TORQUE CHARACTERISTICS OF WOUND ROTOR MOTORS USED IN BRIDGE DRIVE SYSTEMS

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MOTOR CHARACTERISTICS

Probably the most common type of electric motor used as the prime mover in movable bridge drives has been, and still is, the AC wound rotor induction motor. Its most notable characteristics from the bridge drive designer's viewpoint are its high starting torque, and the variety of speed/torque curves realizable, both of which can be altered in the field for any given motor.

Modern wound rotor motors commonly used on movable bridges are of the crane and hoist type, and are generally assumed to follow a typical wound rotor induction motor speed/torque curve. Figure 1 is one such speed/torque curve often presented in motor text books. Of particular interest, especially to machinery designers, is the peak or maximum torque, in this case termed the break-down torque. Notice that this "typical" curve implies a maximum available torque of only 200 percent.

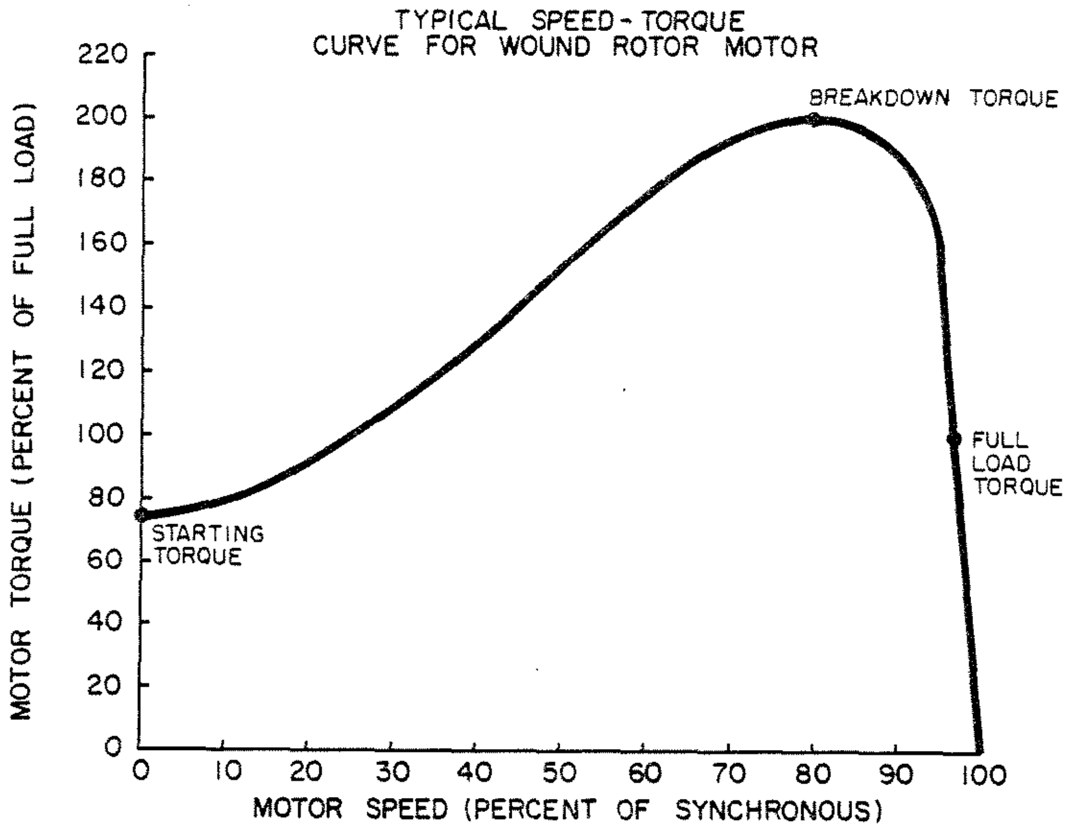


FIGURE 1

A wound rotor motor built according to the current standards of the National Electrical Manufacturers Association (NEMA) may well surprise anyone who assumes that Figure 1 is an accurate quantitative representation of his prospective motor. Modern wound rotor motors are capable of far higher breakdown torques. NEMA MG1 (1978), Paragraph MG1-18.509 A., states:

> "The break-down torque for alternating current wound-rotor crane motors, with rated voltage and frequency applied, shall be not less than 275 percent of full-load torque."

Notice that while a minimum breakdown torque of 275 percent of full-load torque is required, no maximum torque is established. However, Part B of the same paragraph offers some guidance by advising machinery designers that:

> "For the selection of gearing and other mechanical design features of the crane, 375 percent of rated full-load torque shall be used as the maximum value of break-down torque for an alternating current wound-rotor crane motor."

Although this paragraph still does not explicitly establish a maximum torque constraint for motor manufacturing, it does imply that motor users should assume that the motors will not deliver more than 375 percent of their rated full-load torque at the breakdown point.

To appreciate what these minimum and maximums may mean, let's look at an actual case. Recently, the Author had an opportunity to witness the testing of a set of main and auxiliary drive motors for a new tower-drive vertical lift bridge. The motors were 50 HP and 20 HP, 600 RPM, drip proof, wound rotor crane motors. The motors were subjected to the "complete test", on the manufacturer's dynamometer. For a summary of the tests, see Table 1. The measured torque/speed curve of one of the motors is shown in Figure 2. The other motors displayed similar curves.

TABLE 1

TEST RESULTS FOR 8 WOUND ROTOR MOTORS

Test Date	H.P.	Serial No.	Full Load RPM	Full Load Torque	Breakdown Torque
2-6-84	20	051020	582.6	180.4	575.6
4-9-84	20	051020	581.4	180.5	573.3
2-27-84	20	051021	580.5	181.0	564.5
4-9 & 10	20	051021	580.4	180.8	555.5
2-16-84	20	051022	580.2	180.2	576.9
4-10-84	20	051022	580.1	180.9	582.6
2-22-84	50	042039	588.1	445.2	1518.0
4-10-84	50	042039	588.0	446.1	1514.0
2-9-84	50	042040	588.9	445.7	1318.3
4-13-84	50	042040	587.1	445.2	1312.3
2-21-84	50	042041	588.3	445.0	1518.5
4-12-84	50	042041	587.8	446.5	1514.7
2-21-84	50	042042	588.1	445.5	1407.1
4-11-84	50	042042	587.5	446.8	1383.1
2-28-84	50	042043	588.1	446.4	1481.2
4-11-84	50	042043	587.7	446.1	1492

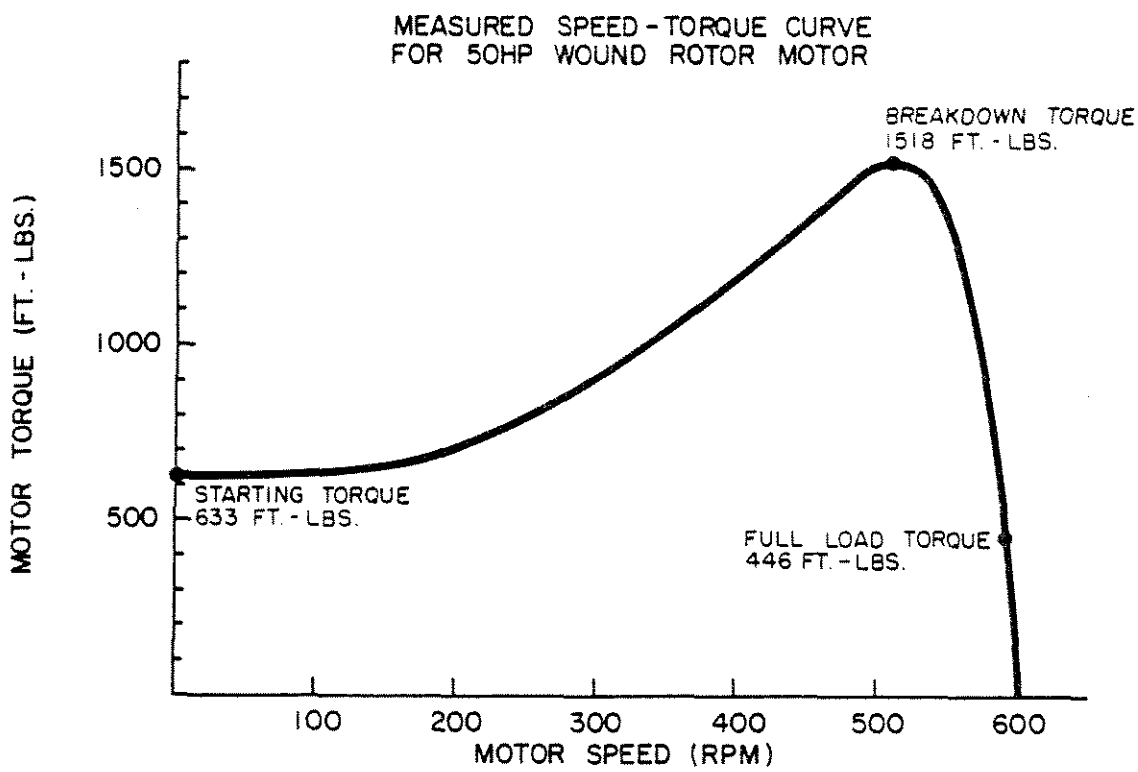


FIGURE 2

Typically, the three points on the curve of most interest would be the rated full-load torque (and speed), the starting or locked rotor torque, and the break-down torque. From the curve of Figure 2, it is seen that this motor develops its rated horsepower at 588 RPM, or just two percent slip. It can also be seen that its locked rotor torque is better than some authors suggest. But the most significant point to be seen on Figure 2 is the break-down torque, which peaks at 340 percent of rated full-load torque. This is significantly higher than the 200 percent shown in some text books, or the 275 percent minimum required by NEMA. But of particular importance, it is significantly higher than the 150 percent suggested for bridge machinery design by AASHTO (and AREA). This will be discussed in more detail later in this paper.

To exploit the potentially high starting torques available with a wound rotor motor, the user must exercise his option of altering the speed/torque characteristics by varying the external rotor circuit resistance. Figure 3 shows a family of speed/torque curves the user could experience by changing the values of rotor resistance. In general, notice that increasing the rotor resistance shifts the break-down torque to successively lower speeds, until finally it occurs at zero speed, for maximum starting torque. Further increases in rotor circuit resistance then simply lower the starting torque to produce soft start characteristics.

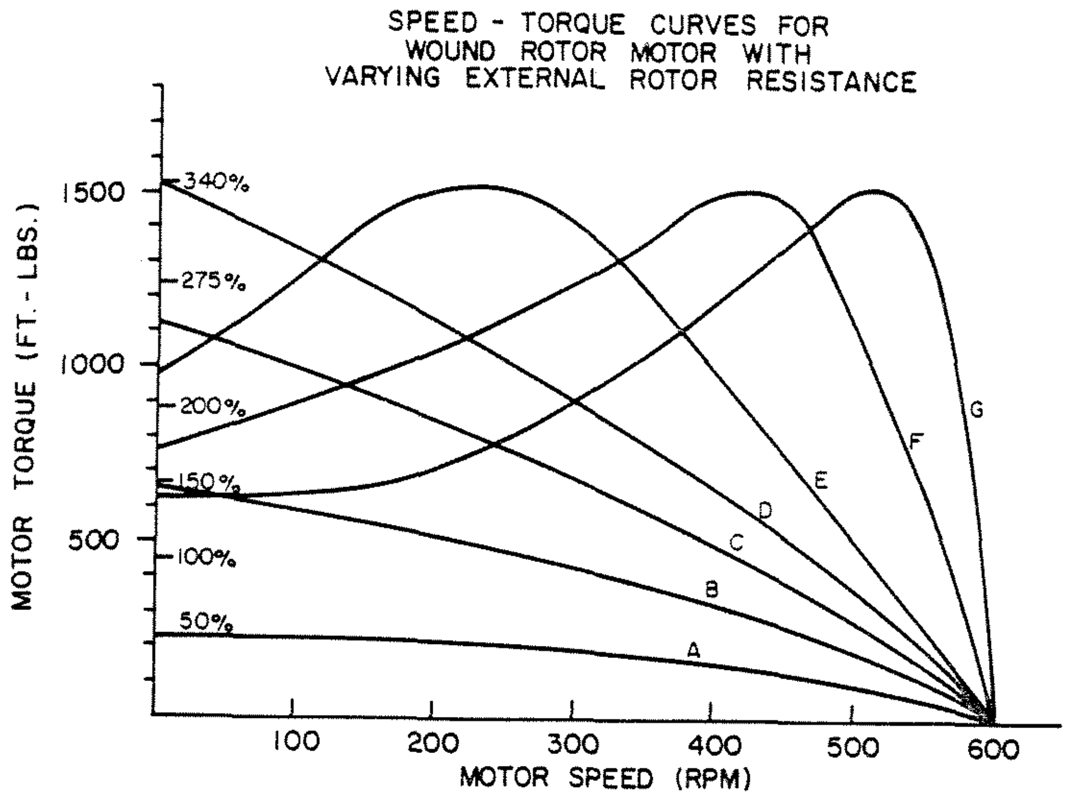


FIGURE 3

CONTROL SCHEMES

To evaluate a wound rotor motor's behavior in a drive system, we also need to be concerned with the characteristics of the motor controller. Just how does the controller effect the available torque from the motor? Does it provide true torque limiting, or just motor overload (overheat) protection?

One of the oldest, simplest, and most common controllers found on older bridges is the stepped resistance controller. In a typical installation, the rotor resistance is varied by manually operating a drum switch, much like that used in trolley cars. A bank of heavy-duty tapped resistors was provided for the rotor circuit, and the resulting family of torque curves was utilized as shown in Figure 4. By stepping through the sequence of resistance values, motor operation is switched from curve to curve. By making these transitions at the correct moment, the average torque can be kept high but the torque peaks kept within reason, say, below 180 percent. In practice, much was and sometimes still is left to the judgement of the bridge operator. With no accurate way for the operator to determine actual torque output from the motor, it often is simply his personal preference as to when he switches to the next lower resistance step during acceleration. It seems likely that the bridge machinery could at least occasionally be subject to the motor's full break-down torque.

OPERATING CURVE (DASHED LINE) FOR WOUND ROTOR MOTOR WITH STEPPED ROTOR RESISTANCE STARTING

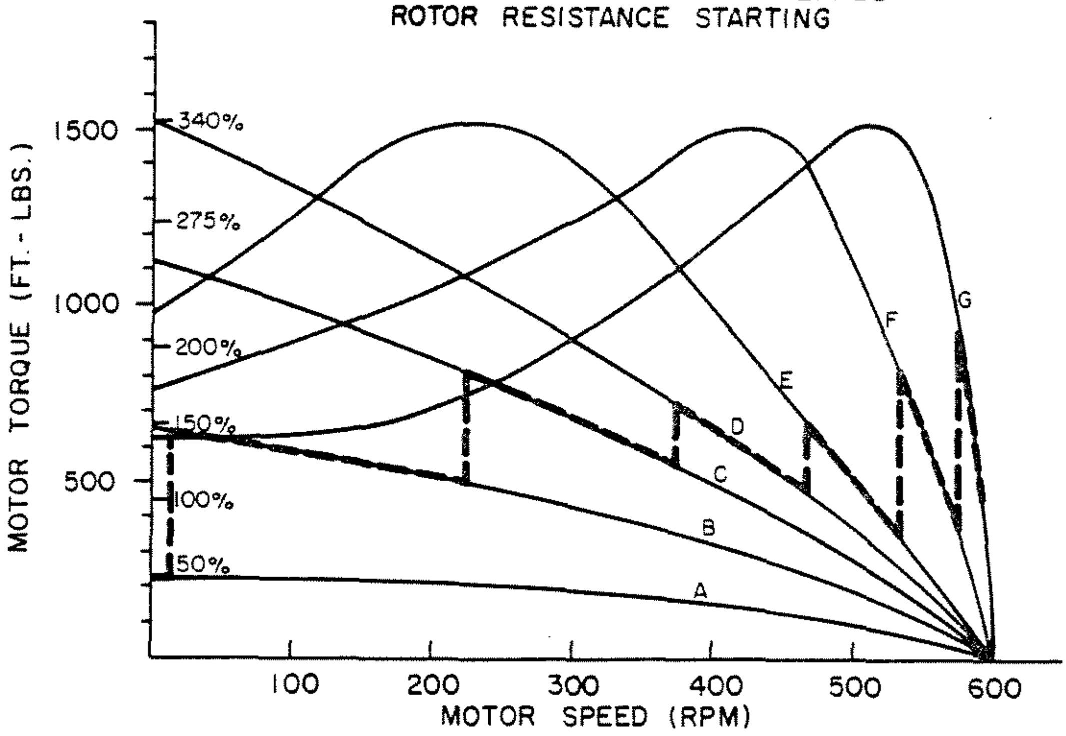


FIGURE 4

Machinery designers should take note that essentially no explicit form of torque limiting exists with the stepped resistance scheme. Motor overload relays, if provided, generally react too slow to be of value in terms of torque limiting.

A newer type of motor controller being applied with increasing frequency on bridges is a variable voltage electronic controller. In this scheme, the motor voltage is varied by a three-phase bank of silicon controlled rectifiers (SCR's), much the same as a solid state light dimmer. Tachometer feedback is usually employed along with an internally generated ramped reference voltage, which together provide linear acceleration and deceleration, as well as overall speed control. Adjustable current limiting is usually provided, and also serves as a means of torque limiting. Although some squirrel cage motors have been used, usual practice is to use a wound rotor motor and a fixed value of external rotor resistance to give about 20 to 25 percent slip at rated torque, producing a torque characteristic somewhat similar to a NEMA Design D squirrel cage motor. This choice of resistance may yield a starting torque nearly equal to the breakdown torque. The controller/motor operating characteristic is usually a four-quadrant envelope similar to Figure 5. This particular operating envelope is taken from the instruction manual for one specific manufacturer's SCR controller, and is assumed to be representative of other similar controllers.

MANUFACTURER'S SPEED-TORQUE OPERATING ENVELOPE FOR THYRISTOR SPEED CONTROLLER

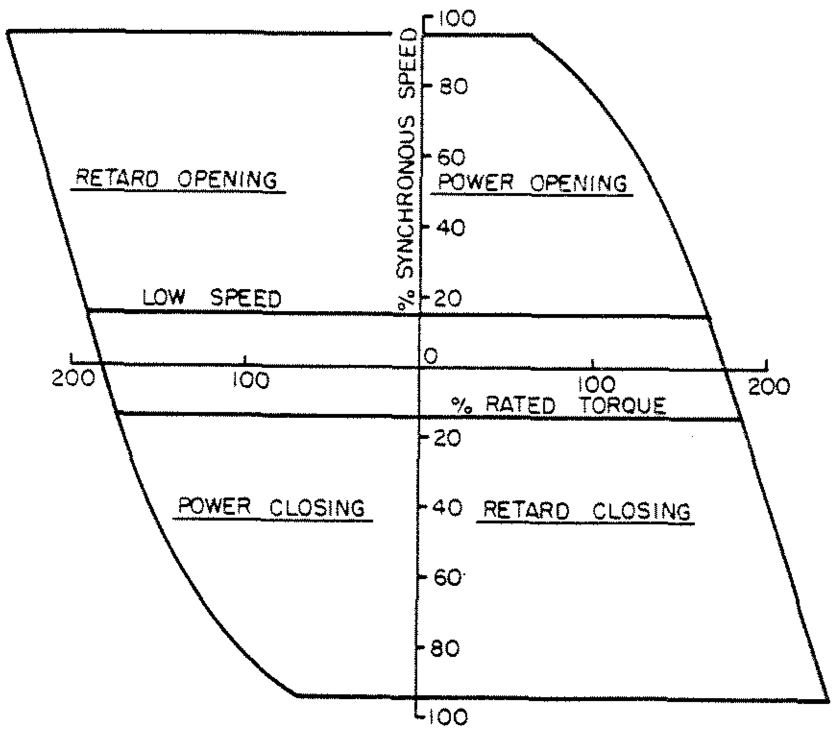


FIGURE 5

There are several reasons why the actual value of torque provided is still a matter for concern, even though torque (current) limiting of the SCR controller is used. First, the external rotor resistance alters the ratio of torque per ampere. Often, the exact ratio for the specific resistance selected is not accurately known, thereby invalidating whatever torque and ammeter relationships one may try to establish. Second, this ratio of torque per ampere varies as a function of speed. So using current limiting to achieve torque limiting results in a limiting value that is not constant as the motor accelerates. And third, the chopped waveform that results from an SCR drive is a substantial distortion of the fundamental sine wave upon which motor behavior and ammeter calibrations are based. It has been established by other segments of industry that the chopped waveform results in somewhat unpredictable torque and increased heating in motors, due to the negative sequence components in the three-phase voltage being applied. And concerning the ammeter, it must be recognized that as the SCR drive is adjusted for a specific value of current limiting, as measured on the ammeter, our meter indication and therefore the actual limiting value being set is subject to the error of measurement, the degree of which is generally unknown and varies with the degree of waveform chopping at any given instant. Although the adjustable current limiting is a useful and desirable feature, it should not be relied upon too heavily as a means of torque limiting in a quantitative sense.

BRIDGE MACHINERY

In review of the preceding material, it has been established that a wound rotor motor may deliver as much as 340 percent of rated full-load torque at its break-down point, or as its starting torque, depending on external rotor resistance. It has also been established that two of the more common controllers can't be counted on for torque limiting in a literal or quantitative sense. In reality, it can probably be generalized from these two controllers and say no controllers of wound rotor motors should be assumed to provide accurate torque limiting. On this basis, then, our concern shifts to the bridge drive machinery which must handle this motor torque.

For the design of movable bridge machinery, AASHTO directs that 150 percent of an electric motor's full-load rated torque should be used at normal allowable unit stresses (AASHTO Standard Specifications for Movable Highway Bridges, 1978, Paragraph 2.5.4):

> "The machinery for moving the span shall be designed at normal allowable unit stresses for the following percentages of full-load rated torque of the prime mover for the time specified at Condition A, Article 2.5.3 speed:
>
> Electric Motors .... 150 percent
>
> ...".

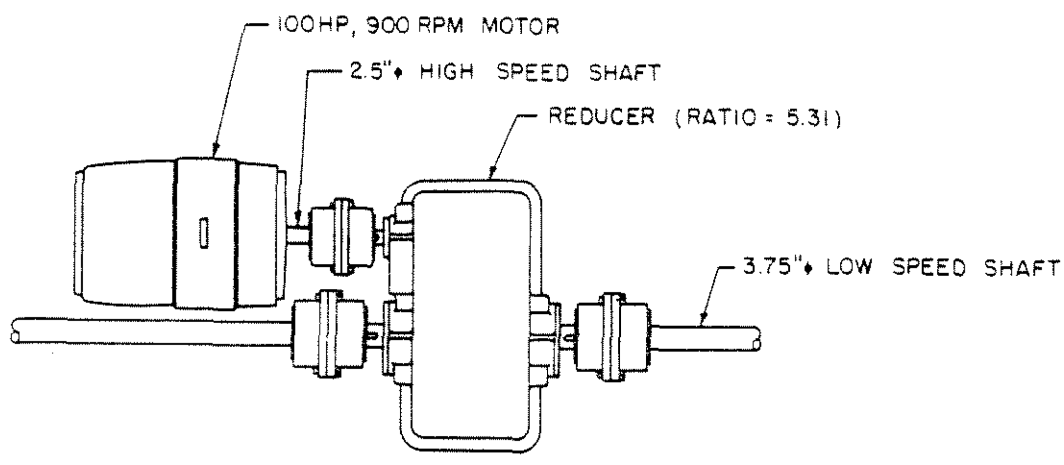
AREA also issues this directive (AREA Chapter 15, Part 6, Paragraph 6.3.10). In their electrical sections, AASHTO and AREA require that the bridge control system should limit the torque peaks during acceleration to "...preferably not exceed 180 percent of the rated full-load torque of the motor" (AASHTO Paragraph 2.10.14; AREA Paragraph 6.7.5.5). The practicality of this last requirement may be, as previously implied, sometimes questionable.

The 340 percent of full-load torque exhibited during the motor test discussed previously, is significantly greater than either the 150 percent or 180 percent suggested by AASHTO and AREA. Even NEMA's minimum breakdown torque requirement of 275 percent is significantly greater, as is NEMA's recommendation to assume 375 percent as the maximum breakdown torque when designing the crane (or in our case, bridge) machinery. However, lest we overreact to this simple comparison of numbers, a sample machinery calculation may help put things in perspective.

EXAMPLE MACHINERY CALCULATION

Assumptions

Assume that power calculations for a hypothetical movable bridge indicate the selection of a 100 Horsepower, 900 RPM motor. And assume further that we need a ratio in our primary reducer of 5.31. Looking at the manufacturer's selection tables, we find we need a Size 6, single reduction model (see Figure 6).



MACHINERY ARRANGEMENT FOR EXAMPLE CALCULATION

FIGURE 6

Motor: 100 Horsepower at 882 RPM, Wound Rotor Motor, Breakdown Torque 340% of F.L.T.

Reducer: Size 6, Type S, Ratio 5.31
High Speed Shaft Diameter: 1.75 inches
Low Speed Shaft Diameter: 3.0 inches

High Speed Shaft

Since AASHTO, Article 2.6.7, requires a minimum shaft diameter of 2.5 inches for bridge drive machinery, we will increase the reducer high speed shaft to 2.5 inches, and then check fiber and shear stresses for the applied motor torques.

From Article 2.5.15 we use the two following equations:

$$f = \frac{16K}{\pi d^3}\left(M + \sqrt{M^2 + T^2}\right)$$

$$S = \frac{16K}{\pi d^3}\sqrt{M^2 + T^2}$$

Where: f = Unit extreme fiber stress in tension or compression (psi).

S = Unit shear (psi).

d = Diameter of shaft at section considered (inches).

M = Simple bending moment computed for the distance center-to-center of bearings (assume 168 in-lbs).

T = Simple torsional moment (in-lbs).

K = 1.39 as computed according to Article 2.5.11.

The results for 100, 150, and 340 percent of rated motor full-load torque are tabulated in Table 2, based on forged alloy steel, AASHTO M102, Class G.

TABLE 2

STRESS IN A 2.5 INCH DIAMETER REDUCER INPUT SHAFT

High Speed Reducer Input Shaft Torque (2.5" Dia.)	Motor Torque (Inch-Lbs.)	"f" Extreme Fiber Stress (PSI)	* Maximum Allowable "f" (PSI)	"S" Shear Stress (PSI)	* Maximum Allowable "S" (PSI)
100%	7,145	4,506	16,000	4,403	8,000
150%	10,718	6,707	16,000	6,604	8,000
340%	24,295	15,071	16,000	14,967	8,000

* - Maximum allowable stresses for Forged Alloy Steel, AASHTO M102, Class G, and AREA ASTM A668, Class G.

Note that the maximum allowable shear stress is exceeded for 340 percent of the motors full-load torque.

Low Speed Shaft/Line Shaft

For the low speed shaft, the torques were computed assuming 2 percent loss in the reducer. To compute M, the distance between pillow blocks was arbitrarily chosen to be 8 feet, with a shaft weight of 133.6 pounds, and a 56 pound coupling 15 inches beyond the pillow block, resulting in 7,253 in-lbs for M.

Using the previously given equations for fiber and shear stress, it was found that the shear stress governed the shaft diameter. Various diameters were tried, using 150 percent of the motor full-load torque according to Article 2.5.4. It was found that a 3.75 inch diameter shaft was the smallest nominal diameter that would satisfy the shear stress requirement for forged alloy steel, AASHTO M102, Class G.

The fiber and shear stresses are tabulated in Table 3 for 100, 150, and 340 percent of motor full-load torque applied to the reducer high speed shaft.

TABLE 3

STRESS IN A 3.75 INCH DIAMETER REDUCER OUTPUT SHAFT

Low Speed Reducer Output Shaft Torque (3.75" Dia.)	Shaft Torque (Inch-Lbs.)	"f" Extreme Fiber Stress (PSI)	* Maximum Allowable "f" (PSI)	"S" Shear Stress (PSI)	* Maximum Allowable "S" (PSI)
100%	37,181	6,069	16,000	5,085	8,000
150%	55,775	8,524	16,000	7,550	8,000
340%	126,426	17,973	16,000	17,000	8,000

Output torques are based on a reducer ratio of 5.31 and losses of 2% in the reducer.

* - Maximum allowable stresses for Forged Alloy Steel, AASHTO M102, Class G, and AREA ASTM A668, Class G.

Notice that in the case of the 2.5 inch high speed input shaft, which was actually somewhat oversized to comply with AASHTO's minimum allowable shaft size of 2.5 inches, Article 2.6.7, the shear stress is 187 percent of the allowable shear stress when the motor torque goes to 340 percent. And in the case of the 3.75 inch low speed output shaft, which was sized according to the 150 percent criteria, the shear and fiber stresses are 212 and 112 percent of the allowable shear and fiber stresses, respectively. Although these stresses are still far below the yield stresses, the allowable stresses given are the result of deratings for keyways, component geometry, etc. When these allowable stresses are exceeded, we are in effect, defying the deratings. Just how far the stresses should be allowed to exceed the allowables, if at all, is a matter for serious consideration.

SUMMARY AND CONCLUSIONS

The modern AC wound rotor motor is capable of delivering significantly more torque than may have been anticipated by AASHTO or AREA. Tables 2 and 3 illustrate that when the AASHTO and AREA criteria are followed, stresses in machinery components (shafts as the specific examples) could exceed the AASHTO and AREA allowable unit stresses.

The Author suggests a review of the AASHTO and AREA 150 percent allowance for electric motor torque in the machinery design, with consideration given to increasing it in recognition of the higher torques anticipated with modern wound rotor motors.

REFERENCES

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4. Nailen, R. L., Solid State Devices Protect Motors via Soft Starts, Specifying Engineer, October, 1980.