{V_1} \\ \overline{V_2} \end{bmatrix} \qquad (1)$$

Where:
- a is the rotational operator, whose magnitude is equal to one and its angle is 120º;
- $\overline{V_A}$ is the voltage phasor in phase A;
- $\overline{V_B}$ is the voltage phasor in phase B;
- $\overline{V_C}$ is the voltage phasor in phase C;
- $\overline{V_0}$ is the zero sequence component voltage;
- $\overline{V_1}$ is the positive sequence voltage; and
- $\overline{V_2}$ is the negative sequence voltage.

Based on this method, Brazilian Electricity Regulatory Agency (ANEEL) sets the unbalance factor as (2) and also determines that the reference value in the distribution system buses, except for low voltage, must be equal or less than 2% [17].

$$VUF = \frac{\overline{V_2}}{\overline{V_1}} * 100\% \qquad (2)$$

Voltage unbalance has basically two origins: one related to the structure of the grid and other related to the load [15].

The unbalance related to the structure is caused by asymmetry of the electrical system at the level of transmission and distribution. The lack of transmission lines transposition and the presence of unbalanced transformers and unbalanced capacitor banks are examples of causers of the aforementioned disturbance. Due to the small variation of the system parameters this type of cause is practically constant.

The unbalance related to nature of load depends of the operating characteristics of customers. In this situation, the existent inequality between phase voltages occurs due to some factors, for example: presence of unbalanced three-phase loads, bad single-phase load distribution and variation on demand cycles of each phase.

On the induction motor, voltage unbalance creates a torque with opposition to the movement of the rotor, which in addition to the natural torque, culminates in a pulsing torque on the axis of the machine. Thus, there is reduction on the speed and on the resulting torque and increase of the losses and the temperature of the motor. In this context, it can be observed the wear of the mechanical elements of the machine and, consequently, the lifetime reduction of the TIM.

3. Models of the TIM

In this study, three models are used for analysis of the behavior of the TIM, namely: time domain model, frequency domain model and by artificial neural networks (ANN). The choice of these models is due to their wide acceptance in the power community.

The computational tool named Matlab/Simulink is used for time domain model execution. This modeling employs in its calculations the Park transformation.

Frequency domain model and by ANN are developed in Matlab script. For frequency domain modeling it is determined the equivalent circuits of the TIM. Referring to the ANN modeling, the toolbox of artificial neural networks contained in Matlab is applied.

A. Time domain modeling

By differential equations, the time domain modeling makes viable the achievement of electrical and mechanical parameters that rule the behavior of the motor over time. Thereby, studies related to dynamic behavior of the machine becomes feasible.

The present model, which adopts the software Matlab/Simulink for developing the time modeling study, was created with a TIM connected to a direct current generator (DCG) in order to obtain the torque and the efficiency of a squirrel-cage induction motor.

The parameters for the simulation of the TIM and the DCG are shown in Table I.

Table I. – Required parameters for simulation in time domain model

Machine	Parameter	Value
TIM	Nominal power [VA]	1155
	Line-line voltage [V]	220
	Frequency [Hz]	60
	Stator resistance [Ω]	4.822
	Rotor resistance[Ω]	1.845
	Stator inductance [Ω]	0.878
	Rotor inductance[Ω]	0.448
	Mutual inductance [H]	0.161
	Number of poles	4
DCG	Armature resistance [Ω]	4.143
	Armature inductance [H]	0.018
	Field resistance [Ω]	212.700
	Field resistance [H]	17.200
	Mutual inductance [H]	1.358

B. Frequency domain modeling

This is the most classical strategy for representing the induction motor [12]. Such modeling allows the machine behavior emulation by equivalent circuits when in steady-state.

In this strategy, when a TIM is subjected to unbalanced voltages, two equivalent circuits are employed: the first associated to the positive sequence voltage, presented in Figure 4, and the second related to the negative sequence voltage, exposed in Figure 5.

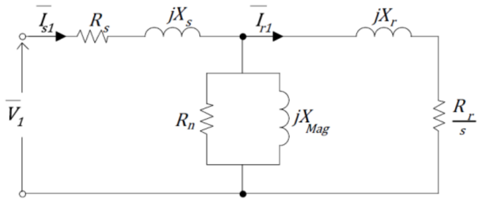

Figure 4. Positive sequence equivalent circuit.

Where:

- $\overline{V}_1$ is the positive sequence voltage;
- R_s and X_s are the resistance and reactance per phase of the stator, respectively;
- R_n and X_{mag} are the resistance and reactance per phase of the core, respectively;
- R_r and X_r are the resistance and reactance per phase of the rotor, respectively;
- s is the slip; and
- I_{s1} and I_{r1} are the positive sequence current of the stator and the rotor, respectively.

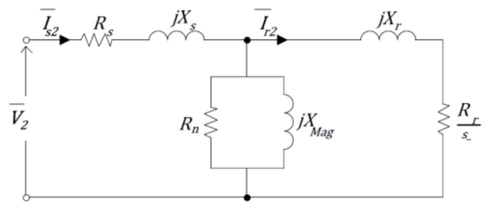

Figure 5. Negative sequence equivalent circuit

Where:

- $\overline{V}_2$ is the negative sequence voltage;
- I_{s2} and I_{r2} are the negative sequence currents of the stator and the rotor, respectively; and
- s_- is the slip of negative sequence, defined in (2).

$$s_- = 2 - s \tag{2}$$

Analyzes employing the frequency domain model, for conditions where there are unbalanced voltages, is performed by superposition of effects generated by positive and negative sequence voltages. In practice, the positive sequence voltage induces a rotating magnetic field in a direction and negative sequence voltage produces, in the stator, currents with reverse sequence which induces an opposite rotating magnetic field.

Regarding the effects of the zero sequence, these are not meaningful for torque, since parallel phasor voltages does not generate rotating magnetic field and, therefore, they do not develop torque [18]. Generally, also there is no way for circulating the zero sequence current in the machine, once the motors are often connected in triangle or ungrounded wye.

C. Artificial Neural Networks Modeling

The ANN system adopted in this work has four networks in total, namely: starting torque, maximum torque, full-load torque, and efficiency. Their type is multilayer perceptron with backpropagation error.

For the structure composition of the ANN, acquisition of the parameters is realized by 163 laboratory experiments. In each of these situations, torque and efficiency of the motor are acquired. Thereby, it is possible to verify the corresponding behavior of each parameter analyzed.

The inputs for the ANN modeling are the line voltage magnitudes and the outputs are torque efficiency of the TIM. In this research, 130 voltage combinations are admitted for training of the ANN and 33 for verification.

4. Methodology

The simulations and tests proposed in this item aimed to identify the discrepancies between theoretical models and results obtained through laboratory experiments. For this investigation, it was selected the interval of VUF between 0% and 4% and line voltage range of 201-231 V with nominal angles in phase voltages. The choice of this voltage range is due to ANEEL, which establishes as acceptable the aforementioned levels of voltage for a system with nominal voltage equal to 220 V [17].

The simulated and tested motor has the following parameters, provided by the manufacturer: 1 HP, 220/380 V, 4 poles, 60 Hz, 1730 rpm, rated torque equal to 4.10 N.m and rated current equal to 2.98 A. The equivalent circuit parameters are the same as shown in Table I.

In laboratory tests, the TIM was connected to a DCG. By determining the load of this generator, it was possible to adjust the TIM to work in nominal condition. In this situation, the following parameters were measured: starting torque equal to 11.4 N.m, maximum torque equal to 11.0 N.m and full-load torque equal to 4.1 N.m. However, measuring the efficiency was not directly; it was calculated based on the value of output and input power. Thereby, in nominal condition, the efficiency was 71.5%.

5. Comparative Evaluation

In this section, experimental and computational results are shown. In order to compare the experimental values of torque and efficiency with those obtained by ANN, frequency and time domain models, 33 voltage combinations are chosen. In Figures 3, 4 and 5 the results obtained for starting torque, maximum torque and full-load torque, respectively, are shown. These figures are in percentage of rated torque of the TIM.

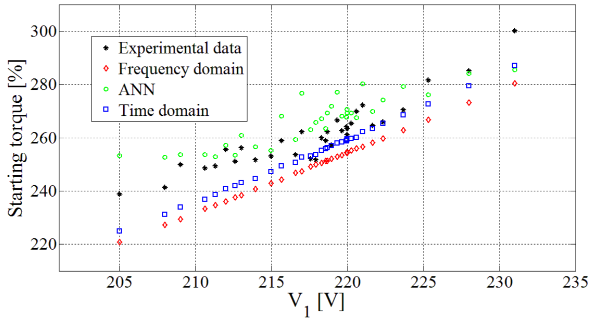

Fig. 3 – Starting torque in relation to V_1

It can be observed in Figure 3 linearity between the behavior of starting torque and the value of positive sequence voltage, especially in relation to results of frequency and time domain models. It is noted a high correlation between frequency and time domain models. Most of experimental results have larger values than those obtained by these two modeling. It is verified, furthermore, the attempt to approximate results generated by ANN with experimental values.

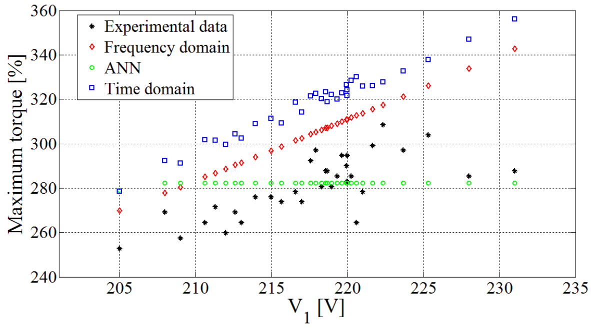

Fig. 4 – Maximum torque in relation to V_1

As shown in Figure 3, it can be seen in Figure 4 a high correlation between values obtained by frequency and time domain models. It is identified in Figure 4 a straight line with null slope formed by results obtained with ANN. This is due to the dispersion of experimental values. Also, considerable differences are observed for the three modeling.

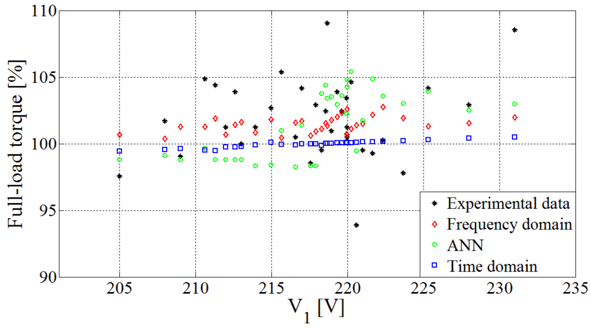

Fig. 5 – Full-load torque in relation to V_1

It can be observed from Figure 5, when specifying V_1, a greater variation on the experimental results in comparison with the computational ones. Furthermore, results obtained by ANN modeling shows that their behavior have significantly varied in function of V_1. The full-load torque determined by frequency and time domain modeling tends to increase with the elevation of V_1. It can be seen in Figure 5 changes with levels approximately of 15% in full-load torque by experimental results, while time domain model indicates a change of approximately 1%.

Figure 6 shows the results obtained for efficiency of TIM.

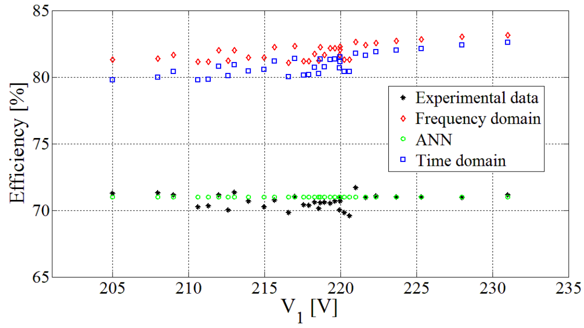

Fig. 6 – Efficiency in relation to V_1

In Figure 6, considerable differences are verified between efficiency obtained from simulations in frequency and time domain models with respect to those acquired experimentally and by ANN modeling. It can be noted that results obtained in frequency and time domain models are closer to values declared by the manufacturer (around 80%). However, laboratory experiments and ANN modeling, which was trained and validated with laboratory tests, provided efficiency close to 70%.

Table II presents the average errors compared to experimental values, acquired by the studied models. Also, standard deviations obtained by the modeling for each parameter are shown.

Table II. – Average error and standard deviation between simulated and experimental parameters.

Parameter	Model	Average Error (%)	Standard Deviation (%)
Starting torque	Frequency domain	4.45	5.04
	Time domain	2.72	5.17
	ANN	2.74	3.54
Maximum torque	Frequency domain	8.45	5.04
	Time domain	13.22	4.92
	ANN	4.00	0.20
Full-load torque	Frequency domain	2.43	0.59
	Time domain	2.70	0.25
	ANN	2.93	2.40
Efficiency	Frequency domain	15.86	0.73
	Time domain	14.48	0.96
	ANN	0.65	0.00

From Table II and considering the starting torque, it can be verified that smaller average errors for this parameter are obtained by time domain and ANN modeling.

Starting torque provided by frequency domain modeling achieves average errors close to 4%. This percentage is around 60% higher compared to errors assigned by the other two models, which are close to 2.7%. Investigating the standard deviations for the aforementioned torque, ANN modeling has the lowest value (around 3.5%) while the other two models provide standard deviations near to 5%.

Additionally, in relation to maximum torque, it is observed the lowest average error equal to 4% for ANN modeling while frequency and time domain models exhibit average errors of 8.45% and 13.22%, respectively. As observed for starting torque, the standard deviation obtained by ANN model for maximum torque is almost zero, while the remaining two are around 5%. These results are provoked by high dispersion found in experimental results.

For full-load torque, the three modeling present maximum average error around 3%. However, in relation to standard deviations, the ANN model has obtained a value close to 2% and values less than 1% are found for frequency and time domain models.

For efficiency, large discrepancies are noted between average errors obtained by frequency and time domain models in respect to those found by ANN modeling. The average errors for frequency and time domain modeling are around twenty times greater than the results obtained by the simulation in ANN model, which has obtained average error and standard deviation less than 1%.

6. Conclusions

This paper presented theoretical and experimental results for the performance of a three-phase induction motor supplied with different conditions of voltage unbalance. Three theoretical modeling with wide acceptance in power community were employed in this research, namely: time domain model, frequency domain model and ANN model.

Results of laboratory experiments were adopted as reference for comparative evaluation between the models. Discrepancies in the order of 13% for maximum torque and of 16% for efficiency were observed when analyzing the theoretical results obtained by frequency and time domain models, respectively. It was verified that the model developed in time domain has greater fidelity to practical results when dealing with full-load torque.

As noticed, experimental values for efficiency had discrepancies around 15% and 16% compared to results found by time and frequency domain models. Such differences are due to the fact that results obtained by these models are closer to the ones furnished by the manufacturer. Moreover, efficiency values found by ANN proved to be close to those obtained experimentally.

From analyzes performed in this study, ANN modeling proved to be more reliable for the behavior performance of the TIM in three of four parameters investigated: maximum torque, full-load torque and efficiency.

References

[1] C. Y. Lee, B. K. Chen, W. J. Lee and Y. F. Hsu, “Effects of Various Voltages on the Operation Performance of an Induction Motor under the Same Unbalance Factor Condition”, In: Industrial and Commercial Power Systems Technical Conference (1997), pp. 51–59.

[2] Y. J. Wang, “Analysis of Effects of Three-Phase Voltage Unbalance on Induction Motors with Emphasis on the Angle of the Complex Voltage Unbalance Factor”, In: IEEE Power Engineering Review (2001), vol. 21, no. 9, pp. 270–275.

[3] A. Siddique, G. S. Yadava and B. Singh, “Effect of Voltage Unbalance on Induction Motors”, In: Conference Record of the 2004 IEEE International Symposium on Electrical Insulation, Indianapolis (2004), pp.26-29.

[4] P. G. Kini and R. C. Bansal, “A Novel Approach Toward Interpretation and Application of Voltage Unbalance Factor”, In: IEEE Transactions on Industrial Electronics (2007), vol. 54, no 4, pp. 2315–2322.

[5] P. G. Kini and R. C. Bansal, “Effect of Voltage and Load Variations on Efficiencies of a Motor-Pump System”, In: IEEE Transactions on Energy Conversion (2010), vol. 25, no 2, pp. 287–292.

[6] M. Anwari and A. Hiendro, “New Unbalance Factor for Estimating Performance of a Three-Phase Induction Motor With Under- and Overvoltage Unbalance”, In: IEEE Transactions on Energy Conversion (2010), vol. 25, no 3, pp. 619–625.

[7] J. Faiz, H. Ebrahimpour and P. Pillay, “Influence of Unbalanced Voltage on the Steady-State Performance of a Three-Phase Squirrel-Cage Induction Motor”, In: IEEE Transactions on Energy Conversion (2004), vol. 19, no. 4, pp. 657–662.

[8] O. C. N. Souto, J. C. de Oliveira, J. H. Vilela and L. M. Neto, “Efeitos da Qualidade da Energia Elétrica sobre a Operação de Motores de Indução Trifásicos”, In: II Brazilian Conference about Power Quality, São Lourenço (1997).

[9] J. Pedra, “Estimation of typical squirrel-cage induction motor parameters for dynamic performance simulation”, In: IEE Proceedings – Generation, Transmission and Distribution (2006), vol. 153, no 2, pp. 137–146.

[10] J. Pedra, “On the Determination of Induction Motor Parameters From Manufacturer Data for Electromagnetic”, In: IEEE Transactions on Power Systems (2008), vol. 23, no 4., pp. 1709–1718.

[11] O. C. N. Souto, “Modelagem e Análise do Desempenho Térmico de Motores de Indução Sob Condições Não Ideais de Alimentação”, PhD Thesis, Faculty of Electrical Engineering, Uberlândia, Brazil (2001), pp. 323.

[12] A. Goedtel, “Estimativa de torque de carga aplicado em eixos de motores de indução trifásicos através de redes neurais artificiais”, Dissertation, Faculty of Engineering, University of São Paulo, Bauru, Brazil (2003), pp. 141.

[13] A. Goedtel, I. N. da Silva, P. J. A. Serni, “Uma abordagem neural para estimativa de torque em motores de indução”, In: Journal Control & Automation (2006), vol.17, no. 3, pp. 364–380.

[14] A. Goedtel, “Estimador Neural de Velocidade Para Motores de Indução Trifásicos”, PhD Thesis, School of Engineering of São Carlos, University of São Paulo, São Carlos, Brazil (2007), pp. 159.

[15] J. M. Matos, “Avaliação dos Efeitos do Desequilíbrio de Tensão Sobre os Motores de Indução Trifásicos”, Graduate work, Faculty of Technology, University of Brasília, Brazil (2012), pp. 79.

[16] A. L. Ferreira, “Análise do Comportamento do Fator de Desequilíbrio Frente a Variação da Amplitude e do Ângulo

da Tensão", PhD Thesis, Faculty of Technology, University of Brasília, Brasília, Brazil (2008), pp. 163.
[17]ANEEL. "Proceedings of Distribution of Electrical Energy in the National Electrical System – PRODIST; Module 8 – Power Quality", Brasília, Brazil (2012), p. 30.
[18] I. BARBI,. "Teoria Fundamental do Motor de Indução", UFSC Publisher, Florianópolis, Brazil (1985), pp. 220.