Capacitor Starting of Large Motors

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Abstract—**The basic requirements of a capacitor starting system for use in reducing voltage flicker during start-up of large induction motors are presented. Flicker calculations, control circuits, switching requirements, overstressing, and flicker reduction are discussed along with test results from several installations on the Houston Lighting and Power Company system.**

INTRODUCTION

FULL VOLTAGE starting of large induction motors can cause serious voltage flicker problems on a power system. The use of high horsepower motors in rural areas, a combination common to many pipeline pumping stations, usually represents a worst case condition with regard to voltage flicker and poses a problem to both the utility and the customer. Fortunately, there are a number of solutions to such a problem.

Some of the usual methods include auto-transformer, reactor, and unit transformer starters. Unfortunately for the user, all of these methods result in reduced starting torque, such that a motor starting under load may not be able to accelerate fully.

Capacitor starting represents a different approach to the problem of motor starting, and it has one very significant advantage over the methods mentioned above. It does not reduce the starting torque of the motor. This paper will demonstrate the calculations involved in designing a capacitor start installation, describe a control system, and show the results of such an installation.

THE PROBLEM OF STARTING LARGE INDUCTION MOTORS

An induction motor at rest can be modeled as a transformer with the secondary terminals short circuited. Thus when voltage is applied, a heavy surge of current is drawn from the power system that in turn causes a dip in system voltage. The magnitude of this dip is proportional to the magnitude of the surge and the impedance of the system. Because of the highly inductive nature of the motor circuit at rest, the power factor of the surge is quite low, usually on the order of 10 to 20 percent. As the motor accelerates to rated speed, the surge decays and the system voltage recovers.

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This dip is detrimental to a power system in two ways. First, if the magnitude of the dip is large enough, it can cause erratic operation of voltage sensitive devices such as computers and relays. Even the contactor serving the motor being started could drop back out due to low voltage. Second, it creates an annoying flicker in the lighting facilities being served by the power system. Both magnitude and frequency of flicker affect the customers on the system, and too much of either can cause complaints. In order to control such problems, most utilities have limitations regarding the magnitude and frequency of dips produced by the starting of large motors.

If across-the-line starting of a motor produces dips which exceed the flicker limitations imposed by the utility, most customers resort to the installation of some form of reduced voltage starter. Since the motor appears as a fixed impedance while at rest, reducing the applied voltage results in a corresponding reduction in starting current. Starting kVA is in turn reduced by the square of the applied per unit voltage. Since starting torque is directly proportional to starting kVA, the torque of the motor is reduced drastically. For example, a 35 percent reduction in starting voltage results in a 57 percent reduction in starting torque. If the load torque requirements exceed the torque produced by the motor for any speed less than rated speed, the motor will "lock-in" at that speed and fail to accelerate further. The motor will continue to draw a large magnitude of current, overheat, and either trip a protective device or burn up.

OPERATION OF A CAPACITOR START SYSTEM

A capacitor start system, nicknamed "Capstart," acts to reduce motor starting currents seen by the power system by cancelling out a large portion of reactive current drawn by the motor during acceleration. In reducing the current drawn from the system, it reduces the magnitude of voltage dip on the system. To effectively reduce the flicker problem, a control and switching system must be provided to energize the capacitors at the instant the motor is started and turn them off once the motor has reached rated speed. A capacitor that is on-line all of the time will change the steady-state voltage levels as seen by the power system, but will not alter the magnitude of voltage dip that occurs when the motor is started.

Thus an effective Capstart installation requires three things:

1) an adequately sized capacitor bank,
2) a control system to tell the switches to close whenever the motor tries to start,
3) a fast-closing switching device.

CALCULATIONS FOR A CAPACITOR START SYSTEM

A typical motor start calculation involves the circuit shown in Fig. 1. One simply adds up the utility, transformer, and motor impedances; calculates starting current; and with that calculates the voltage dip at various points in the system. It is important to note that Z_{motor} represents the "starting" impedance of the motor and is calculated using motor horsepower, system voltage, starting code, and starting power factor.

When doing the same type of calculation for a Capstart installation, one simply includes the capacitor impedance at its proper point in the circuit. For example, a primary voltage capacitor would be connected as shown by the dotted lines in Fig. 1.

To further demonstrate this sort of calculation, the following example is included.

Given:

motor: 1500 hp, code G (X6.3), starting PF = 15 percent

$Z_{utility}$: $0.539 + j2.403\,\Omega = 2.463\angle 77.36^\circ\ \Omega$

$Z_{transformer}$: $0.177 + j1.765\ \Omega = 1.774\angle 84.27^\circ\ \Omega$

V_{system}: 12.47 kV P-P, 7.2 kV P-G

Calculation of Starting Current:

$$Z_{motor} = \frac{(7200)(12.47)(\sqrt{3})}{(1500)(6.3)} [0.15 + j0.989]\ \Omega$$

$$= 2.468 + j16.275\ \Omega = 16.461\angle 81.38^\circ\ \Omega$$

$$Z_{total} = Z_{utility} + Z_{xfmr} + Z_{motor}$$

$$= 3.184 + j20.443 = 20.689\angle 81.15^\circ\ \Omega$$

$$I_{start} = \frac{V_{P\text{-}G}}{Z_{total}} = 348.01\ \text{A}.$$

Calculation of Worst Case Voltage Dip:

$$V_D(\text{utility}) = \frac{(I_{start})(Z_{utility})(100)}{V_{P\text{-}G}} = 11.90\ \text{percent},$$

$$V_D(\text{customer}) = \frac{(I_{start})(Z_{utility} + Z_{xfmr})(100)}{V_{P\text{-}G}}$$

$$= 20.44\ \text{percent}.$$

Now assume that a 3600 kvar starting capacitor has been installed in shunt with the motor.

Calculation of Impedances:

$$Z_c = -j\left[\frac{(V_{P\text{-}G}^2)(3)}{\text{kvar}(1000)}\right] = -j43.2\ \Omega = 43.2\angle -90^\circ\ \Omega$$

$$Z_m \| Z_c = 26.30\angle 76.14^\circ = 6.300 + j25.534\ \Omega$$

$$Z_{total} = 7.016 + j29.702 = 30.519\angle 76.71^\circ\ \Omega.$$

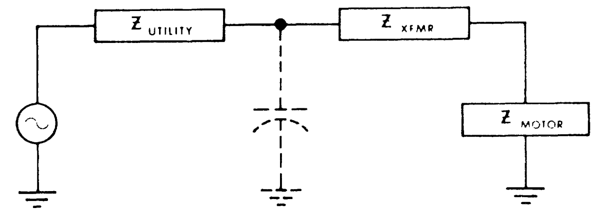


Fig. 1.

Calculation of Worst Case Voltage Dip:

$$I_{start} = 235.92\ \text{A}$$

$$\text{percent } V_D(\text{utility}) = 8.07\ \text{percent}$$

$$\text{percent } V_D(\text{customer}) = 13.86\ \text{percent}$$

$$\text{Change percent } V_D = -32\ \text{percent}.$$

The 32 percent drop in flicker magnitude as seen by the utility is approximately equivalent to an 80 percent autotransformer reduced voltage starter.

CONTROLLING THE CAPACITORS

The second requirement for a Capstart installation is a control device to energize the capacitors the instant the motor begins to start and de-energize them once the motor reaches full speed. Fig. 2 shows a schematic of such a control system. This design requires one external, normally open relay contact which closes each time the motor starts. Some utilities use this method of sensing and control for Capstarts, while others monitor line current and energize the capacitors whenever a sudden surge of current is drawn [1].

For the control system shown in Fig. 2, the sequence of operation is as follows. When the external relay contact closes signaling the starting of the motor, relay K1 becomes energized and power is applied to the close circuit of the capacitor switches through a normally closed contact of K2. A contact from K1 energizes TD1, and after a time delay of about 10 s K2 is energized. This de-energizes the close circuit of the capacitor switches and applies power to the trip circuit. Relay K2 seals itself in through the external contact to prevent the start cycle from inadvertently repeating. The timing of relay TD1 is adjustable and should match the maximum acceleration time for the motor being started.

CAPACITOR SWITCH REQUIREMENTS

Besides being rated for the proper voltage and capacitive load currents, the switching device for the capacitors must be capable of rapid closing, on the order of 10 cycles or less. Most vacuum switches are solenoid actuated and satisfy this requirement nicely. Some oil switches are also solenoid actuated and work well, but most are motor-spring actuated and are far too slow to use in this application unless an optional quick-close feature is incorporated. Both single-phase and three-phase switches are acceptable for use on a Capstart installation.

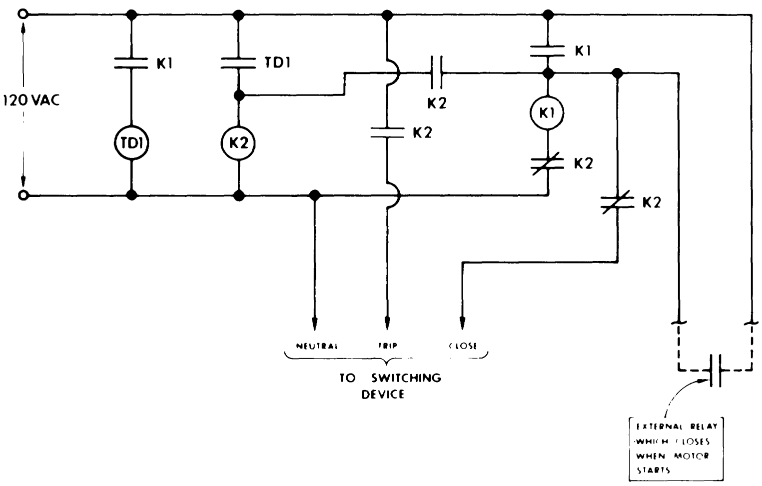


Fig. 2.

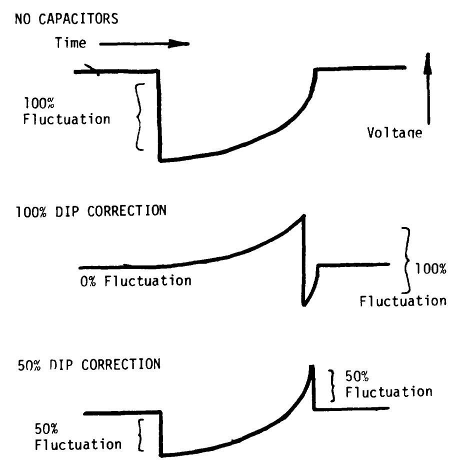


Fig. 3.

OVERSTRESSING THE CAPACITORS

A common technique for getting "the most for the money" from Capstarts is called "overstressing." It involves the application of considerably more than rated voltage to the capacitors by connecting a phase to ground rated capacitor phase to phase. Since the effective kVA of the capacitor is proportional to the square of the applied per unit voltage, the effective kVA undergoes a 200 percent increase. It takes 1/3 as many capacitor units to achieve the same electrical effect as when they are connected phase to ground. This technique is considered practical because the duty cycle of a starting capacitor is quite low. The additional losses in the capacitor produced by the overvoltage do not last long enough to cause excessive overheating of the unit and subsequent failures. As a precaution, most control mechanisms used with overstressed capacitors incorporate a 10 s timer to prevent the capacitors from being damaged in case the motor fails to accelerate properly.

MAXIMUM DIP REDUCTION

One of the common questions asked by a utility or customer contemplating the use of a Capstart is "How much dip can be eliminated by the system?." Theoretically it is possible to cancel 100 percent of the initial motor starting dip with capacitors. But in practical applications this is not done because the dip produced by switching off the capacitors would have the same magnitude as the motor dip being cancelled. Optimum flicker reduction is accomplished by sizing the capacitors to cancel only 50 percent of the initial starting dip of the motor as shown by the motor starting curves in Fig. 3.

The 50 percent dip correction curve shows twice as many dips but only half of the magnitude as compared to the other two curves. Studies have shown that halving the voltage dip on a feeder can increase the tolerable frequency of flicker by a factor of eight or more [2]. Therefore, doubling the number of dips is not usually a problem.

RESULTS OF A CAPSTART INSTALLATION

Houston Lighting and Power Company has six Capstart installations in operation throughout the system. The first such installation was built in 1967 to serve a 400-hp, 2400-V, code J motor. The distribution system serving this motor consisted of a 5000 kVA substation transformer, four miles of 12.47 kV feeder, and three 167 kVA, 7200–2400 V transformers. Voltage charts installed at the substation and at the motor site showed the dips in Fig. 4 when the motor was started without capacitors.

Next the motor was started with a 2700-CkVA Capstart. The charts in Fig. 5 show a considerable reduction in starting dip at both the substation and on the feeder near the motor. Part of this decrease can be attributed to the inherent damping of the chart recorder.

A more accurate representation of voltage flicker during motor startup can be obtained through the use of an oscillograph recorder. Utilizing this kind of high-speed recording device allows one to evaluate closing time and transient effects as well as the amount of dip reduction resulting from a Capstart installation. Oscillograph recordings were therefore chosen to help evaluate the largest and most recent installation on the Houston Lighting and Power Company system, a 3150-CkVA bank serving a 1500 hp motor. The distribution system serving this motor consisted of a 42-MVA substation transformer, three miles of 12.47 kV feeder, and a 3750 kVA, 12 470–2400-V pad-mounted transformer. The recorder was

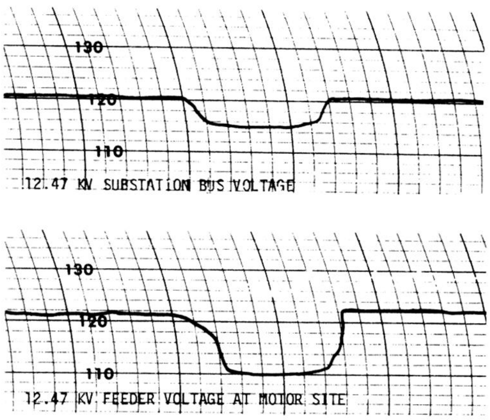


Fig. 4.

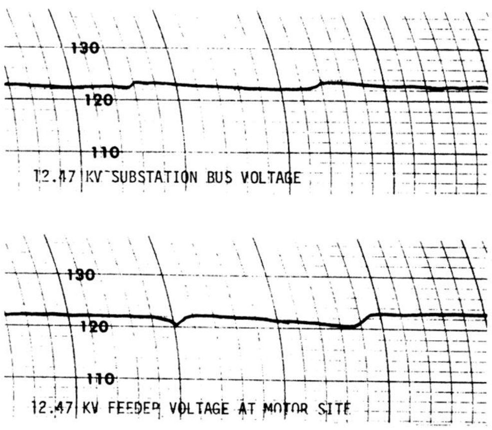


Fig. 5.

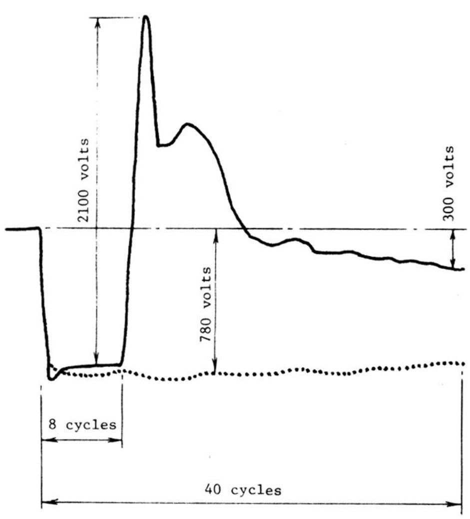


Fig. 6. 12.47-kV feeder voltage at motor site (—— with capstart and · · · · without capstart).

connected so as to monitor 12.47-kV feeder voltage at the motor site, and the graphs in Fig. 6 were plotted from the peak magnitudes of each positive half cycle of the voltage waveforms.

As seen in Fig. 6, the voltage dip produced by across-line starting without capacitors is approximately 780 V. With the Capstart bank, the maximum sustained dips were 300 V during start-up and 480 V when the capacitors dropped off. This indicated a flicker reduction of nearly 39 percent. It further indicates that the bank is slightly oversized since the initial Capstart dip is less than 50 percent of the uncorrected starting dip. Closing time of the oil switches was measured to be eight cycles and a transient surge of over 2000 V and lasting approximately 10 cycles was observed when the capacitors were first energized.

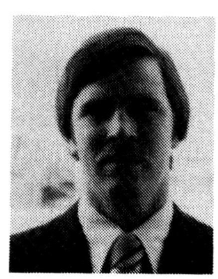
CONCLUSIONS

Capstart systems are an important alternative to consider in difficult motor starting situations. Proper controls and high speed switching are essential to a Capstart system but are not difficult to obtain. Capacitors can be overstressed to obtain three times their normal capacity and up to 50 percent of across-line starting dip can be eliminated. Capstart systems have been used by utilities for many years and are a practical and effective method of reducing motor starting voltage flicker.

REFERENCES

[1] W. E. Shula, "Capacitors help to start large motors," *Elec. World*, pp. 44–47, Nov. 1, 1974.

[2] Electric Distribution Systems Engineering Manual, *Ebasco Services Inc.*, New York, NY, 1967.



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