Proceedings of the Korean Nuclear Society Autumn Meeting
Seoul, Korea, October 2001

Motor Torque Analysis for Motor-Operated Valves Performance Evaluation

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ABSTRACT

This paper is to see the availability of electrical signatures as a means for evaluating performance of MOVs which are extensively used in safety-related systems in nuclear plants. To estimate motor torque, two methods such as d-q frame conversion and air-gap method are suggested and estimated results are compared with measured values. The error between measured and estimated torques is within acceptable error bound with below 1 % under varied load. Frequency domain analysis of calculated torque has been done as well. It is shown that monitoring of peak frequency could give useful clues to detect anomalies of MOV. As results, electrical signatures at MOV motor is expected to be an available tool for estimating motor capacity and monitoring of electrical and mechanical abnormalities.

1. INTRODUCTION

Motor-operated valves(MOVs) are commonly used in critical safety-related applications in nuclear plants. In recent years, considerable regulatory and utility attention has been given to MOV-related safety issue. In order to resolve such a safety issue, direct sensor-based measurements of mechanical parameters like stem torque and thrust have been adopted. These measurements are necessary to ensure that each valve's design basis requirements are met. However, this type of testing does not necessarily provide the most effective or efficient method for the long-term periodic verification of MOV performance. Recently, some techniques using electrical signatures input to a motor have been developing for evaluating MOV performance and monitoring degradation based on the fact that the change of electrical signatures are usually incurred by mechanical load change or anomalies in MOVs.

Within an electro-mechanical system of an typical MOV, motor torque is converted into stem torque, which is an actual operating force to push and pull a valve disc, through various transfer interfaces like actuator gears and a stem nut as shown in Fig.1[4]. As the first step for estimation of mechanical stem torque, two methods such as d-q frame conversion and air-gap method using 3-phase currents and voltages at motor are proposed in this paper, In addition, frequency domain analysis of electrical signatures is introduced to see the feasibility of the frequency analysis method as an available tool for monitoring the anomalies of MOV components.

2. TORQUE ESTIMATION

D-Q frame conversion

The motor torque calculation error is caused by improper adoption of the time varying characteristics of the motor. The d-q stationary reference frame allows analyzing the motor without depending on the rotor position, which generates a result

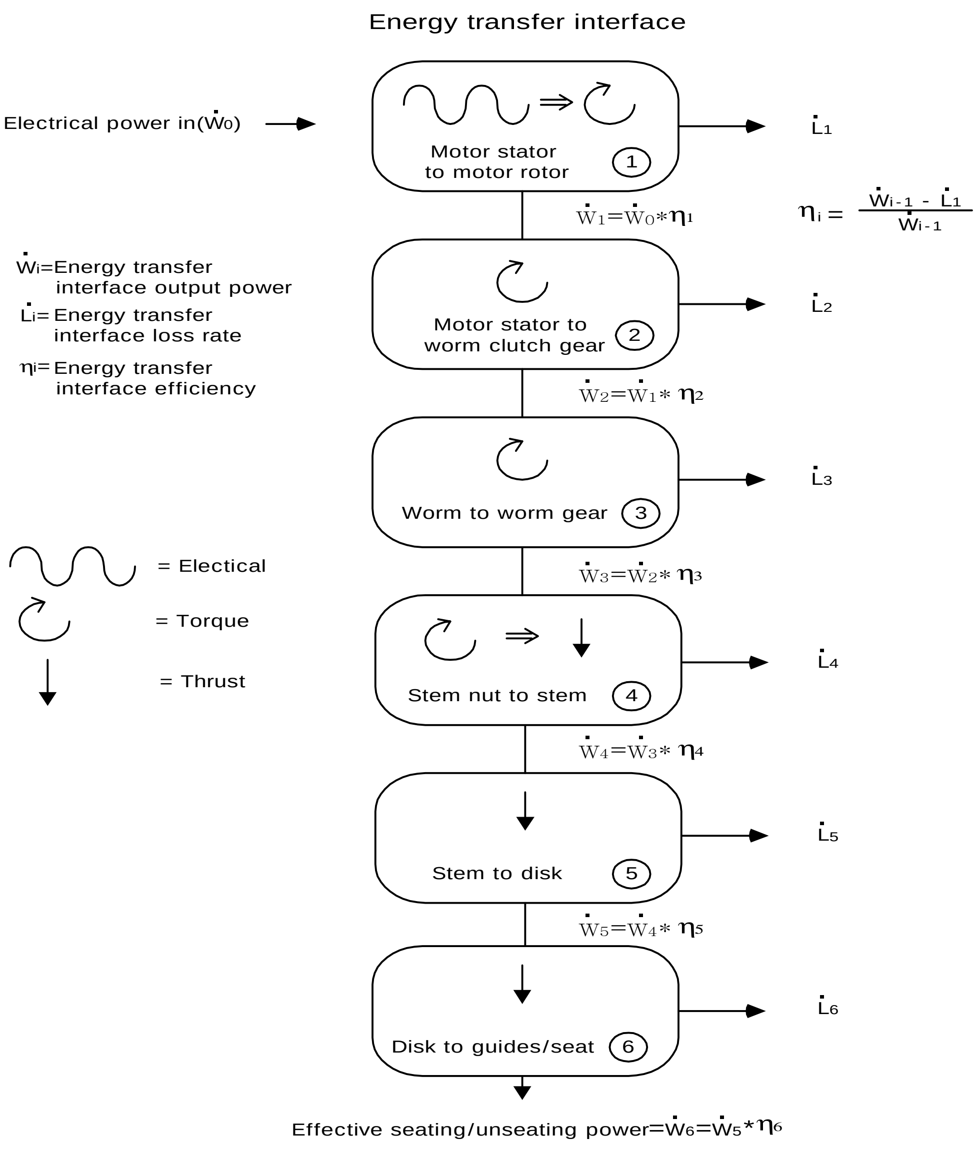

Figure 1. Simplified Energy transfer schematic

with higher accuracy. By frame conversion, 3-phase motor power, voltage and current can be transferred to the d-q reference frame as shown in Fig.2 and Eq.(1)

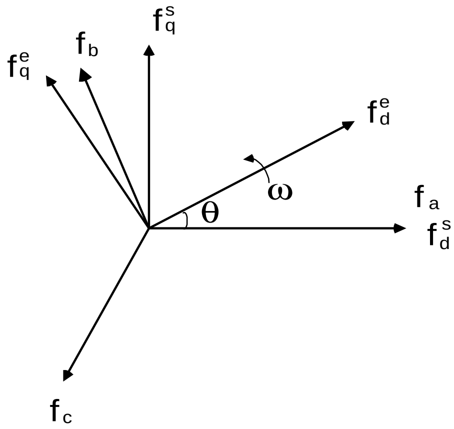

Figure 2. Frame conversion for torque estimation

$$f_{dqn}^{w} = T(\theta) f_{abc} \quad (1)$$

where, $f_{dqn}^{w} = [f_d^w \;\; f_q^w \;\; f_n^w]^T$, $f_{abc} = [f_a \; f_b \; f_c]^T$

$$T(\theta) = \frac{2}{3}\begin{vmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{vmatrix}$$

where, $\theta =$ rotor position at the reference frame

From these equations, we obtain d-q voltage equations at motor stator.

$$\begin{aligned} V_{ds} &= r_s i_{ds} + p\lambda_{ds} - w\lambda_{qs} \\ V_{qs} &= r_s i_{qs} + p\lambda_{qs} + w\lambda_{ds} \\ V_{ns} &= r_s i_{ns} + p\lambda_{ns} \end{aligned} \quad (2)$$

where, p = differential operator

For the calculation of motor flux, the motor parameters of the equivalent circuit, d-q frame voltage, and current are used in Eq.(3).

$$\begin{aligned} \lambda_{ds} &= \int_0^t (V_{ds} - r_s i_{ds}) d\tau \\ \lambda_{qs} &= \int_0^t (V_{qs} - r_s i_{qs}) d\tau \end{aligned} \quad (3)$$

where, r_s = stator winding resistance

λ_{ds} = motor magnetic flux of d axis

λ_{qs} = motor magnetic flux of q axis

i_{ds} = motor current of d axis

i_{qs} = motor current of q axis

Using the stator current and the stator flux obtained from Equation (3), motor torque can be calculated in Eq.(4)

$$T_e = \frac{3}{2}\frac{p}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \tag{4}$$

where, p = the number of motor poles

Air-Gap torque

The following voltage equations are for the 3-phase armature windings,

$$\begin{aligned} v_a &= \frac{d\lambda_a}{dt} + r i_a \\ v_b &= \frac{d\lambda_b}{dt} + r i_b \\ v_c &= \frac{d\lambda_c}{dt} + r i_c \end{aligned} \tag{5}$$

where,

λ_a, λ_b, λ_c = flux linkages of windings a, b, and c.

r = the phase resistance

From Eg.(5) the flux linkages can also be given as

$$\begin{aligned} \lambda_a &= \int (v_a - r i_a) dt \\ \lambda_b &= \int (v_b - r i_b) dt \\ \lambda_c &= \int (v_c - r i_c) dt \end{aligned} \tag{6}$$

Subtracting the copper losses and the terms pertinent to the energy stored in the windings from Eq.(6)[3], the air gap torque equation is modified into Eq.(7) with only line voltage and current terms.

$$T = \frac{P}{2 \cdot \sqrt{3}} \begin{pmatrix} (i_a - i_b) \cdot \int [v_{ca} - R(i_c - i_a)] dt \\ -(i_c - i_a) \cdot \int [v_{ab} - R(i_a - i_b)] dt \end{pmatrix} \tag{7}$$

where,

p = number of poles

i_a, i_b, i_c = line currents

R = half of the line-to-line resistance value

From above two methods, torque calculation of induction motor can be accomplished through Eq.(4) and (7). The simulation results obtained from two equations overlapped with exactly same values obtained from each methods as shown in Fig.3. Fig.4 shows torque values directly measured by torque meter. The error range between actual and estimated values under varied load is within 1 % . It is supposed that these two methods could be a good means for estimation of valve stem torque without attachment of a sensor to stem.

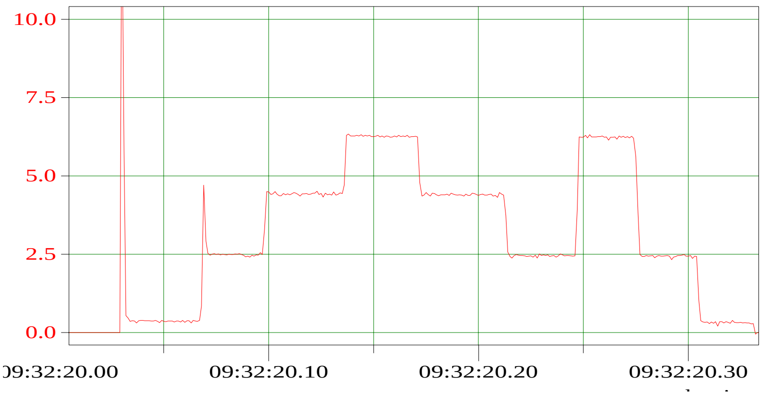

Figure 3. Estimated torque by d-q frame conversion and air gap

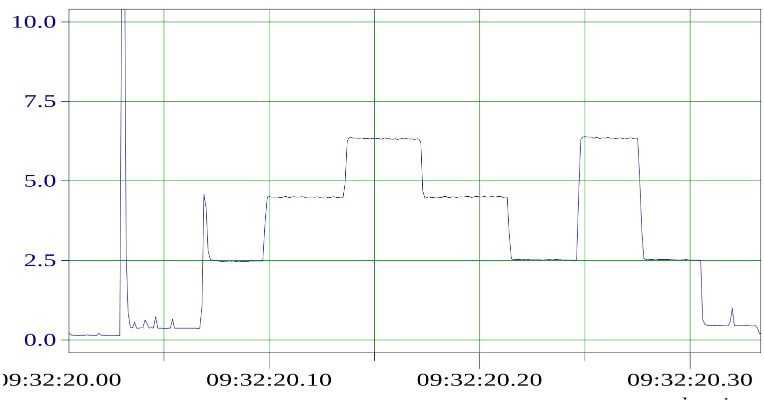

Figure 4. Measured torque by torque meter

3. TORQUE FREQUENCY ANALYSIS

Once torque is calculated through Eq.(4) or Eq. (7), resulting torque signals can be used for motor fault and characteristic analysis. Because calculated torque is harmonic of current and voltage, usage of torque has more advantages than current for analysis of motor character. Frequency domain shows slip frequency and motor speed that are not found at time domain. Fig.5 shows results of frequency analysis of torque, which includes two peaks below 60 Hz. Theoretically, they are known as slip and motor speed frequency.

Slip frequency is defined as follows ;

$$SF = (\text{ synchronous speed} - \text{actual speed }) \times (\text{ number of motor poles }) \tag{8}$$

Variations in motor speed are thus observed as the slip frequency varies. For example, the actual motor speed(AMS) of a four-pole ac (60 Hz) induction motor is determined from the slip frequency as follows ;

$$AMS = 60 \times [\ 30 - (\ SF/4\ )] \qquad (9)$$

where, SF is in hertz and AMS is in rpm.

The change of slip frequency is a good indicator of motor degradation. High slip pole amplitude followed by several successive harmonics is indicator of motor electrical or mechanical imbalance. Electrical imbalance can be a common symptom associated with rotor bar damage.

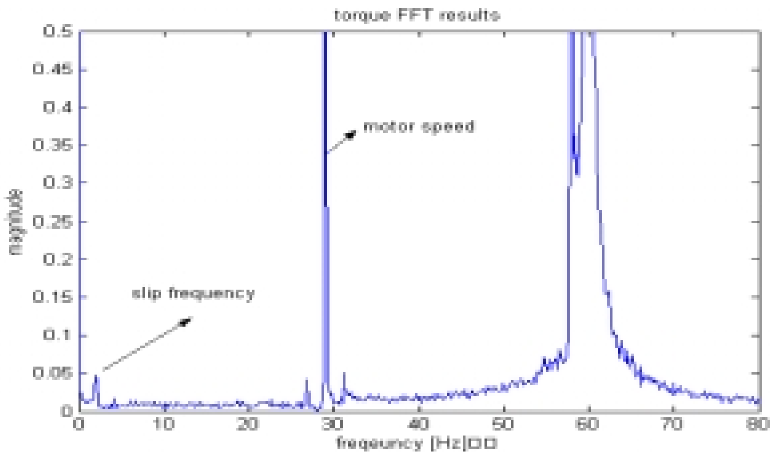

Figure 5. Frequency spectra of motor torque

Fig.6 and Table1 illustrate the change of motor speed frequency with respect to load change. The observed motor speed frequency decreases as the motor load (torque) increases. Since motor speed is also related with slip frequency, it is easily observed in Fig.7 that as motor torque increases, slip frequency moves right or increases. It is also found that the slip frequency is more sensitive to the load change than motor speed [1][2].

4. SIMPLE EXAMPLES OF MOV DIAGNOSIS

Fig.8 presents motor power signal of MOV actuator at time domain. The signature includes features that reflect normal gate valve strokes such as transients associated with valve seating and unseating. This behavior looks similar to current signal [2].
Changes in running current during a valve stroke may reflect changes in stem packing friction loads. The running load associated with stem packing friction is first observed at the point of initial stem movement, a feature more easily seen in Fig.9 (open-to close stroke). This signature presents a close look at significant motor power transients and gradual changes in current which are associated with initial

stem movements, valve seating, and valve unseating. In Fig.9, the no load power

Table 1. The change of motor speed and slip frequency due to Torque change

No	torque(N.m)	RPM	Slip Freq.[Hz]
1	0	1794	0.67
2	2.25	1780	1
3	4.22	1768	1.33
4	6.37	1754	1.5
5	7.35	1746	1.83
6	8.43	1738	2

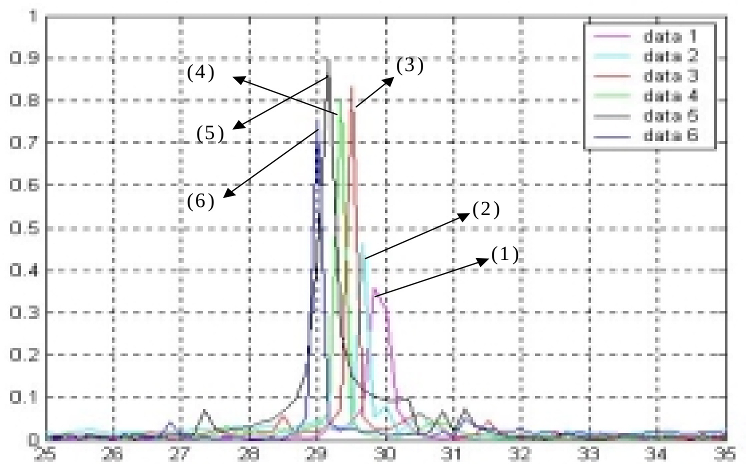

Figure 6. The shift of motor speed due to load change

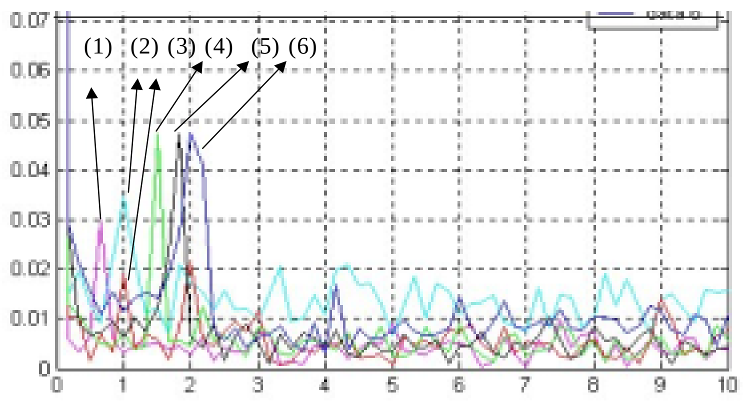

Figure 7. The shift of slip frequency due to load change

results from the free rotation of the worm gear and subsequent drive sleeve rotating that occurs before stem nut-stem thread engagement. At the end of the open-to-close stroke(Fig.8), the valve disc contacts the valve seat and adds to the loads driven by the motor. The magnitude of the motor current peak at torque switch trip reflects the motor power is de-energized on torque switch on.

Data in Fig.10 are obtained and processed from an actual MOV actuator which is one of the same kind actuator installed in the filed. In addition to the slip frequency and motor speed, worm gear tooth mesh(WGTM) frequency are observed in motor torque frequency domain. The change of peak frequency of WGTM implies the mechanical degradation of worm gear. As shown in Fig.8 to 10, electrical signatures at MOV motor can be used as an available tool for estimation of motor capacity and monitoring of electrical and mechanical abnormality [1].

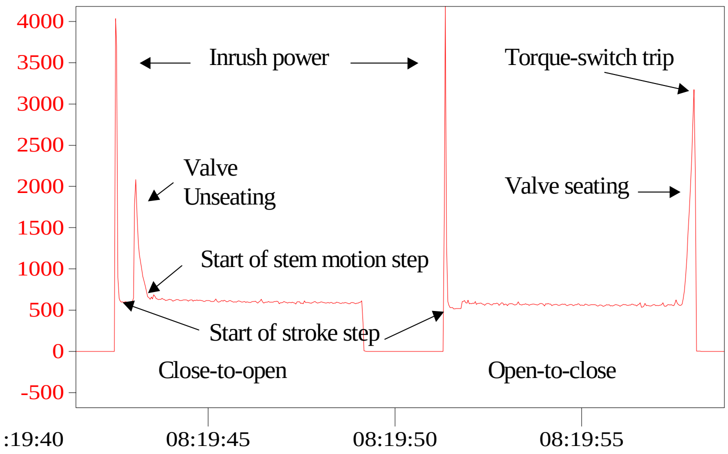

Figure 8. Motor power signature (full stroke of MOV)

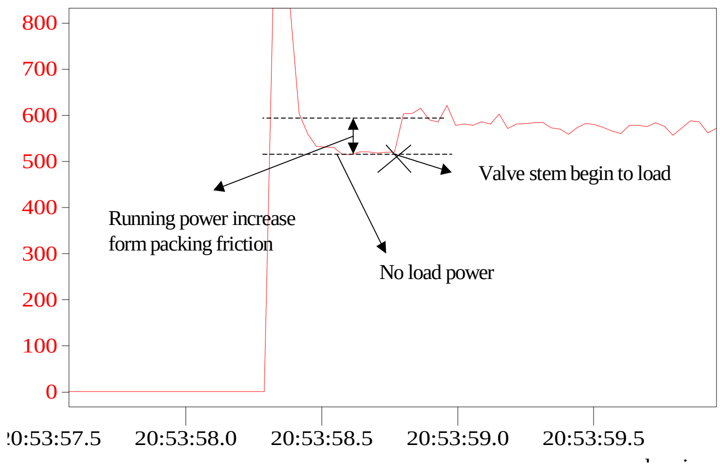

Figure 9. Motor power signature (open-to-close stroke)

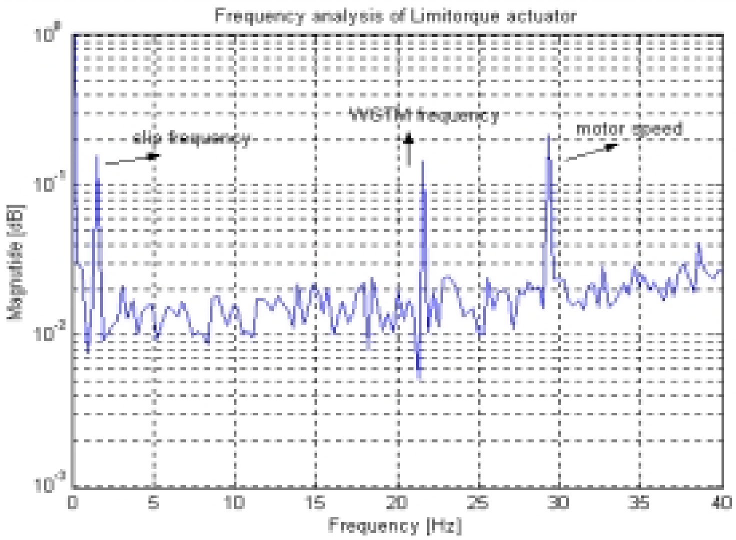

Figure 10. An example of motor torque frequency spectrum analysis

5. CONCLUSIONS

This paper is to see the availability of electrical signatures as a means for evaluating performance of MOVs. To estimate motor torque, two methods such as d-q frame conversion and air gap torque method using 3-phase currents and voltages at motor, are suggested. It is shown that calculated results from both two methods are exactly same. In addition, The error range between measured and estimated torques is acceptable with below 1 % under varied load. It is supposed that these methods could provide the basement for estimation of mechanical stem torque without attachment of sensor to the valve stem.

Calculated torque signatures have been analyzed in frequency domain. It is confirmed as expected that as the motor load(torque) increases the observed motor speed frequency decreases and slip frequency increases. It is also found that the slip frequency is more sensitive to the load than motor speed. In actual valve testing, specific components like a worm gear in an actuator can be characterized in frequency domain. It means that monitoring of peak frequency gives useful clues to detect anomalies of MOV internal components.

In conclusion, it is expected that electrical signatures at motor could be an available tool for estimating motor capacity and monitoring electrical and mechanical anomalies.

6. REFERENCE

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