# Plugging an Induction Motor

CHARLES D. BECK, SENIOR MEMBER, IEEE, AND RALPH G. RHUDY, SENIOR MEMBER, IEEE

*Abstract*—**Plug stopping a low-inertia squirrel-cage induction motor can provide a very quick stop, but the motor draws high peak currents from the power system and delivers high transient torques to the driven machinery. This engineering phenomena is well documented, yet the potential pitfalls of plugging applications are often not appreciated. The induction motor is so widely used in industry that a review of its plugging characteristics may be useful.**

## Introduction

A MILL in a rubber plant is a classic example where very quick stopping is an essential safety requirement. The induction motor has the capability of giving the stopping performance desired, but those making such applications should be aware of the transient characteristics of such an installation.

The speed torque characteristic usually attributed to squirrel-cage induction motors is illustrated in Fig. 1.[1] Braking for quick stopping is provided by plugging. This is accomplished by a reversing motor starter which interchanges two of the three motor leads (Fig. 2). When contactor $F$ is closed the motor operates on speed torque curve $F$, and when $R$ is closed it operates on curve $R$. By averaging curve $R$, one might expect a relatively uniform braking torque of approximately 110 percent; however, this is a steady-state characteristic. The extent to which the transient characteristics may differ from the steady-state in a plugging application is illustrated by both measurements and calculations.

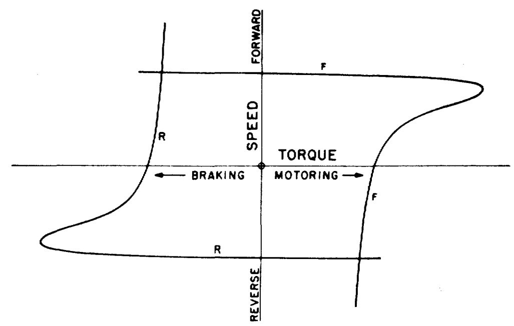



Fig. 1. Induction motor speed–torque curves.

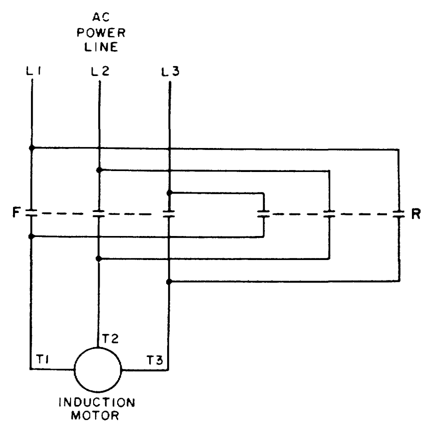



Fig. 2. Reversing motor starter.

## Measured Shaft Torques

Fig. 3 shows the torque recorded from strain gauge sensors mounted on the shaft of a motor driving an empty mill. The torque delivered to the machine rises to a braking peak of five times rated and exhibits transient oscillations throughout the short stopping period. The motor stops in less than 3/4 of a revolution after the plugging circuit is established; that is, 0.1-percent revolutions. A control time of approximately 7/60 to 10/60 of a second (or 0.2- to 0.28-percent revolutions) must be considered in calculating the stopping distance from the point where the stop switch is operated.

The motor turned in the reverse direction before the plugging $R$ contactor opened. There was just about enough reverse rotation to take up the backlash in the drive train, so the reversal was not evident on the mill rolls. Power braking is applied (plugging contactor closed) for slightly less than 2/10 of a second (10 cycles), and to the operator the entire plug stopping sequence constitutes a single violent instantaneous jolt. Much of the noise generated probably comes from the gears, which have considerable backlash.

Paper 69 TP 97-IGA, approved by the Rubber and Plastics Industry Committee of the IEEE IGA Group for presentation at the IEEE 21st Annual Conference of Electrical Engineering Problems in the Rubber and Plastics Industries, Akron, Ohio, April 14–15, 1969. Manuscript received September 18, 1969.

The authors are with the General Electric Company, Schenectady, N. Y. 12305.

[1] Fig. 1 and the motor data used in this paper are for a rubber mill motor having 125-percent starting torque and 250-percent maximum torque.

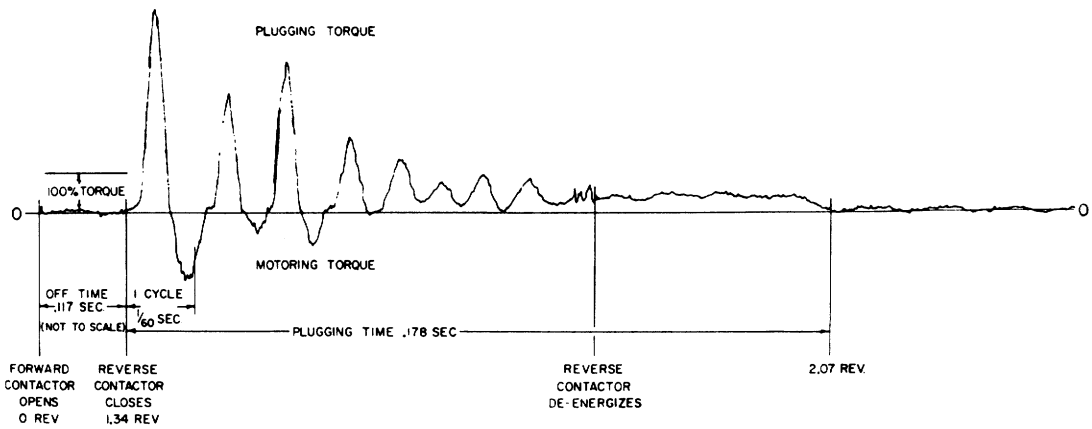



Fig. 3. Motor shaft torques plugging empty mill.

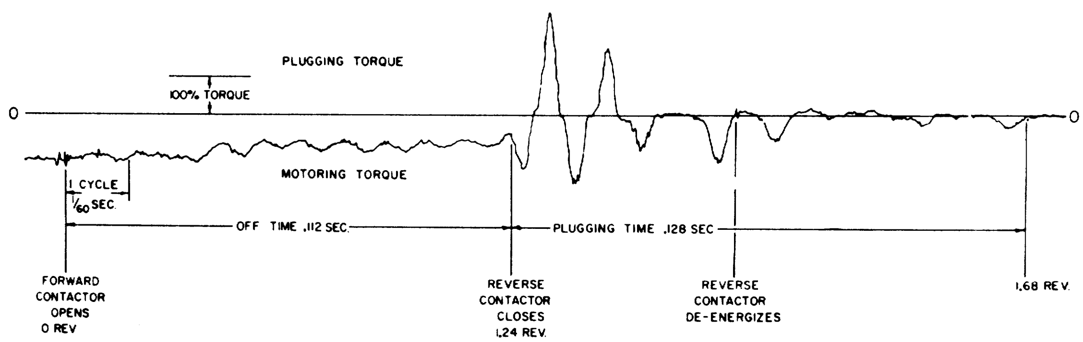



Fig. 4. Motor shaft torques plugging fully loaded mill.

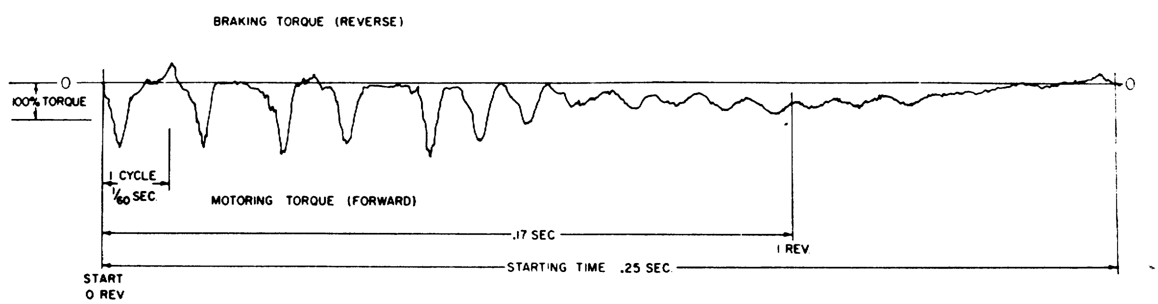



Fig. 5. Motor shaft torques starting empty mill.

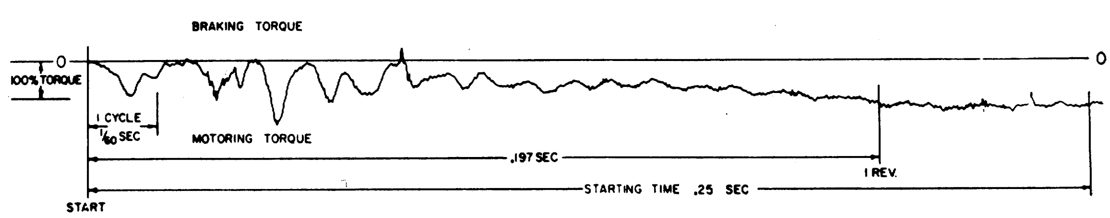



Fig. 6. Motor shaft torques starting fully loaded mill.

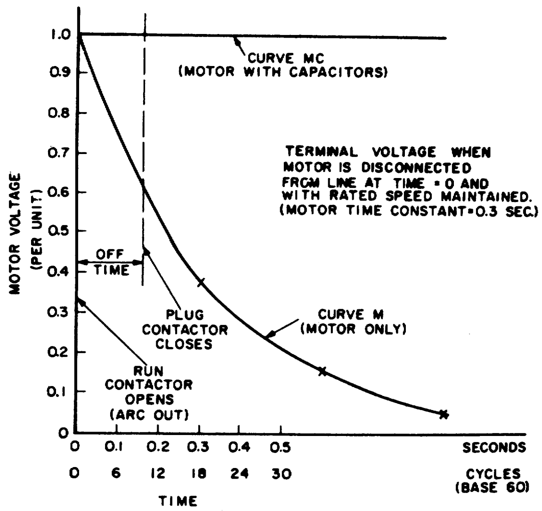



Fig. 7. Motor time constant.

Fig. 4 shows the motor shaft torque during a loaded stop; i.e., a stop with rubber in the mill. The relatively uniform motoring torque on the left is supplied by the motor inertia, as the forward (run) contactor is open and the reverse (plug) contactor has not yet closed. During this interval, the motor slows down so that braking (plug) power is applied for approximately 1/10 second.

Figs. 5 and 6 show starts of the unloaded mill (without rubber in it) and the loaded mill (with rubber in it). The transient torques are also in evidence on starting.

Normally we expect the motor air gap torque to be greater than the shaft torque by the ratio of the total inertia to the load inertia. Thus from Fig. 3 we might conclude that the peak air gap torque is approximately $17^1/_2$ times rated. However, this convenient steady-state relationship can be affected adversely and by a substantial amount, due to flexure of shafts, frames, or foundations and due to backlash which is always present in industrial machines, as will be illustrated later.

## General Considerations

The air gap torque developed during a plug stop depends upon the magnitude of the trapped flux in the machine and upon its phase angle with respect to the reapplied voltage.

When the forward contactor is opened, the trapped flux in the machine decays exponentially. See curve $M$, Fig. 7. A typical time constant for the decay of trapped flux in rubber mill motors is in the order of 1/3 to 3/4 second. Lower line currents and transient torques are developed if the residual flux is allowed to decay before the plugging circuit is established. This may be accomplished by adjustment of the time delay (off time) between the opening of the forward contactor and the closing of the reverse contactor.

When the motor is equipped with terminal connected capacitors, as for power factor correction, this has the effect of maintaining the level of flux in the machine or of increasing the motor time constant. This is illustrated by curve $MC$ of Fig. 7.

The magnitude of the peak torque and the noise associated with a plug stop varies from one stop to another. This is due to the random relationship between the trapped rotor flux and the line voltage at the instant the reversing contactor closes, and thus there is normally no way to control or to predict the exact peak torque for a particular stop.

The average steady-state torque, if the stopping cycle is long enough to permit the transients to decay, is as shown in Fig. 1. This is also illustrated by Fig. 6 (right portion of chart) for a loaded motor start.

It is inconvenient and expensive to appraise an application accurately by field testing because of the cost of making such measurements and the associated interference with production. Also, the unpredictably variable nature of the motor torque and load makes it difficult to correlate data taken for different stops. Thus a time-shared computer program was developed to calculate and to show the transient characteristics for a controlled simulation.

## Computed Torques

Figs. 8–18 show the calculated transient response of an induction motor driving a model of a rubber mill. The response is shown for various initial conditions and for some variations in the parameters of the model. These calculations were made on a time-shared digital computer. The rubber mill is represented by a single inertia driven by the motor through a flexible shaft. Backlash is permitted as assigned. The flexibility of the shaft was chosen arbitrarily to provide resonance with the mill inertia at 120 Hz. The differential equations governing the performance of this motor-inertia system were set up and integrated numerically by computer for the specified

TABLE I

DATA FOR THE 26- BY 84-INCH MILL USED IN THE ILLUSTRATIONS

| | | |
|---|---|---|
| Roll diameter | | 26 inches |
| Roll face | | 84 inches |
| Gear ratio | | 35/1 |
| Mill $Wk^2$ | | 47 lb·ft² |
| Approximate $Wk^2$ of individual machine parts (percent) | | |
| back roll | | 10.0 |
| front (drive) roll | | 7.0 |
| one gear | | 1.5 |
| another gear | | 2.3 |
| low-speed coupling | | 13.0 |
| gear reducer | | 66.2 |
| mill $Wk^2$ | | 100.0 |
| Motor | | |
| hp | | 150 |
| r/min | | 720 |
| volts | | 440 |
| $Wk^2$ | (lb·ft²) | 120 |
| full load amperes | | 208 |
| no load amperes | | 92 |
| base ohms | | 3.67 |
| stator resistance | | 0.027 pu |
| rotor resistance | (run) | 0.0196 pu |
| | (start) | 0.0411 pu |
| stator reactance | (run) | 0.118 pu |
| | (start) | 0.094 pu |
| rotor reactance | (run) | 0.085 pu |
| | (start) | 0.0444 pu |
| mutual reactance | | 2.03 pu |

boundary conditions. The motor equations are given in [1], [2]. Integration was by the Runge–Kutta four-step method, with the Gill modification. Forty equal-time increments were used per cycle (60-Hz basis). The motor parameters and the mill inertia used in the simulation are given in Table I. Figs. 8–18 were taken directly from the output of the computer terminal teletypewriter. Data for every second calculated time point was printed. Time is indicated in cycles, on a 60-Hz basis. In all cases, the plugging $R$ contacts closed at a time arbitrarily designated as 1.0 cycle.

Figs. 8 and 9 show transient values of shaft torque, motor air gap torque, motor speed, and line currents to the motor for the first few cycles of a plug stop. The boundary conditions were instantaneous plugging (no time delay between opening the forward contacts and closing the reverse contacts), no backlash, and the trapped flux–voltage relationship corresponding to a torque transient of maximum severity. Peak values of air gap torque, shaft torque, and line current are approximately 15.6, 7.3, and 16.3 pu, respectively.

The pulsation frequency of the air gap torque is 60 Hz, corresponding to the frequency of the power supply while the principal component of the shaft torque has a frequency of 120 Hz, corresponding to the resonant frequency of the mechanical system. The maximum current offset possible is not exhibited in Fig. 9, as two of the line currents are offset almost equally and in opposite directions.

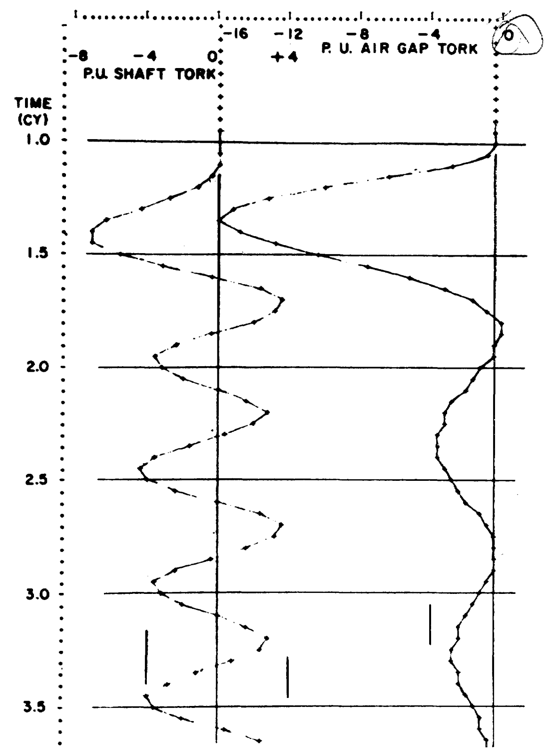



Fig. 8. Computed plug stop shaft torque, air gap torque, off time 0, backlash 0, line resistance 0.

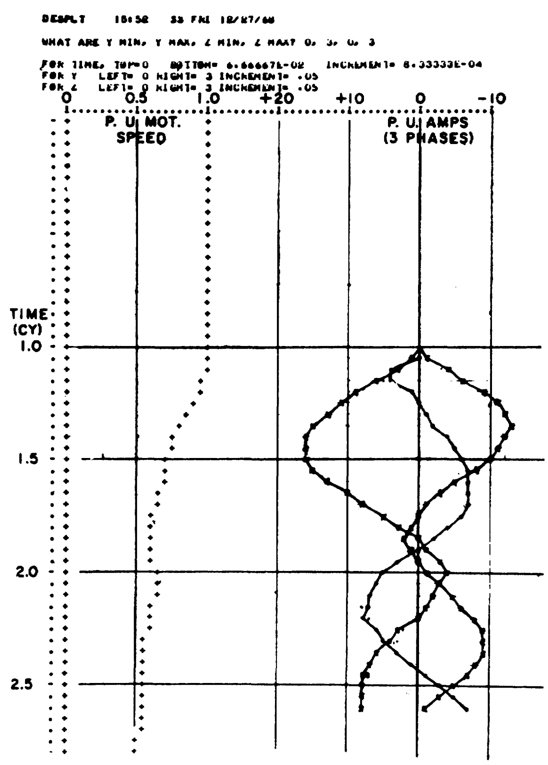



Fig. 9. Computed plug stop, motor speed, line currents (same as Fig. 8).

ING416 15117 55 FRI 12/27/68

OFF TIME, PLUG TIME, STOP TIME? .0166667, .0166667, .0666667

MECH. NAT. FREQ. = 120.108 CPS

| TIME | MOT. SPEED<br>I AS | LOAD SPEED<br>I BS | AG TORK<br>I CS | SH. TORK |
|---|---|---|---|---|
| .750000 | 1.0001 | 1.0001 | -9.54123E-04 | -3.30972E-04 |
| | -.455864 | .127706 | .328158 | |
| .800000 | 1.00010 | 1.0001 | -8.70214E-04 | -4.36741E-04 |
| | -.397880 | -1.85290E-02 | .416409 | |
| .850000 | 1.00009 | 1.00010 | -7.90200E-04 | -6.21498E-04 |
| | -.300863 | -.163062 | .463925 | |
| .900000 | 1.00008 | 1.00009 | -7.25623E-04 | -8.06161E-04 |
| | -.174286 | -.291735 | .466021 | |
| .950000 | 1.00008 | 1.00008 | -6.85848E-04 | -9.13346E-04 |
| | -3.05242E-02 | -.391935 | .422459 | |
| 1.000000 | 1.00007 | 1.00007 | -6.76661E-04 | -8.97821E-04 |
| | .116352 | -.453825 | .337473 | |
| MOTOR HAS BEEN PLUGGED. R2= .0411 | | | | |
| 1.05 | .999540 | 1.00005 | -.499017 | -3.98403E-03 |
| | .292165 | -1.4185 | 1.12634 | |
| 1.1 | .993089 | .999760 | -2.60695 | -7.79260E-02 |
| | .388044 | -3.63338 | 3.24534 | |
| 1.15000 | .974909 | .997362 | -5.94566 | -.422288 |
| | .358738 | -6.17829 | 5.81955 | |
| 1.20000 | .94284 | .988493 | -9.72709 | -1.26424 |
| | .130049 | -8.66775 | 8.53770 | |
| 1.25000 | .89963 | .966869 | -12.9938 | -2.68852 |
| | -.367362 | -10.7472 | 11.1146 | |
| 1.30000 | .85173 | .926738 | -15.0256 | -4.50412 |
| | -1.1709 | -12.1486 | 13.3195 | |
| 1.35000 | .806355 | .866147 | -15.5366 | -6.23982 |
| | -2.25907 | -12.7242 | 14.9833 | |
| 1.40000 | .768534 | .789378 | -14.638 | -7.29174 |
| | -3.54214 | -12.4497 | 15.9918 | |
| 1.45000 | .739575 | .707117 | -12.6877 | -7.16400 |
| | -4.87551 | -11.4028 | 16.2783 | |
| 1.50000 | .717336 | .633896 | -10.1384 | -5.69545 |
| | -6.08674 | -9.73441 | 15.8211 | |
| 1.55000 | .697894 | .583569 | -7.43065 | -3.16976 |
| | -7.00501 | -7.64257 | 14.6476 | |
| 1.60000 | .677718 | .564502 | -4.92407 | -.255066 |
| | -7.48605 | -5.35141 | 12.8375 | |
| 1.65000 | .655437 | .576358 | -2.85757 | 2.21140 |
| | -7.43029 | -3.0932 | 10.5235 | |
| 1.70000 | .632539 | .609832 | -1.33942 | 3.5161 |
| | -6.79472 | -1.08959 | 7.88432 | |
| 1.75000 | .612724 | .649588 | -.367662 | 3.32893 |
| | -5.59828 | .468662 | 5.12962 | |
| 1.8000 | .60023 | .679430 | .129465 | 1.82867 |
| | -3.92057 | 1.44081 | 2.47976 | |
| 1.85000 | .597798 | .687840 | .251526 | -.357577 |
| | -1.89372 | 1.75015 | .143575 | |
| 1.90000 | .605157 | .671845 | 9.65517E-02 | -2.38265 |
| | .311489 | 1.39005 | -1.70154 | |
| 1.95000 | .618689 | .637753 | -.251639 | -3.49137 |
| | 2.50279 | .422037 | -2.92403 | |
| 2.00000 | .632449 | .59845 | -.723726 | -3.299 |
| | 4.40445 | -1.03232 | -3.45213 | |
| 2.05000 | .640185 | .568309 | -1.25987 | -1.93012 |
| | 6.07502 | -2.80361 | -3.2714 | |
| 2.10000 | .637569 | .557588 | -1.80563 | 3.54838E-02 |
| | 7.12477 | -4.69055 | -2.43423 | |
| 2.15000 | .623779 | .568486 | -2.31182 | 1.78961 |

Fig. 10. Computer output sheet (conditions as in Fig. 8).

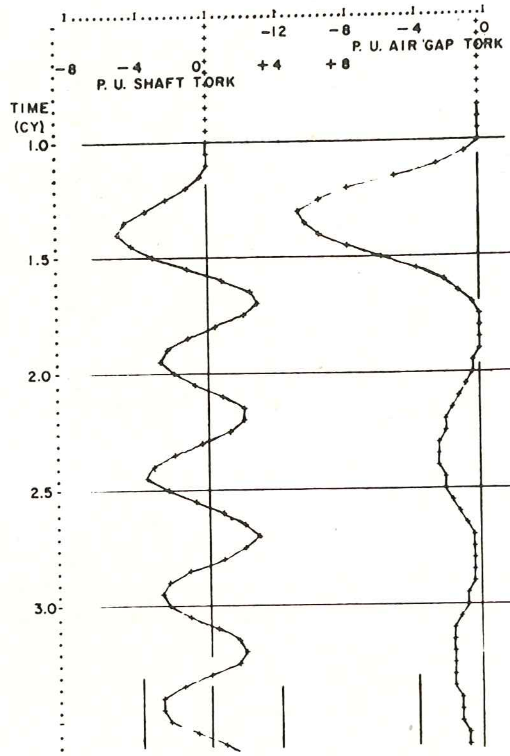



Fig. 11. Computed plug stop, shaft torque, air gap torque, off time $6^1/_2$ cycles, backlash 0, line resistance 0.

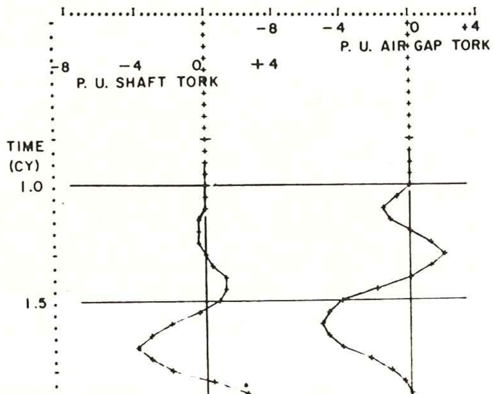



Fig. 12. Computed plug stop, shaft torque, air gap torque, off time $6^3/_4$ cycles, backlash 0, line resistance 0.

Fig. 10 shows a copy of the numbers generated by the computer for the plugging transient illustrated in Figs. 8 and 9. As in the curves, data is shown here for every other time interval for which calculations were made. Prior to time 1.0 cycle, the motor was running, steady state, at approximately synchronous speed, no load. Two rows of output data, in per-unit values, are shown for each time. In successive columns, the first row gives time, motor speed, load speed, air gap torque, and shaft torque. The second row gives the three line currents. Braking torques are negative quantities.

Fig. 11 shows the torque transients when the closing of the reverse $R$ contactor is delayed for a period of $6^1/_2$ cycles (60-Hz basis) following opening of the forward $F$ contactor. Otherwise, conditions are the same as for the transient of Figs. 8–10. That is, backlash is zero, and the trapped flux–voltage relationship corresponds to a transient of maximum severity.

Comparison of Figs. 8 and 11 shows that the delay of $6^1/_2$ cycles in closing the reverse $R$ contactor reduces the peak value of both air gap torque and shaft torque by about 1/3. Again, air gap torque and shaft torque exhibit principal frequencies of pulsation of 60 and 120 Hz, respectively.

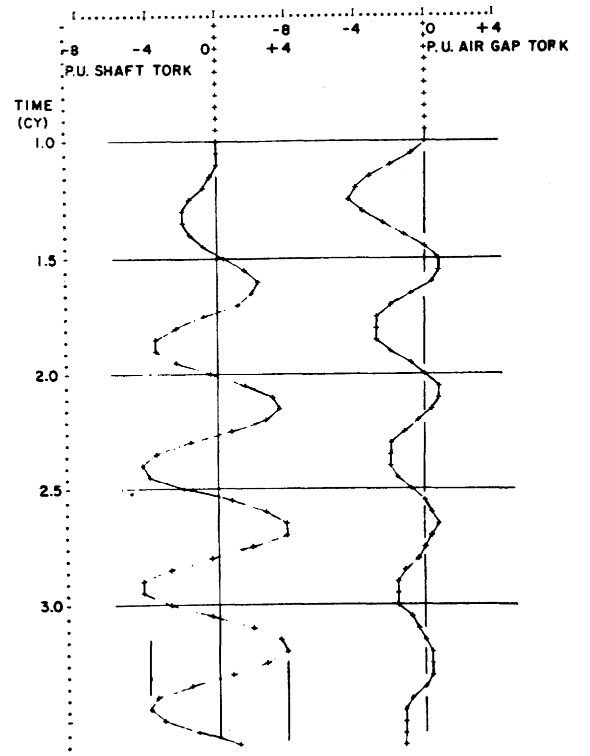



Fig. 13. Computed plug stop, shaft torque, air gap torque, off time $6^1/_2$ cycles, backlash 0, line resistance 0.2 pu.

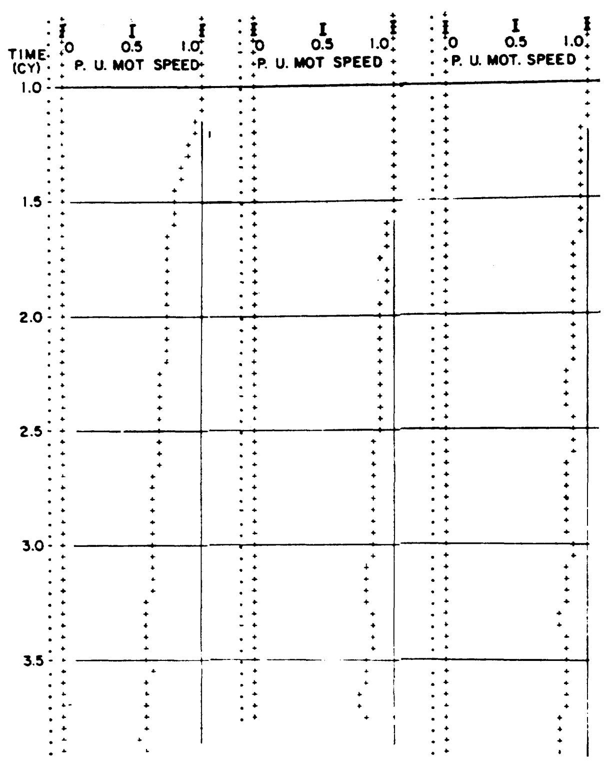



Fig. 14. Computed plug stop, motor speed, left to right for Figs. 11–13.

The conditions for the transient of Fig. 12 are the same as those for Fig. 11 except the closing of the reverse $R$ contactor is delayed for $6^3/_4$ cycles rather than $6^1/_2$ cycles, as shown in Fig. 11. The principal difference is in the phase relationship between trapped flux and terminal voltage, which in the case of Fig. 12, corresponds to a torque transient of minimum severity. Air gap and shaft torque peaks shown in Fig. 12 are about 50 and 75 percent, respectively, of those shown in Fig. 11.

The conditions for the transient of Fig. 13 are the same as those for Fig. 11 except that in the case of Fig. 13 a resistance of 0.2 pu is added in series with each line. The gross effect of this resistance is to reduce the voltage applied to the motor windings. This case is unique among those investigated in that both torques shown have a pulsation frequency of 120 Hz.

Calculated values of motor speed corresponding to the transients shown in Figs. 11–13, are shown in Fig. 14. The rate at which the motor speed drops depends upon the trapped flux–voltage phase relationship. This is illustrated by comparison of the speed traces shown at the left and the center of Fig. 14. Observations made during the field measurements support this conclusion, at least in a qualitative sense, in that the noise and apparent shock associated with plug stops appear to vary considerably from one stop to another. The calculated motor speed shown on the right of Fig. 14 corresponds to the torque transient of Fig. 13, where a series resistance was present in the lines to the motor. The consequent reduction in severity of the torque transient is accompanied by reduced deceleration of the motor (longer time to stop).

Figs. 15–18 show calculated values of torque and speed for initial conditions previously considered but with backlash between the inertia of the motor and the mill. With the exception of backlash, Figs. 15 and 16 correspond to Fig. 8, and Fig. 17 corresponds to Fig. 11. Comparison of these figures shows that backlash has very little effect on air gap torque but has a great effect on shaft torque. Backlash causes shaft torque to increase greatly in magnitude and to become peaked in shape. Comparison of these calculations of torque with the test data of Figs. 3–6 makes it appear quite likely that the sharp torque peaks observed in the field tests may have been due to backlash. As was indicated earlier, the mill simulation was by a single lumped inertia and a flexible shaft. In the actual mill, there are a number of elements, each having torsional flexibility and inertia, with an indefinite backlash between elements.

## Instrumentation

The torques shown in Figs. 3–6 were measured by strain gauges bonded directly to the motor shaft. The gauges are connected to an FM–FM transmitter attached to and rotating with the shaft. Torque signals were transmitted to an FM receiver by an antenna system and used to operate a light beam oscillograph. Time was recorded

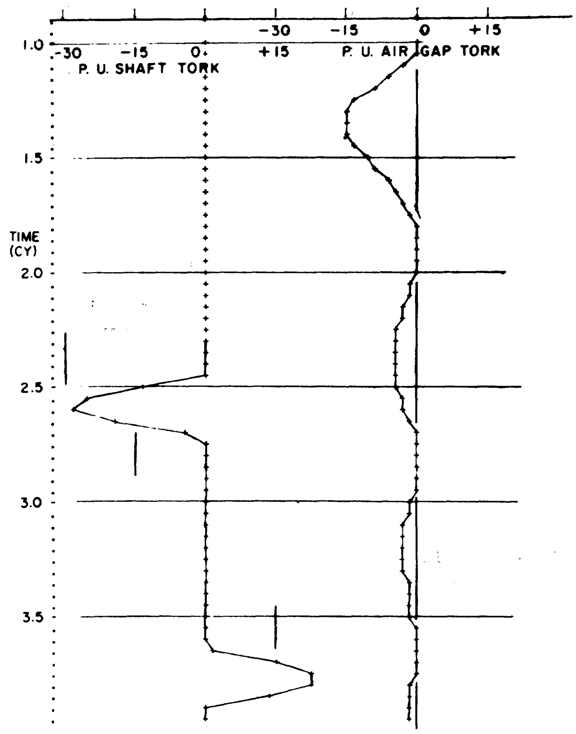



Fig. 15. Computed plug stop, shaft torque, air gap torque, off time 0, backlash 45°, line resistance 0.

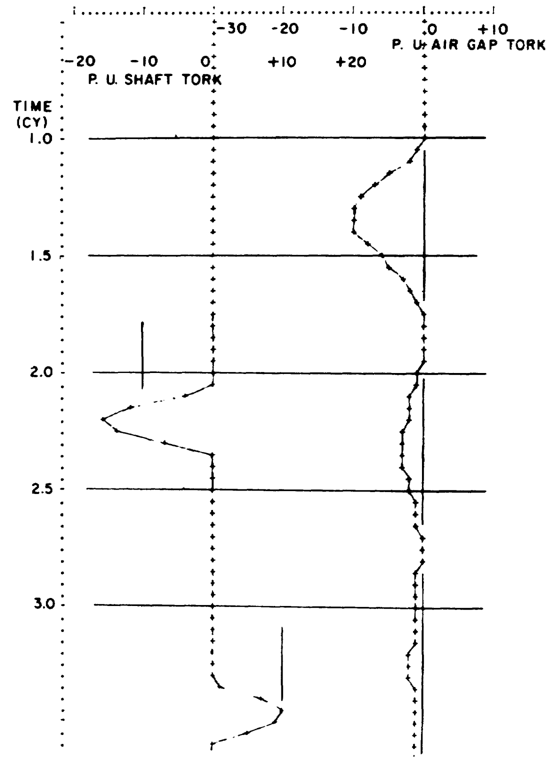



Fig. 17. Computed plug stop, shaft torque, air gap torque, off time $6^1/_2$ cycles, backlash $22^1/_2$°, line resistance 0.

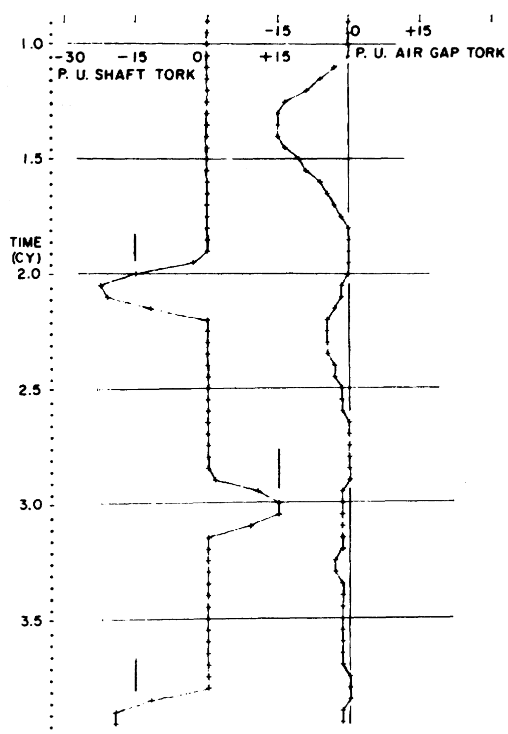



Fig. 16. Computed plug stop, shaft torque, air gap torque, off time 0, backlash $22^1/_2$°, line resistance 0.

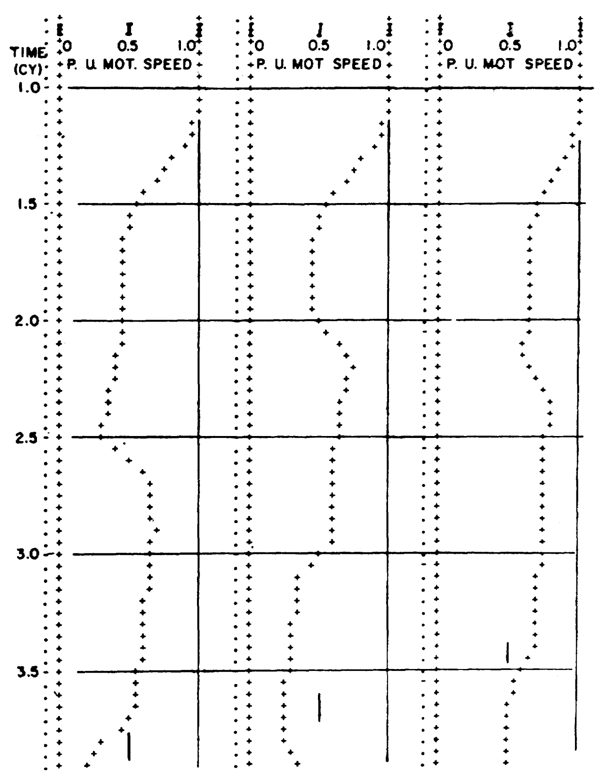



Fig. 18. Computed plug stop, motor speed, left to right for Figs. 15–17.

from a crystal oscillator. Motor rotation versus time (mill stopping distance) was monitored by a magnetic pickup which counted metallic pins equally spaced around, and bonded to, the motor shaft.

### Application Considerations

Since the 1940's typical specifications for rubber mill motors for driving open roll mills and similar mixing machinery have stated: "At rated voltage, motor will develop 125-percent starting torque and 250-percent maximum running torque. Service factor—1.15."

Standard induction motors in comparable frame sizes may have maximum and locked rotor torques as low as 175 and 60 percent, respectively. While not specified in any general standards, locked rotor currents are usually in the range of 550 to 650 percent of rated amperes. Motors designed to provide the higher torques specified for rubber mill applications often require locked rotor currents above this range.

Standard induction motors (speeds up to 1800 r/min) are suitable for plugging duty. However, unless otherwise specified, plugging duty is normally limited to an occasional plug, say, two per day. Rubber mill motors may be subjected to an average of twenty starts (and plug stops) per day. This substantially increases the duty to which the motor, the motor starter, and the circuit breaker are subjected.

### Power System

Overvoltage is another cause of excessive torques and of high transient currents. Operation of motors at or near rated voltage takes on additional importance when motors are plugged; torque increases at least as the square of the voltage.

On weak power systems, plugging current may cause excessive voltage drop. Low voltage may prevent the line contactor or the plugging contactor tips from fully wiping closed, and the tips may weld. This points up the practical value of a backup line disconnect for each motor starter.

### Circuit Breaker

The recommended trip setting for molded case breakers is nominally 12 to 14 times motor full load current to insure motor starting without tripping the breaker on transient inrush starting current. This is for standard, general purpose, nonplugging, motor applications. Most circuit breakers trip, or are caused to trip, by an overcurrent of only one half-cycle duration. Incidentally, breaker trips are rated in rms amperes. The actual plugging current on the first half cycle may exceed the calculated motor locked rotor current by as much as the rule-of-thumb factors listed below:

| | |
|---|---|
| 1) plugging with trapped flux in motor (trapped flux decays rapidly, but plugging current may also be 10 to 15 percent greater than locked rotor), | 2.0 |
| 2) dc offset (based on $X/R$ ratio of 0.55 to 0.6 typical of 750 to 1000 kVA unit substations, | 1.3 |
| 3) line voltage (if high), | — |
| 4) manufacturing tolerance on motor and circuit breakers trip | 1.15 |
| suggested factor | 3.0. |

Thus for a motor locked rotor current of $7^1/_2$ times rated, the breaker trip setting should be set at a minimum of 22 to 25 times rated motor current to avoid nuisance tripping.

### Motor Starter

Specifying higher than normal torques is equivalent to specifying a higher (nominal) hp motor. Thus for satisfactory performance it may be necessary to apply a higher nominally rated starter, particularly when the motor is to be plug stopped frequently.

Plugging provides a quick way to stop a mill. This is desirable from a safety standpoint, but it does shock the machinery violently. In practice there is a need for very few quick (or safety) stops; routine stops can be made by coasting and may be initiated from a remotely located push button.

### Plugging Switch

The plugging switch is a vital part of any plugging motor application because its performance determines the effectiveness of a stop. For example, if the contacts open momentarily during a plug, a second series of transient torques will be initiated when the reverse contactor recloses. Such spurious contact operation can occur from a lack of maintenance or from unstable foundations.

Plugging switches should be equipped with lockout coils to prevent the closing of the reverse contactor except where sequenced by the opening of the forward contactor. Without this feature it is possible for the reverse contactor to apply power to the motor when it is rotated manually, as might occur during servicing.

### Capacitors

A motor equipped with terminal connected power factor correcting capacitors will have increased transient torques and peak currents when plugged. Capacitors are usually sized to correspond, approximately, with the magnetizing kVA of the motors. When the motor is disconnected from the line, the capacitors tend to hold normal voltage on the motor terminals as long as the motor speed stays up. This has the effect of increasing the time constant for the decay of rotor flux (see curve $MC$, Fig. 7). The examples of Figs. 8 and 11 indicate that power factor correcting capacitors may increase the peak torques from $10^1/_2$ to 15 times rated torque.

The switching of power factor correcting capacitors with the motor should be avoided on applications that require plugging.

## Conclusion

High transient torques, applied across a backlash in the driven equipment, violently shock the machinery and the motor. The machinery and foundations should be designed to maintain accurate alignment of the machinery, to keep backlash to a minimum, and to avoid resonant frequencies so as to minimize displacements and stresses that might be imposed upon bearings, shafting, gears, etc.

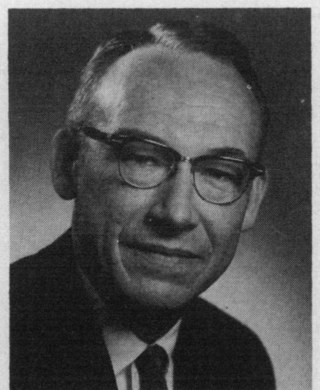

## Acknowledgment

The authors wish to thank D. E. Steeper for doing the computer simulation work.


## References


[1] P. C. Krause and C. H. Thomas, "Simulation of symmetrical induction machinery," *IEEE Trans. Power Apparatus and Systems*, vol. PAS-84, pp. 1038–1053, November 1965.

[2] F. J. Maginniss and N. R. Schultz, "Transient performance of induction motors," *AIEE Trans.*, vol. 63, pp. 641–646, September 1944.


**Charles D. Beck** (M'54–SM'59) was born in Beloit, Wis., on May 17, 1917. He received the B.S. degree in engineering from the University of Wisconsin, Madison.

He is presently employed by the General Electric Company, Schenectady, N. Y., as an Industry Systems Application Engineer. His primary interests are in the rubber, textile, and plastics industries.

Mr. Beck is a Registered Professional Engineer in the State of New York.



**Ralph G. Rhudy** (M'46–SM'55) was born in Virginia on July 19, 1920. He received the B.S. degree in electrical engineering from the University of Tennessee, Knoxville, in 1942 and the M.S. degree from Union College, Schenectady, N.Y., in 1968.

He joined the General Electric Company in June 1946 and graduated from the G. E. Advanced Engineering Program in June 1949. Since 1950 he has worked as Design Engineer, Project Engineer, and Consulting Engineer in the general area of ac rotating machines, with much of this time spent on special products such as electromagnetic pumps and canned rotor motors. He is the author of several technical papers and holds a number of patents in these fields. He is presently Consulting Engineer, ac machines, Medium AC Motor Department.