Electronic Torque Meter for Low-Power Induction Motor Applications

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***Abstract*-An important parameter for a drive system is its developed torque. In practice up to now, torque-speed converters or torque-sensors are usually used to determine the developed torque. These devices are costly and in many cases difficult to fix to a motor shaft due to mechanical or constructive constraints. The research paper presented here proposes an alternative indirect method for motor torque assessment. The method focuses on low power induction motor applications and is based on the evaluation of the power factor considering its variation with motor load. The lowest power factor is at no-load operation, and the highest value occurs at rated motor load. An electronic circuit for implementing the proposed method is suggested. The experimental results based on known conventional torque measurement methods are used to benchmark the corresponding results obtained via the proposed torque measurement method. The results corroborate each other.**

Keywords- Induction Motor Characteristics, Power Factor, Torque evaluation, Electronics;

I. INTRODUCTION

The torque developed by three-phase induction motors is a very important factor for any drive system. Torques cannot be measured directly. Usually speed-torque converters or torque sensors are used to determine the torque of such motors [1, 2, 3]. These devices are fixed on the motor shaft and produce signals proportional to the speed. It is not always possible to attach them on the motor shaft due to mechanical or constructive constraints [4, 5]. In addition, these devices are quite expensive and there are limitations to their accuracy.

The method of torque T assessment proposed in this paper does not require any speed converters. The torque is evaluated from basic motor characteristics like the output power P_{out}, current I, power factor $\cos\varphi$ and efficiency η. It is well known that at escalating motor loading, the speed n reduces, but the input and output power P_{in}, P_{out}, the current I, the power factor $\cos\varphi$, and the efficiency η, all increase. At full load the a.c. motor parameters are at their nominal/rated values: P_N, I_N, $\cos\varphi_N$, and η_N as indicated on the motor's manufacturer data plate. At no-load, the power factor and the current are much lower than the rated values. Accordingly, $\cos\varphi_0 < \cos\varphi_N$, and $I_0 < I_N$. If not specified, the parameters like I and $\cos\varphi$ could be easily measured or calculated to reveal the induction motor characteristics as shown in Fig. 1.

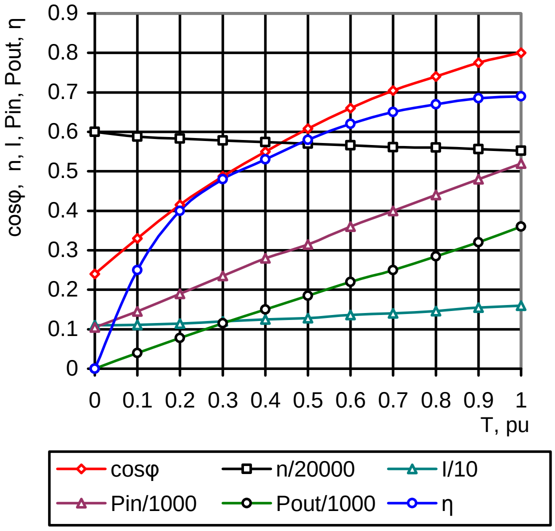

Fig. 1 Basic induction motor characteristics

II. EXPERIMENTS

Experiments were conducted on two cage motors whose rated parameters are shown in Table 1.

TABLE 1: CAGE MOTOR PARAMETERS

Parameter	Motor 1	Motor 2
Power, W	100	370
Phase Voltage, V	220	240
Current, A	0.6	1.6
Speed, rpm	1300	2700
PF $\cos\varphi_0$	0.23	0.24
PF $\cos\varphi_N$	0.74	0.80
Torque, Nm	0.70	1.25

The experimental results are shown in Table 2 and Table 3. The *PF-T* characteristics for motors 1 and 2 are shown in Fig. 2 and Fig. 3 respectively where the torque is expressed in per-unit (pu).

TABLE 2: MOTOR 1 AT V = 220V, F = 50 Hz

T, Nm	T/T_N, pu	n, rpm	I, A	P_{in}, W	P_{out}, W	cos φ
0	0	1465	0.31	28	0	0.23
0.05	0.07	1460	0.32	34	8	0.28
0.1	0.14	1455	0.34	45	15	0.34
0.2	0.28	1445	0.36	61	30	0.45
0.3	0.43	1440	0.39	81	45	0.53
0.4	0.57	1410	0.42	99	55	0.61
0.5	0.70	1390	0.46	118	72	0.67
0.6	0.857	1365	0.51	140	86	0.72
0.7	1.00	1340	0.57	162	98	0.74
0.8	1.14	1310	0.64	185	110	0.76
0.9	1.28	1250	0.71	207	122	0.78

TABLE 3: MOTOR 2 AT V = 235V, F = 50 Hz

T, Nm	T/T_N, pu	n, rpm	I, A	P_{in}, W	P_{out}, W	cos φ
0	0	2980	1.08	98.5	0	0.24
0.05	0.04	2960	1.09	120	15.4	0.27
0.25	0.20	2915	1.14	187	76.3	0.41
0.40	0.32	2880	1.21	240	124	0.49
0.60	0.48	2855	1.28	310	176	0.58
0.75	0.60	2820	1.36	360	224	0.65
1.10	0.88	2780	1.52	470	314	0.76
1.25	1.00	2760	1.61	521	361	0.80
1.50	1.20	2730	1.78	615	423	0.84

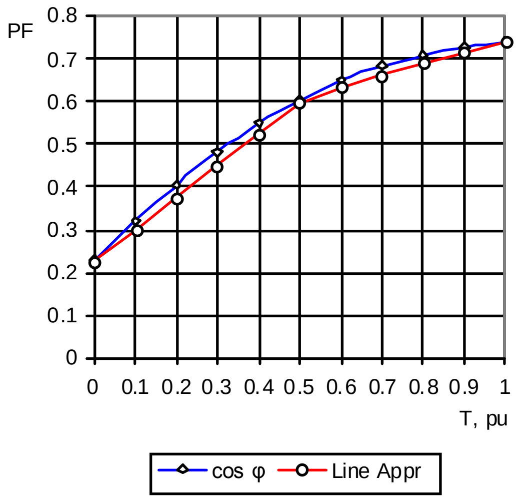

Fig. 2 Approximation of the *PF-T* characteristic of motor 1

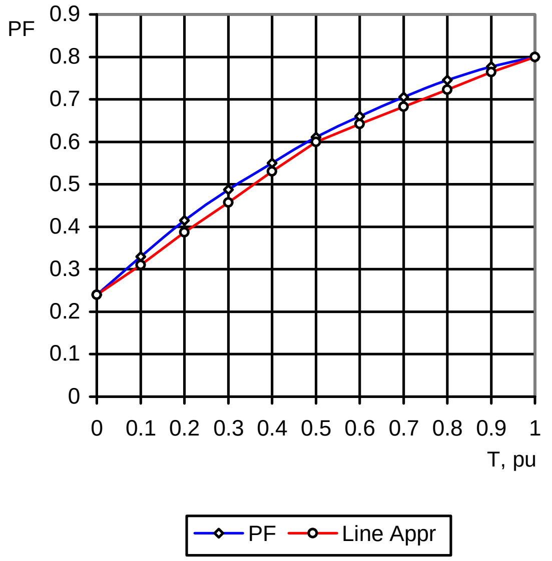

Fig. 3 Approximation of the (*PF-T*) characteristic of motor 2

III. BASIS OF THE PROPOSED METHOD

The method is based on the evaluation of the segmented line approximation of the power factor-torque *PF-T* characteristic. The power factor depends not only on the loading but also on the size of the motor. For motors with low power in the range of P_N < 500W, the following are true:

- The rated currents are smaller and the number of stator turns is bigger in order to produce the necessary flux. As a result the active coil resistances and copper losses are high, and efficiency is reduced.
- The air-gaps between rotors and stators cannot be reduced in proportion to the motor sizes. The air gaps are of the same magnitudes as those for large motors due to constructive and technological constraints. This causes high magnetizing and no-load currents.

As a result the motors with low power in the range of 100 < P_N < 500 W are characterized by higher PF at no-load and lower PF at full load, also lower efficiencies and larger no-load currents are typically related to bigger motors in the rated parameter ranges [2, 6], as shown in Table 4.

TABLE 4: TYPICAL PARAMETER RANGES FOR LOW POWER MOTORS

Motor Parameter Description	Parameter	Torque	
		Motor 1	Motor 2
No-Load Power Factor	$cos\ \varphi_0$	0.2	0.3
Rated Power Factor	$cos\ \varphi_N$	0.72	0.82
Efficiency	η	0.56	0.68
No-Load Current Ratio	I_0 / I_N	0.45	0.7

The *PF-T* characteristic is non-linear. The slope of the curve is high at low loading but decreases at higher loading. It could be accepted that the slope changes at a load torque $T_T = 0.5T$ considered as the turning loading point value. The power factor corresponding to this load is referred to as cos φ_T. Hence the *PF-T* characteristic can be represented by two straight lines as shown in Fig. 2 and Fig. 3. Taking into account the area of low loadings for which $0 < T_1 < T_T$, the resulting equations are as follows:

$$\frac{\cos\varphi_T - \cos\varphi_O}{T_T} = \frac{\cos\varphi_1 - \cos\varphi_O}{T_1}, \tag{1}$$

$$T_1 = T_T \frac{\cos\varphi_1 - \cos\varphi_o}{\cos\varphi_T - \cos\varphi_o}. \tag{2}$$

Taking into account the area of high loadings where $T_T < T_2 < T_N$, the resulting equations are:

$$\frac{\cos\varphi_N - \cos\varphi_T}{T_N - T_T} = \frac{\cos\varphi_2 - \cos\varphi_T}{T_2 - T_T}, \tag{3}$$

$$T_2 = \frac{T_N(\cos\varphi_2 - \cos\varphi_T) + T_T(\cos\varphi_N - \cos\varphi_2)}{(\cos\varphi_N - \cos\varphi_T)}. \tag{4}$$

The rated full-load torque T_N is 1pu. Equations (2) and (4) reveal that at any loading, the power factors $\cos\varphi_1$, $\cos\varphi_2$ and $\cos\varphi_T$ could be used to provide an estimation of the torque developed by the motor. The power factors $\cos\varphi_0$ and $\cos\varphi_N$ are assumed to be known from the manufacturer's data. The determination of the torque T_T and the power factor $\cos\varphi_T$ at the turning point is critical for the accuracy of this method. From the studies of the experimental motor characteristics and from general experience, at half the rated loading $T_T = 0.5T_N$, the power factor increases up to the value of $\cos\varphi_T = 0.6$. It is also essential to determine the angle φ between the phase voltage and current at any loading to enable the calculation of the corresponding torque.

At $T_T = 0.5T_N$, equations (2) and (4) become:

$$T_1 = T_T\frac{\cos\varphi_1 - \cos\varphi_o}{\cos\varphi_T - \cos\varphi_o},\ T_2 = T_N\frac{\cos\varphi_N - \cos\varphi_2 - 2\cos\varphi_T}{2(\cos\varphi_N - \cos\varphi_T)}. \tag{5}$$

IV. PROPOSED ELECTRONIC METHOD FOR IMPLEMENTING MOTOR TORQUE MEASUREMENT

A block diagram of the torque meter derived from implementation of equations (1) to (4) above is shown in Fig. 4.

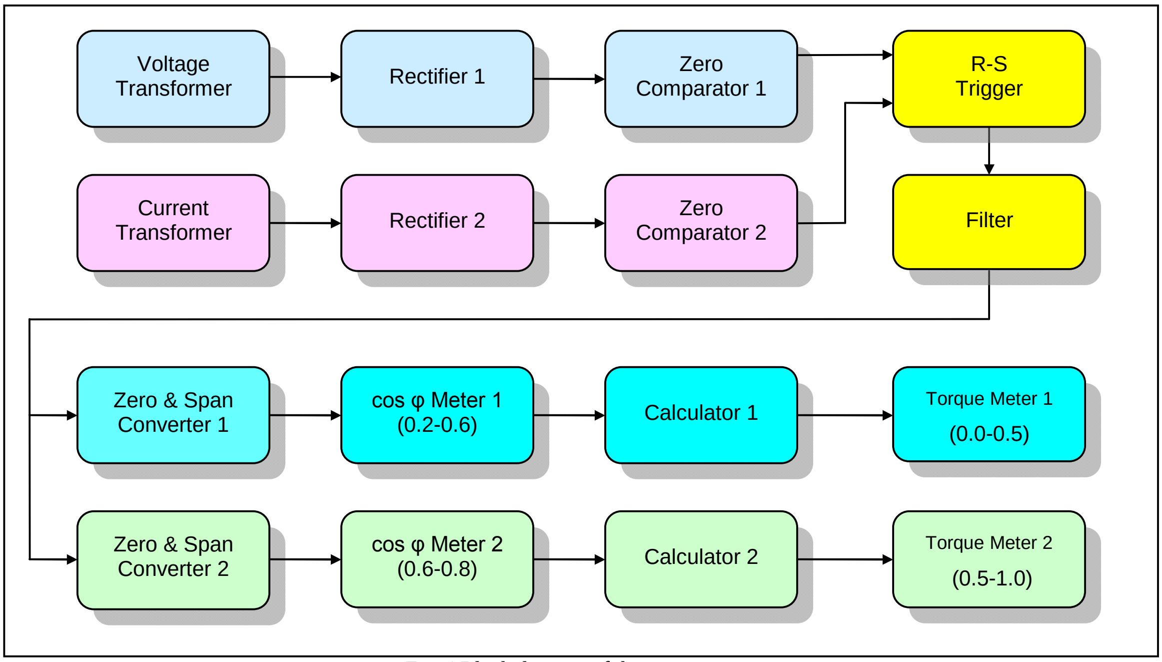

Fig. 4 Block diagram of the torque meter

The block diagram in Fig. 4 is implemented using the electronic circuit diagram shown in Fig. 5 that is used to simulate the measurement of induction motor torque at different power factors. A voltage and a current transformer take into account the supply voltage and current of the induction motor respectively.

Two Zero Comparators produce pulses with phase difference corresponds to the phase lag φ between the voltage and the current. These pulses control an R-S Trigger, resulting in its square wave output voltage. The width of the square pulses is equal to the phase difference φ. These pulses are filtered, resulting in a filter DC output voltage proportional to the angle φ.

The filter output is applied simultaneously to two parallel channels in order to achieve better linearity in measuring the power factor and the torque. Each channel includes a Zero and Span Converter [7, 8], producing output signals directly proportional to the power factor $\cos\varphi$.

The first channel generates the readings of $\cos\varphi_1$ ranging from $\cos\varphi_0$ to $\cos\varphi_T$. These readings are measured by the meter XMM1 while the second meter, XMM3, measures $\cos\varphi_2$ within the range of $\cos\varphi_T$ to $\cos\varphi_N$. Calculators 1 and 2 are incorporated into each channel [9], enabling the calculation of the torques T_1 and T_2 from the values $\cos\varphi_1$, $\cos\varphi_2$ and $\cos\varphi_T$ using equations (2) and (4). The torque results at low loadings are displayed by XMM2, the first torque meter while at the display on XMM4, the second torque meter, indicates the results at high loadings.

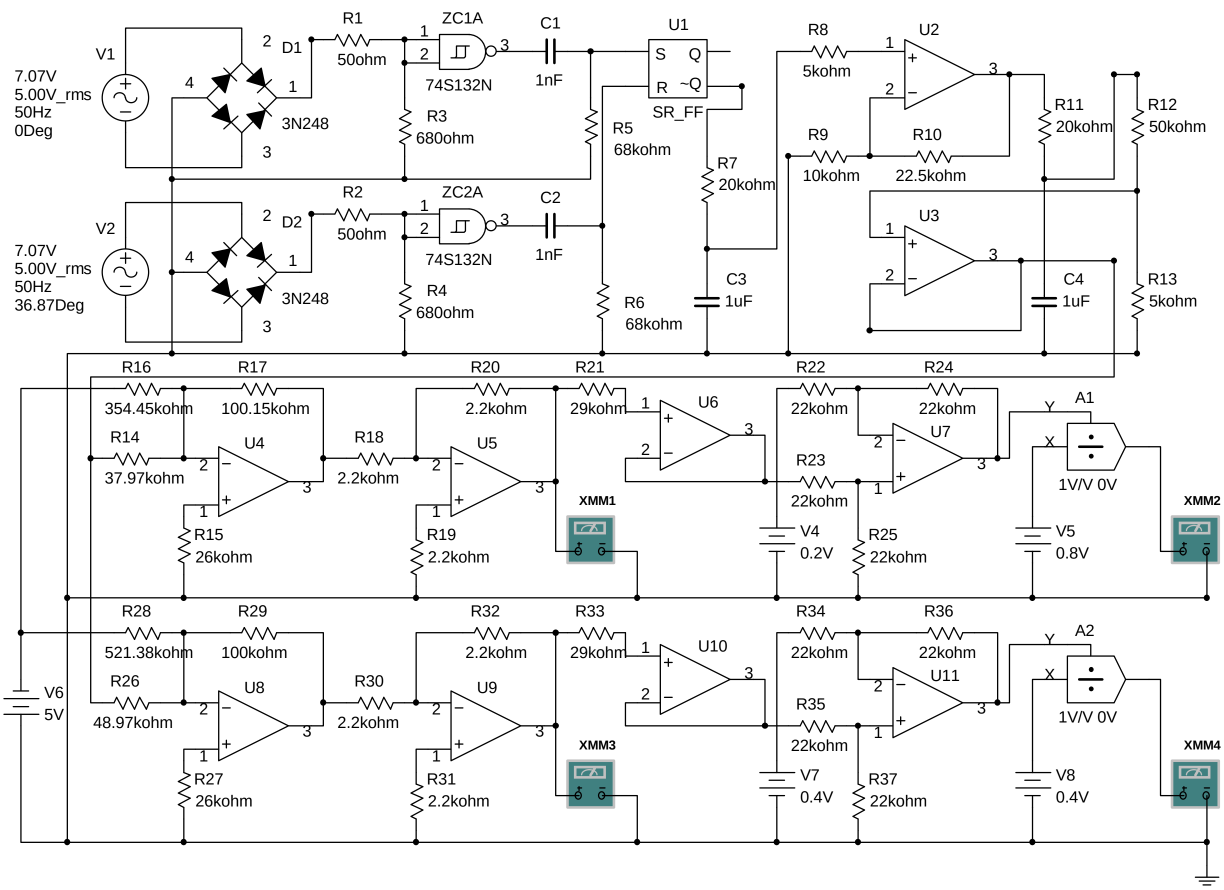

Fig. 5 Electronic circuit diagram for the proposed induction motor torque meter

V. PROCEDURE FOR THE PROPOSED IMPLEMENTATION

The torque meter of Fig. 5 was used for torque measurements by simulating loads with different phase lags and thus power factors. The corresponding torques were read by the two properly calibrated instruments as indicated in Table 5:

TABLE 5: TORQUE AND POWER FACTOR MEASUREMENTS FOR THE CASE OF MOTOR 1 AND MOTOR 2

Parameter	Motor 1	Motor 2
T_T	0.5 pu	0.5 pu
$\cos\varphi_T$	0.6	0.6
$\cos\varphi_0$	0.23	0.24
$\cos\varphi_N$	0.74	0.8

The torque meters could be calibrated and properly tuned with the aid of Calculator 1 and Calculator 2 for any other value of the loading turning point corresponding to torque T_T.

VI. RESULTS FROM THE IMPLEMENTATION OF THE PROPOSED METHOD

One set of experimental results was obtained with the aid of a traditional torque meter. The second set of results was obtained by calculation with equation (5). Finally, the last set of results was obtained by means of a MULTISIM-based electronic simulation, using the electronic circuit of Fig. 5. Comparisons of the experimental and the calculated results with the simulated results obtained from the proposed method are presented in Table 6 and Table 7. It is seen that the results corroborate each other closely. While the results of calculations and simulation are almost identical, the error between the simulation and experimental results at different loadings lies within the acceptable tolerance of less than 10% [8, 9, 10].

TABLE 6: COMPARISON OF RESULTS FOR THE CASE OF MOTOR 1

cos φ	**T, pu Experimental**	**T, pu Calculated**	**T, pu Simulated**	**Error, %**
0.23	0.0	0.0	0.0	0.0
0.3	0.085	0.094	0.093	10
0.35	0.145	0.158	0.157	8.9
0.4	0.21	0.23	0.22	9.5
0.45	0.275	0.297	0.288	8.1
0.5	0.37	0.36	0.36	-2.7
0.55	0.45	0.43	0.436	-4.4
0.6	0.54	0.5	0.502	-7.4
0.65	0.64	0.66	0.654	3.1
0.7	0.78	0.83	0.84	6.4
0.75	1.0	1.0	1.0	0.0

TABLE 7: COMPARISON OF RESULTS FOR THE CASE OF MOTOR 2

cos φ	**T, pu Experimental**	**T, pu Calculated**	**T, pu Simulated**	**Error, %**
0.24	0.0	0.0	0.0	0.0
0.3	0.8	0.083	0.084	8.4
0.35	0.14	0.152	0.151	8.7
0.4	0.2	0.22	0.22	10
0.45	0.27	0.29	0.288	7.4
0.5	0.34	0.36	0.36	5.9
0.6	0.5	0.5	0.5	0.0
0.65	0.6	0.625	0.623	4.16
0.7	0.7	0.75	0.74	7.1
0.75	0.84	0.875	0.873	4.16
0.8	1.0	1.0	1.0	0.0

VII. CONCLUSIONS

The proposed method is applicable for automatic measurement of the torque developed by low power induction motors. The method is based on the evaluation of the power factor premised on the linearization of the motor's *PF-T* characteristic that typically increases non-linearly with its loading. The method utilizes the nominal motor data indicated on the motor's nameplate.

An electronic circuit of a torques-meter is proposed. It enables the measurement of the power factor, as well as the torque by evaluating the phase lag between the phase voltage and the motor current. The circuit of the torque meter is easy to be realized and calibrated. As a result, such torque-meters could be assembled and implemented in practice as well as be employed to advance the induction motors studies. This paper provides a theoretical and experimental analysis of the torque meter performance at different induction motor loads. The analysis results back up the results obtained from the actual realisation of the suggested practical electronic torque meter device. Theoretical, experimental, and simulation results substantiate each other very closely. Whereas outcome result differences may be due to linearization of the *PF-T* characteristic, the errors are however less than 10%, which is well within acceptable error tolerances.

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