A universal model of three-phase asynchronous motors for electrical power system analysis

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ABSTRACT

The high incidence of three-phase asynchronous motors (TAM) in global energy consumption and its influence on the operation of electrical systems makes it necessary to develop models that allow their analysis effectively. Based on this, this paper presents a universal model of TAM based on the relationship between the active and reactive power of the TAM and the deviation of voltage and frequency. It can be applied to any general-purpose TAM and is very useful when representing these motors in electrical power system studies. The model parameters were obtained from a statistical analysis performed on 70 TAM of different classifications. The results are validated by comparing them with those obtained from the solution of the equivalent circuit, demonstrating its validity by less than 6% errors.

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1. INTRODUCTION

Three-phase asynchronous motors (TAM) are one of the main components of electrical power systems [1]–[3]. For this reason, in power flux and stability studies, using models that reflect its behavior and are easy to represent is required [4]. Due to the importance of TAM, they have been the subject of numerous studies focused mainly on improving technology to increase the level of efficiency [5], [6], on control strategies in the TAMs drive system to ensure the maximum operational efficiency [7] and on methods to estimate the operational efficiency of TAM [8]. However, few studies have delved into the adequate representation of TAM in electrical power systems. Studies often consider TAM constant power or impedance models [9], [10]. An example of the consequences of this error is the voltage collapse that occurred on the West Coast of the United States in 1996, whose causes could not be adequately explained until better modeling of TAM was done [11]–[14].

Some authors have used the equivalent circuit of the TAM in the analysis of electrical power systems [11], [15]–[17]. This method requires knowledge of the parameters of the circuit, which almost any manufacturer does not offer. This makes it necessary to model the TAM to use other software to calculate these parameters [18]–[20] or to incorporate it into the electrical network analysis software [21].

In [22], it is shown that the classic polynomial ZIP model can represent the TAM. In addition, it is incorporated in network analysis software. In that study, it is explained how from the knowledge of the exact equivalent circuit parameters of the motor, the parameters of the ZIP model can be determined, including the type of mechanical load driven by the motor and its magnitude. However, there is still the difficulty of relying on other software to determine the parameters of the equivalent circuit. This paper pretends to solve this problem, proposing a universal model per unit that applies to any general-purpose motor, both medium and low voltage. Statistical analysis was made to arrive at this universal model with 36 low-voltage and 34 medium-voltage motors. The motors have different power and number of poles guaranteeing a broader application of the proposed universal model.

2. METHOD

2.1. ZIP model of TAM

The general expression of the ZIP model in per unit, active and reactive power as a function of voltage and frequency deviation is [23]–[25]:

$$P = P_o.\left[p_1.\left(\frac{V}{V_{base}}\right)^2 + p_2.\left(\frac{V}{V_{base}}\right) + p_3\right].\left(1 + K_{pf}.\Delta f\right) \tag{1}$$

$$P_{pu} = \left(p_1.V_{pu}^2 + p_2.V_{pu} + p_3\right).\left(1 + K_{pf}.\Delta f\right) \tag{2}$$

$$Q = Q_o.\left[q_1.\left(\frac{V}{V_{base}}\right)^2 + q_2.\left(\frac{V}{V_{base}}\right) + q_3\right].\left(1 + K_{qf}.\Delta f\right) \tag{3}$$

$$Q_{pu} = \left(q_1.V_{pu}^2 + q_2.V_{pu} + q_3\right).\left(1 + K_{qf}.\Delta f\right) \tag{4}$$

where P_o y Q_o is the active and reactive power values at frequency and voltage rated; V_{base} is the base voltage (generally coincides with nominal voltage), p_1, p_2, p_3, q_1, q_2, q_3; $K_{pf,}$ and K_{qf} are the model's parameters. The variables with subscript pu are expressed per unit.

According to [22] and [26], the variation of the active and reactive power of the motor as a function of voltage and frequency can be approximated, with outstanding accuracy, to a second-degree polynomial, which is the configuration of the ZIP model. The influence of the type and magnitude of the load driven by the motor was considered by assuming, in one case, constant torque load and, in another, variable torque load. It was also shown that the parameter K_{qf} is not worth considering since the variation of reactive power with frequency deviation is, on the one hand, very complex from the mathematical point of view and, on the other hand, of little interest to power system analysts.

2.2. Universal ATM model in function of active power, reactive power, and voltage

To get the universal model, it is necessary to determine how the power and number of poles influence the voltage-related parameters. The data used to obtain the models is shown in Tables 1 and 2. Table 1 shows the data of 36 low voltage motors (i.e., 440 V) of 2,4, 6, and 8 poles and powers between 11 kW and 355 kW.

Table 2 shows 34 high voltage motors (i.e., 3000, 6000, and 10000 V) and 2, 4, 6, and 8 poles. Of these motors, 24 are 50 Hz, and 10 are 60 Hz, with powers between 100 kW and 3,500 kW. With this great variety in the characteristics of the motors, it is possible to obtain a model with a wide scope in its application.

Accordingly, a universal model was obtained whose parameters are a function only of the load, expressed by a load factor Kc, defined as the ratio between the power delivered by the motor on the shaft in its actual conditions and its rate capacity. Since it is difficult to know the power that the motor has on its shaft, this parameter is defined as the ratio between the actual power consumed and its nominal input power, which is equal to the nominal output power divided by the efficiency:

$$K_c = \frac{P_{en}}{P_{en,n}} \tag{5}$$

where P_{en} is the real power at the input and $P_{en,n}$ is the rated input power.

Although this model has six parameters, only four are linearly independent since it must be satisfied that [9], [10], [12].

$$p_1 + p_2 + p_3 = 1 \tag{6}$$

$$q_1 + q_2 + q_3 = 1 \tag{7}$$

Because of this, with the load factor Kc, it is only necessary to determine the functional relationships of the four parameters, p_1, p_2, q_1, and q_2. To arrive at these functional relationships, a statistical analysis was performed. The average values and standard deviation of these parameters were determined for the motors analyzed, considering four values of Kc: 1.00, 0.75, 0.50, and 0.25. These results are shown in Table 3. Figure 1 shows the relationship between parameters p1 and p2 and Kc's load factor according to the values shown in Table 3.

The following equations were obtained using a curve fitting method for these two parameters.

$$p_1 = -0{,}16\, K_c^2 - 0{,}296\, K_c + 0{,}075 \tag{8}$$

$$p_2 = 0{,}56\, K_c^2 - 0{,}5\, K_c - 0{,}04 \tag{9}$$

$$p_3 = 1 - (p_1 + p_2) \tag{10}$$

On the other hand, Figure 2 shows the relationship between the parameters q1 and q2 and the load factor Kc according to the values shown in Table 3. Similarly, the following equations were obtained using the same curve fitting method for these two parameters.

$$q_1 = 0.888 - 0.774\, K_c - 0.36\, K_c^2 \tag{11}$$

$$q_2 = 0.36\, K_c^2 - 2.3\, K_c + 0.343 \tag{12}$$

$$q_3 = 1 - (q_1 + q_2) \tag{13}$$

The (8)-(13) are the universal per unit model of the TAM sought.

Table 1. Low-voltage motor catalog data case studies

No.	Poles	f(Hz)	P_n (kW)	N_n(rpm)	V_n (V)	I_n (A)	T_{max}(pu)	η_{100} (%)	fp(pu)
1	2	60	11	3,541	440	17.4	3.2	90.9	0.91
2	2	60	15	3,539	440	23.5	3.4	90.9	0.9
3	2	60	22	3,513	440	34.3	2.9	91.3	0.92
4	2	60	22	3,554	440	35.5	3.4	91.6	0.88
5	2	60	35	3,544	440	55.6	2.9	92.7	0.89
6	2	60	37	3,560	440	57.8	3.3	92.9	0.9
7	2	60	43	3,544	440	67.5	2.7	93	0.89
8	2	60	45	3,562	440	71.1	2.5	93.3	0.89
9	2	60	55	3,568	440	87.2	2.8	93.5	0.88
10	4	60	15	1,772	440	25.1	3	92	0.85
11	4	60	22	1,777	440	36.9	3	92.8	0.84
12	4	60	30	1,781	440	50.1	3	93.5	0.84
13	4	60	37	1,780	440	60.4	3	93.4	0.86
14	4	60	45	1,782	440	73	3.3	94	0.86
15	4	60	55	1,781	440	89.7	2.4	94.5	0.85
16	4	60	64	1,781	440	102	3.4	94.3	0.87
17	4	60	75	1,784	440	121	2.8	94.1	0.86
18	4	60	90	1,783	440	145	2.7	94.6	0.86
19	6	60	11	1,174	440	20.2	3	90.2	0.79
20	6	60	22	1,187	440	37.5	2.9	92.5	0.83
21	6	60	37	1,186	440	62.5	2.7	93.5	0.83
22	6	60	55	1,191	440	88	2.5	93.7	0.85
23	6	60	75	1,192	440	123	2.9	94.1	0.85
24	6	60	90	1,192	440	150	2.9	94.6	0.83
25	6	60	105	1,191	440	171	2.5	95	0.85
26	6	60	132	1,191	440	217	3	95.1	0.84
27	6	60	150	1,192	440	246	3	95.2	0.84
28	8	60	55	892	440	96.3	2.7	93	0.81
29	8	60	75	891	440	132	2.7	93.4	0.8
30	8	60	105	890	440	176	2.3	93.9	0.84
31	8	60	132	894	440	234	2.6	94.4	0.78
32	8	60	160	894	440	283	2.5	94.4	0.78
33	8	60	185	893	440	311	2.3	94.9	0.82
34	8	60	250	893	440	425	2.5	95	0.81
35	8	60	330	892	440	560	2.6	95.3	0.81
36	8	60	355	893	440	582	2.6	95.6	0.83

Table 2. Medium-voltage motor catalog data case studies

No.	Poles	f(Hz)	P_n (kW)	N_n(rpm)	V_n (V)	I_n (A)	T_{max}(pu)	η_{100} (%)	η_{75}(%)	fp(pu)
1	2	50	132	2,971	3,000	29.0	2.7	94.6	94.5	0.92
2	2	50	335	2,975	3,300	67.0	2.7	96.0	96.1	0.91
3	2	50	710	2,986	3,000	154	2.8	97.1	97	0.91
4	2	50	1,000	2,988	3,000	215	2.8	97.1	96.9	0.92
5	2	50	1,730	2,991	3,000	370	3.0	97.6	95	0.92
6	2	50	2,240	2,986	6,000	252	2.2	96.9	96.9	0.88
7	4	50	100	1,487	3,000	25.0	2.4	93.9	93.2	0.83
8	4	50	400	1,491	3,000	95.0	2.2	96.4	96.3	0.86
9	4	50	630	1,492	6,000	72.0	2.4	96.9	96.8	0.87
10	4	50	1,120	1,493	6,000	125	2.3	97.3	97.3	0.88
11	4	50	1,400	1,493	6,000	157	2.3	97.6	97.6	0.88
12	4	50	2,500	1,490	3,000	556	2.0	96.7	96.8	0.89
13	6	50	160	988	3,000	42.0	2.0	94.6	94.5	0.78
14	6	50	280	989	3,000	71.0	2.0	95.6	95.6	0.80
15	6	50	560	993	3,000	131	2.0	96.8	96.8	0.85
16	6	50	900	994	3,000	207	2.1	97.1	97.2	0.86
17	6	50	1,250	995	6,000	145	2.2	97.4	97.4	0.85
18	6	50	2,000	993	6,000	230	2.3	96.6	96.9	0.87
19	8	50	180	741	6,000	24.0	1.9	94.4	94.4	0.77
20	8	50	560	745	10,000	42.0	2.3	95.8	95.6	0.80
21	8	50	710	744	10,000	51.0	2.1	95.5	95.7	0.84
22	8	50	900	743	3,000	211	2.2	96.2	96.4	0.85
23	8	50	1,120	743	6,000	129	2.1	96.1	96.4	0.87
24	8	50	1,400	743	6,000	152	2.1	96.3	96.5	0.86
25	2	60	2,500	3,580	6,000	282	2.6	97.0		0.88
26	2	60	2,800	3,589	6,000	316	2.5	95.8		0.89
27	4	60	1,500	1,788	6,000	165	2.2	96.5		0.91
28	4	60	750	1,785	6,000	84.0	2.1	96.7		0.89
29	4	60	3,500	1,790	6,000	386	2.4	97.0		0.90
30	6	60	250	1,178	6,000	29.7	2.4	93.0		0.87
31	6	60	250	1,178	6,000	30.0	2.4	93.0		0.85
32	6	60	250	1,170	6,000	30.0	2.4	89.1		0.90
33	8	60	630	895	6,000	80.0	2.9	93.6		0.81
34	8	60	630	893	6,000	84.0	2.7	93.0		0.77

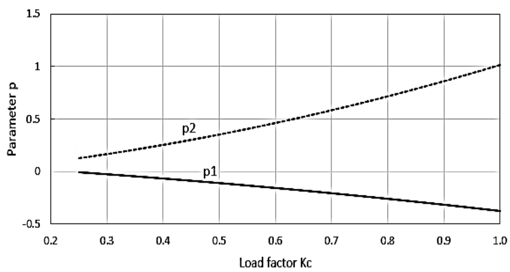

Figure 1. Parameters p_1 and p_2 in the universal model as a function of the load factor Kc

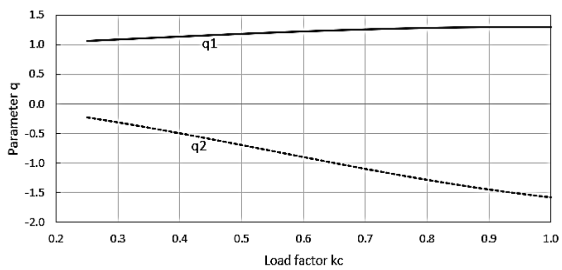

Figure 2. Parameters q1 and q2 in the universal model as a function of the load factor Kc

Table 3. Average values and standard deviations of the parameters of the model

	K_c	1.00	0.75	0.50	0.25
p_1	Average	-0.38	-0.24	-0.11	-0.01
	Standard deviation	0.10	0.06	0.03	0.02
p_2	Average	1.02	0.65	0.35	0.12
	Standard deviation	0.16	0.11	0.07	0.03
q_1	Average	1.30	1.27	1.18	1.06
	Standard deviation	0.09	0.07	0.06	0.04
q_2	Average	-1.59	-1.21	-0.69	-0.22
	Standard deviation	0.30	0.29	0.20	0.13

2.3. Universal ATM model in function of active power, reactive power, and frequency

To derive the universal model of the asynchronous motor relating the active power to the frequency deviation around the nominal one, the parameters corresponding to this variation were determined for the 36 low voltage and 34 medium voltage motors, both for constant and variable torque loads. Table 4 shows the average values and standard deviations of these parameters. These parameters do not depend on the magnitude of the load but the type of load. It was shown that K_{pf} =0.88 could be selected for constant torque loads and K_{pf} =2.69 for variable torque loads.

Table 4. Average values and standard deviations of the parameters relating to active power variation with frequency deviation for constant and variable torque loads

K_c		1.00	0.75	0.50	0.25	Average total
K_{pfcc}	Average	0.82	0.88	0.91	0.91	0.88
	Standard deviation	0.04	0.02	0.02	0.04	0.04
K_{pfcv}	Average	2.51	2.66	2.77	2.82	2.69
	Standard deviation	0.09	0.07	0.07	0.09	0.13

3. RESULTS AND DISCUSSION

To validate the model, the data of [20] are used. That is, a 6000 V, 2500 kW, 60 Hz, 2-pole medium voltage motor which drives the feed pump with a variable torque load of a power plant. Figures 3 and 4 show the active and reactive power as a function of voltage, considering both the universal model and the exact equivalent circuit solution obtained in [20]. To demonstrate the model's validity as a function of frequency, Figure 5 compares the characteristic obtained with the universal model and that obtained from the equivalent circuit of [20]. As can be seen in Figures 3, 4, and 5, the errors are less than 6% for the admissible voltage values (±10%).

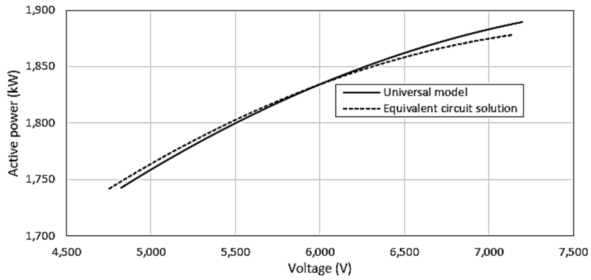

Figure 3. Active power characteristic as a function of the voltage of the asynchronous motor case study using the universal model and the equivalent circuit solution

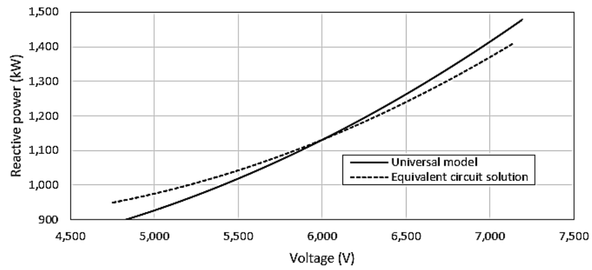

Figure 4. Reactive power characteristic as a function of the voltage of the asynchronous motor case study using the universal model and the equivalent circuit solution

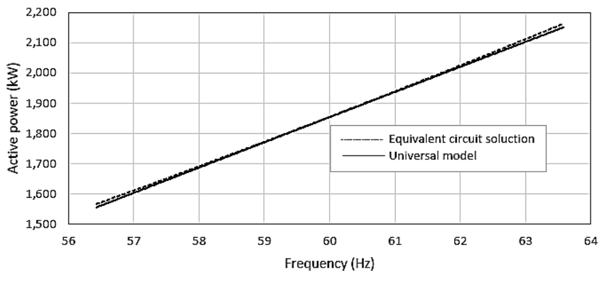

Figure 5. Active power characteristic as a function of frequency deviation in the asynchronous motor case study, using the universal model and the equivalent circuit solution

4. CONCLUSION

From the statistical analysis of 36 low-voltage and 34 medium-voltage motors, it was possible to deduce a universal model per unit, applicable to any general-purpose motor, which allows the model's parameters to be determined and applied to any software for the analysis of electrical power systems. The unit model parameters that relate active power and reactive power to voltage do not depend on the type of load but only on the level of the mechanical load. This makes it possible to develop a simple universal model whose parameters depend only on the motor load. It was also shown that the parameter that relates the active power variation with the frequency deviation depends exclusively on the type of mechanical load driven. It is different for a constant torque load and a variable torque load.

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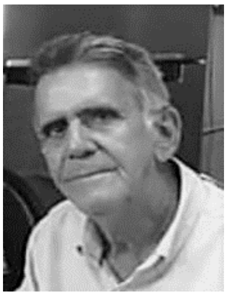

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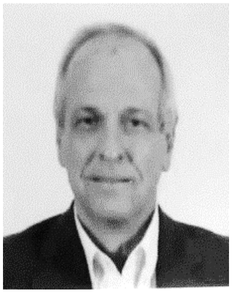

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