

Methodology to Evaluate Motor Capability by Measurements at Motor Control Centers

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Abstract - The aging of power plants and minimal margin in the reserves demands a higher reliability of the critical power system components. Motors in the power generating stations play an important role in the overall reliability of the power system. The increasing demand for the availability, cost-effectiveness and protection of the machinery and equipment is requiring in-service monitoring more and more necessary.

The Sensotorq[®] is a digital torque measurement instrument specifically developed for 3-phase ac motors and generators. From the measured current and voltage on the electrical leads of the motor, the instrument determines torque, speed, mechanical power, and electrical power without using any additional sensor. The ability of measuring these parameters leads us to configure the Sensotorq[®] for maintenance and trending of motor operated valves. Tests show that motor output torque can be measured without the torque transducer at the motor shaft. The Sensotorq[®] has been successfully applied to diagnose and monitor large variable frequency drives (vfd), generators, pumps, agitators, motors, and motor operated valves (MOV's).

The paper will include a number of tests and comparison of data with conventional methods of measuring torque of the MOV motors. The paper will address the effectiveness and economics of the Sensotorq[®] for its application to an MOV maintenance program.

I. INTRODUCTION

In many areas where asynchronous machines are used, it is necessary to measure the mechanically available torque at the motor shaft. On the one hand, this measured value may be required directly for the control of the production process; on the other hand, it is frequently necessary for protecting rotating equipment when the allowable torque is exceeded. For the motor operated valves (MOV's), this can be used to determine the available motor capability and therefore margin available to perform MOV function.

In the conventional type of torque measurement, a metering shaft has to be fitted between motor and working machine. However, there is often insufficient space available for this, especially in existing drives and MOV's. The mechanical measuring procedure, which is based on a soft metering shaft, is very sensitive to overload and torque vibrations. Overloads can lead to irreversible damage of the measuring section. The complexity of the mechanical solution leads to unacceptable costs, especially for the "protective function" option. All this disadvantages of the mechanical torque measurement can be avoided by measuring the torque with the Sensotorq[®] instead of the metering shaft. The Sensotorq[®] determines the torque based on measured motor currents and voltages. It does not require a speed sensor or any other external sensor. Therefore, it is impossible to overload the instrument. Furthermore, it does not require maintenance and it is very easy to install.

II. THEORETICAL BACKGROUND

The internal air gap torque of the motor is calculated from the measured currents, i , and voltages, u , on the basis of a flux vector model. The resulting air gap flux, Ψ , on the stator-side of the motor is given by the voltage equation:

$$\frac{d\vec{\psi}_1}{dt} = \vec{u}_1 - \vec{i}_1 \cdot R_1 \quad (1)$$

R_1 is the stator winding resistance.

The following applies to the α , β components of the stator current flux vector in the fixed coordinate system under the condition $\sum i_k = 0$ [1]:

$$i_{1\alpha} = \frac{2}{3} \left(i_a - \frac{i_b}{2} - \frac{i_c}{2} \right) = i_a \quad (2a)$$

$$i_{1\beta} = \frac{1}{\sqrt{3}} (i_b - i_c) \quad (2b)$$

It follows analogously for the voltages:

$$u_{1\alpha} = \frac{2}{3} \left(u_a - \frac{u_b}{2} - \frac{u_c}{2} \right) = u_a \quad (3a)$$

$$u_{1\beta} = \frac{1}{\sqrt{3}} (u_b - u_c) \quad (3b)$$

In practice, it is sufficient to measure two voltages and two currents, the third value can be calculated from Kirchhoff's laws.

The flux vector in the time range can thus be determined, component by component, by integrating the voltage equation:

$$\psi_{1\alpha} = \int u_{1\alpha} dt - \int i_{1\alpha} \cdot R_1 dt \quad (4a)$$

$$\psi_{1\beta} = \int u_{1\beta} dt - \int i_{1\beta} \cdot R_1 dt \quad (4b)$$

Expressed by the three-phase current phase values, it further follows:

$$\psi_{1\alpha} = \int u_a dt - R_1 \cdot \int i_a dt \quad (5a)$$

$$\psi_{1\beta} = \frac{1}{\sqrt{3}} \left\{ \int (u_b - u_c) dt - R_1 \cdot \int (i_b - i_c) dt \right\} \quad (5b)$$

For a numerical application of these equations, it is advantageous to normalize with the rated values of the machine.

$$\bar{\psi}_1^* = \bar{\psi}_1 \cdot \frac{\omega_n}{\hat{U}_n} \quad (6)$$

$$\bar{u}_1^* = \frac{\bar{u}_1}{\hat{U}_n} \quad (7)$$

$$\bar{i}_1^* = \frac{\bar{i}_1}{\hat{I}_n} \quad (8)$$

$$r_1 = R_1 \cdot \frac{\hat{I}_n}{\hat{U}_n} \quad (9)$$

$$\bar{\tau}^* = \frac{\tau}{T_n} = \tau \cdot \frac{2}{3} \cdot \frac{\omega_n}{p \cdot \hat{U}_n \cdot \hat{I}_n} \quad (10)$$

The equation for calculating the torque is simplified after normalization:

$$\bar{\tau}^* = \bar{\psi}_{1\alpha}^* \cdot \bar{i}_{1\beta}^* - \bar{\psi}_{1\beta}^* \cdot \bar{i}_{1\alpha}^* \quad (11)$$

The mathematical method of calculation, which has been further improved in comparison to a previous version, has a lower frequency limit of 2 Hz. This enables the torque of a converter-controlled asynchronous motor to be calculated down to standstill. Figure 1 shows the connection diagram of the digital torque instrument in the motor supply line.

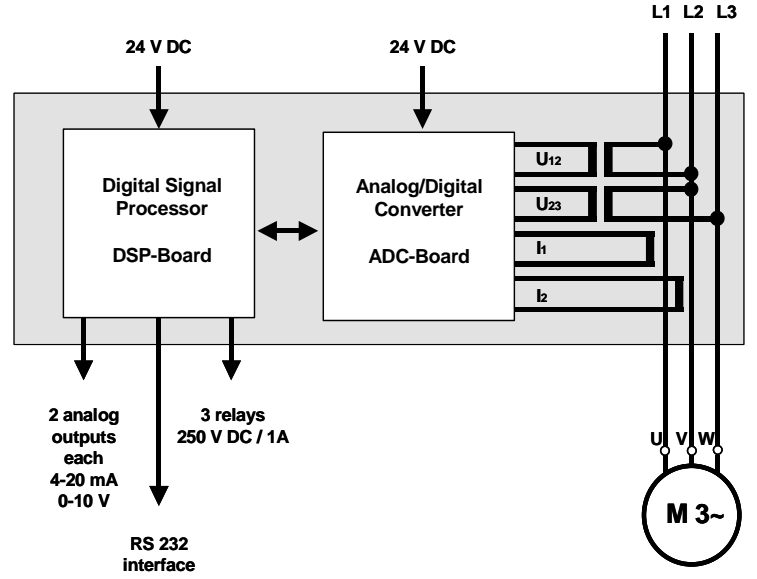


Figure 1: Connection diagram of the SensorTorq®

III. APPLICATION OF THE MODEL

The torque measurement and correction for the no-load torque of the motor results into the torque at the motor shaft. SensorTorq® continuously adjusts the no load torque depending upon the variant used: direct supply or through converter operation. In direct supply, the built-in program automatically detects whether the motor is running at rated voltage or at a different voltage, the no-load operation losses are adjusted accordingly. In converter operation, a frequency dependent correction of the measured no-load torque is made. Furthermore, the program automatically detects a possible field weakening operation of the motor and adapts the torque calculation accordingly.

Extensive comparative laboratory and field tests were performed. Sampled tests are included in this paper. A 4 kW and 30 kW machine with a mechanical metering shaft (accuracy better than 0.2 %) were used as a reference. The accuracy of the digital torque instrument was found to be better than 2 % under both motor and generator operation. Representative results are shown in Fig. 2.

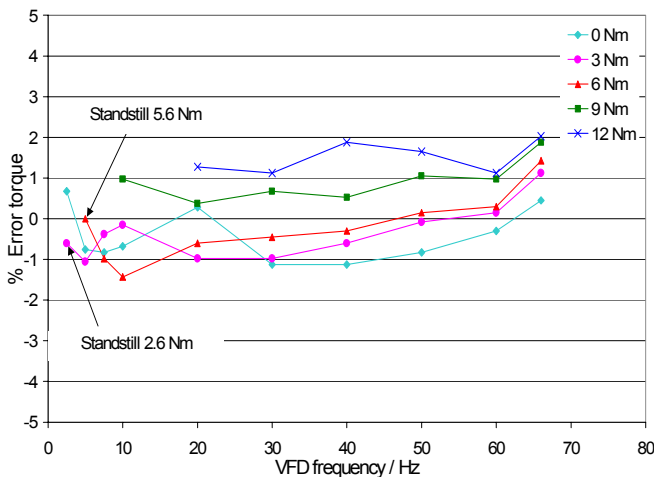


Figure 2 Torque accuracy of Sensorq[®] instrument using a metering shaft with 0.2% accuracy as reference; 1 Nm = 0.74 lb-ft

Figure 3 shows the torque calculated with the Sensorq[®] compared with the torque measured with the metering shaft. This test was done with a two-pole 4 kW asynchronous machine and a mechanical metering shaft (accuracy better than 0.2 %) as reference. The operating frequency was 60 Hz. The load was increased in several steps from no load up to full load and back to no load. One can see, that the torque calculated by the Sensorq[®] matches very well with the reference torque from the metering shaft at each load step.

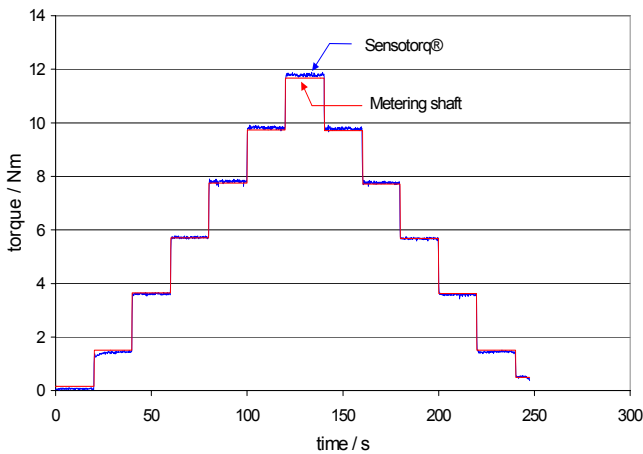


Figure 3 Comparison of Sensorq[®] calculated torque and metering shaft torque at an operating frequency of 60 Hz; 1 Nm = 0.74 lb-ft

The quality of the digital torque instrument can be well assessed by dynamically loading the motor. A representative result from series of measurements of a four-pole 30 kW asynchronous machine in the frequency range from 5 Hz to 60 Hz with U~f control in converter

operation is shown as an example in Fig. 4. The motor was loaded with a rectangular shaped fluctuating torque with an amplitude of 150Nm.

It is worthy of noting that the calculated time signal of the torque closely corresponds to the actual signal of the measuring shaft. The transient behavior at 60 Hz is particularly realistically shown: Sensorq[®] and metering shaft show the same transient behavior after a load change.

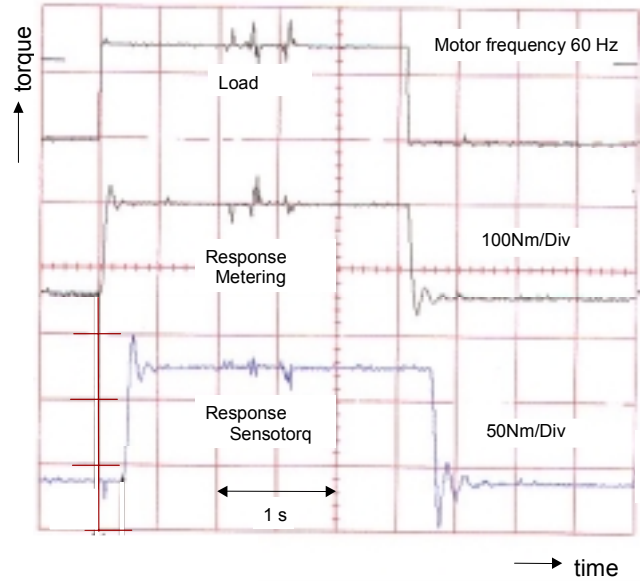


Figure 4 Dynamic resolution of the Sensorq[®] instrument compared to a metering shaft applying a rectangular torque load; 1 Nm = 0.74 lb-ft

The Sensorq[®] allows additional functions to be integrated in the instrument. The transformation of the three-phase current values in the flux vector enables the active power, reactive power and apparent power of the motor, as well as the power factor.

Moreover, for specific operating conditions, the speed of the motor can be calculated from the motor model eliminating the need for an external speed sensor. Based on speed and torque, the mechanical output and the motor efficiency are determined.

When the Sensorq[®] is used for measurements on a gear drive it offers the possibility to determine torque, speed and mechanical power at the gearbox output shaft. The model accounts for gear ratio, gear total efficiency and the load dependant portion of the efficiency.

The internal application of the flux vector can also be used to detect over- and under-voltages, or over-current

in the three phases, and for setting alarms. The direction of the rotating field can also be detected.

The MT Motor Torque capability to deliver torque at degraded voltage and elevated operating temperature

IV. MOV APPLICATION

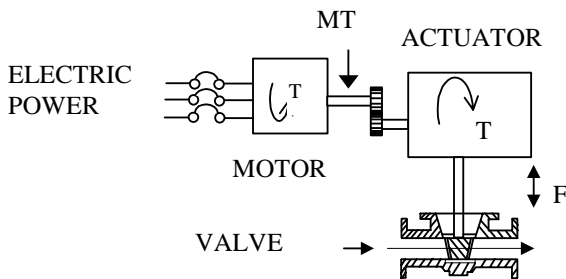


Figure 5 Typical MOV Interface Equipment Layout

The typical MOV interface layout is shown in Figure 5. The valve thrust requirement (F) can be calculated as

$$F = DP \cdot A \cdot FV + PL + P \cdot a \quad (12)$$

Where DP is differential pressure, A is the valve orifice area, FV is valve factor, PL is the packing load, P is line pressure, and a is stem cross section area.

The actuator stem torque T is given by

$$T = TH \cdot SF = F \cdot SF \quad (13)$$

where TH is thrust and SF is Stem Factor.

Torque can also be calculated as

$$T = MT \cdot OAR \cdot Eff \cdot AF \quad (14)$$

where:

- MT = Calculated Motor Torque
= Motor name plate torque x temp correction x (degraded voltage ratio)ⁿ
- n = 1 for DC & ≥ 2 for AC
- OAR = overall unit gear ratio for actuator (SEL - 3)
- Eff. = pull out efficiency (SEL - 7 or 8)
- A.F. = Motor Service factor required for the particular application (SEL - 4)

The importance of F , T , and MT in the field at as-left torque switch setting:

- F Design Basis Requirement per GL 89-10 and Periodic Verification requirement per GL 96-05
- T Limitorque actuator capability (Torque Rating) limiting requirement for torque

Field measurement and evaluation of F , T , and MT are as follows:

F Measured by diagnostic equipment such as MOVATS, VOTES & Teledyne Systems.

T Measured by TTC, TMD/Spring pack calibration or strain gauge mounted on stem. "T" can also be estimated by using measured 'F' and stem factor at design basis or measured coefficient of friction.

MT Indirectly evaluated by measuring 'T' and comparing it with actuator torque at degraded voltage and operability temperatures calculated based on T above.

The uncertainty associated with pullout efficiency as well as measured value of 'T' may not provide the realistic motor torque at as-left torque switch setting.

The advantage of using the Sensorq[®] is in the accuracy and convenience over the classical direct torque measurement methods. It should be stressed that this technique is almost ideal and extremely cost effective for inside containment motors.

V. MOV APPLICATION TESTS

Figure 6 shows a closing and an opening run of a MOV. The torque was measured with the Sensorq[®] and the thrust force with strain gauges mounted on the stem. At the end of the closing cycle the valve head is pressed into the seat causing a sharp increase in torque and thrust force. Comparing measured torque and stem force proportionality was found for the whole run. This result demonstrates that the Sensorq[®] accurately captures the stem torque at very instant of time.

The motor current is almost constant during the whole run. Even when the valve head is pressed into its seat an increase in current cannot be observed. The reason is that the power factor is very small under nearly no-load condition and only starts to rise when the valve enters the seat. Figure 7 shows the power factor and the torque during the closing of the valve.

The inaccuracy in the estimation of the factors (EFF and AF) in equation (14) of section IV can be eliminated by accurately measuring a composite conversion factor.

This can be achieved by accurately measuring motor torque and thrust force.

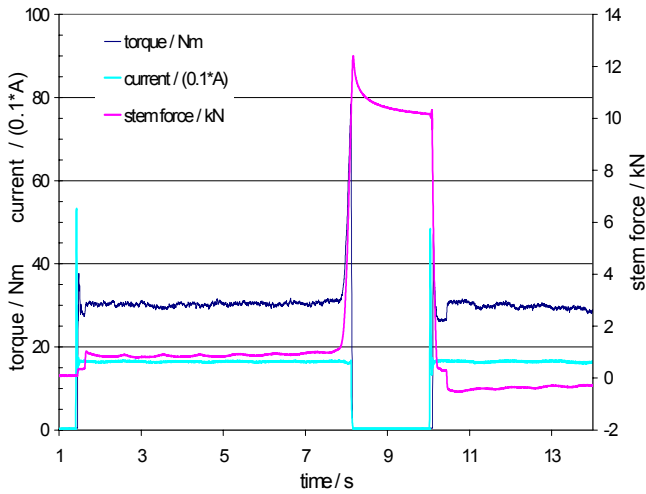


Figure 6 Comparison of motor current, torque and stem force for a closing and opening run of a MOV; 1 Nm = 0.74 lb-ft, 1 kN = 225 lb

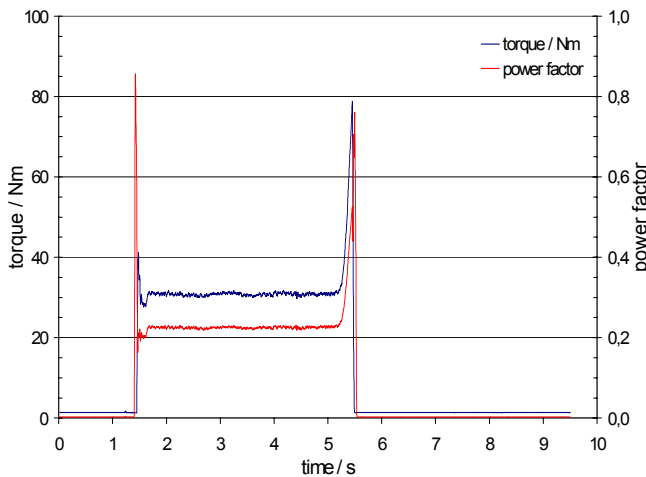


Figure 7 Power factor and torque during the closing run of the MOV used in Figure 6

Figure 8 shows a closing and an opening run of the MOV where the valve is operated against a spring. The stem force as well as the torque increases linearly when the spring is loaded up. This test directly reveals the proportionality between measured force and torque. Again, the current cannot be used as load indicator.

The relationship between the measured torque and thrust can be established based on current industry practice. Therefore, based on the known relationship between the baseline thrust signature and torque of a specific valve, the equivalent thrust can be established from the torque measured at the MCC for a given valve.

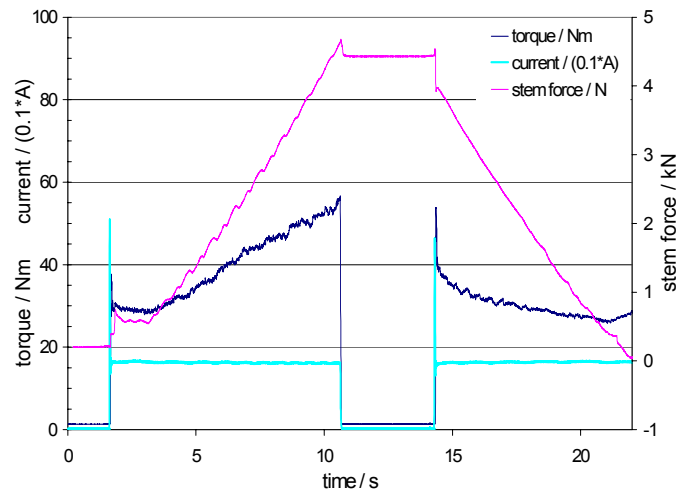


Figure 8 Same measurement as in Figure 6 but with an increasing stem force simulated with a spring inside the valve

VI. CONCLUSIONS

The capability of measuring the motor shaft output torque is presented in this paper. The measurement accuracy is outstanding and is therefore highly attractive for the evaluation for actual available motor torque margin in MOV's. This measurement of torque can be applied to any motor installed in the actuators. In addition to the motor torque measurement, the health of the actuator can be trended. The measurement is simple and cost effective. The features of Sensorq[®] can also be utilized for trending motor performance and health of the actuator.

VII. REFERENCES

- [1] David Brown and E.P. Hamilton III, Electromechanical Energy Conversion, McMillan Publishing Company, 1984

VIII. ACKNOWLEDGEMENT

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