Capacitors Near Loads? The Engineering Viewpoint

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Abstract—Since the National Electric Code has dropped rules for capacitors at motors, the electrical engineer's responsibility has been established. Nevertheless, the Code's 1981 edition suggests a simplified rational method of selecting capacitor size that is discussed here. The electrical engineer is assumed to understand that the purpose of applying capacitors is not merely to take care of an individual motor. Rather, it is to reduce to an economical level the vars carried by the local supply circuit and the whole plant. The most economical safe effective ways to improve power factor within the plant distribution system are reviewed. Time-honored methods as well as new practices brought on by changes in load, particularly machines, and in capacitors are covered. Although addressed to the machine-tool industry, the message applies equally to vendors of all types of electrical utilization equipment: other classes of production machinery and plant facilities. Emphasis is on the utilization system (usually 600 V or lower) where the benefits of capacity and efficiency are added to possible reduction in utility bills.

INTRODUCTION

Why the Equipment Electrical Engineer Cares About Power Factor

ISN'T power factor the *plant* engineer's concern? His supply system appreciates good power factor, whereas motors are not helped much (although switched capacitors may help stabilize voltage levels and may subdue spikes that would otherwise bother sensitive controls. On the other hand, they may augment spikes that are started by switching and other devices). So the machine-tool electrical engineer might feel that s/he "should care less."

However, further thought tells the engineer that if s/he can reduce the cost of electricity to run machines, s/he increases their attractiveness in the long run. S/he knows that, without capacitors, the machines draw more reactive vars than other equipment of the same size and that machine capacitors cure this. Therefore, to help in keeping line and plant current within reason, the electrical engineer looks at capacitors as integral components of the machines.

This becomes more important as loads approach the ratings of lines and substations, a phenomenon that equipment manufacturers foster! To save power-line losses and to prevent premature expenditures for more substations and lines, the utilization motors must include capacitors! The manufacturer does have an economic interest in good power factor.

Basic Thoughts in Applying Capacitors

One design imperative is to get capacitors *on* and *off* the line as needed. If they are on the line when they should not be, damage—serious damage—can result. Capacitors related to motors meet this requirement.

Furthermore, they routinely save the time and cost of adding capacitors after the plant is in operation, and they stay with machines when they are moved. Disconnects and starters already in place for motors obviate the need for capacitor switchgear. This can make up for the greater cost of smaller capacitors.

This is not the complete solution to capacitor application. Often it is more sensible to have separate capacitors with or without contactors, as discussed later. Such practice applies to chopped-wave power users such as SCR dc drives, frequency converters, reduced-voltage motor controls, etc., induction and SCR-controlled furnaces, as well as to certain kinds of induction motor drives.

New Considerations

The removal of restrictions on the size of capacitors at motors from the National Electrical Code (NEC) puts the responsibility on the electrical engineer. S/he can now think in terms of power in the electrical *system* rather than a particular motor—although of course s/he must remember not to endanger the motor or capacitor.

An entirely new element is the construction of capacitors. Metallized windings have found their way into the 480-V field. They are compact, have low losses, and are economical. Our customers have used them for two years with good performance. However, their common mode of failure is different, and we are studying the details of circuitry for the best safety and service to the user. With these thoughts in mind, we can now talk about specifics, always in terms of electromechanical contactors and starters or the equivalent.

SCHEMES FOR CORRECTION AND CONTROL

One on One

The most widely used method on machine tools and in many other fields of application is the simplest, shown as Circuit (A) in Table I. Capacitors are connected directly to the load side of selected motor starters. Thus they are switched on and off the line in synchronism with the load—always desirable and sometimes vital.

Eligible Motors: An appropriately sized capacitor is associated with each motor that is "eligible" for such service. The motor must be

1) a "workhorse," i.e., the main motors that run for many hours, such as the main motor of a machine tool but not an adjustment motor or occasionally operated auxiliary motor;
2) an induction type motor, including wound rotor;
3) large enough in proportion to the machine load (3 hp at least, with 5 or 10 hp more common on machines) (any smaller motors may be compensated by capacitors on larger motors, by methods described later);
4) in continuous operation without repeated abusive transients caused by fast reclosure after deenergization.

Negative, ineligible for capacitor-at-the-load, are multi-speed, reduced-voltage start, plugging, and repeated jogging. Jogging during startup and tryout may be acceptable if not accompanied by reversing, but this may cause nuisance fuse-blowing. Also negative are capacitors on the load side of solid-state starters and NASA-NOLA "power-factor controlled" motors. Caution must be observed if capacitors are used on the line side of such devices, since waveshapes may be badly nonsinusoidal (see "Side Effects").

Paper GID/MTIC 83-1, approved by the Machine Tools Industry Committee of the IEEE Industry Applications Society for presentation at the 1981 Machine Tools Industry Conference, Milwaukee, WI, October 18–20, 1984. Manuscript released for publication April 10, 1984.

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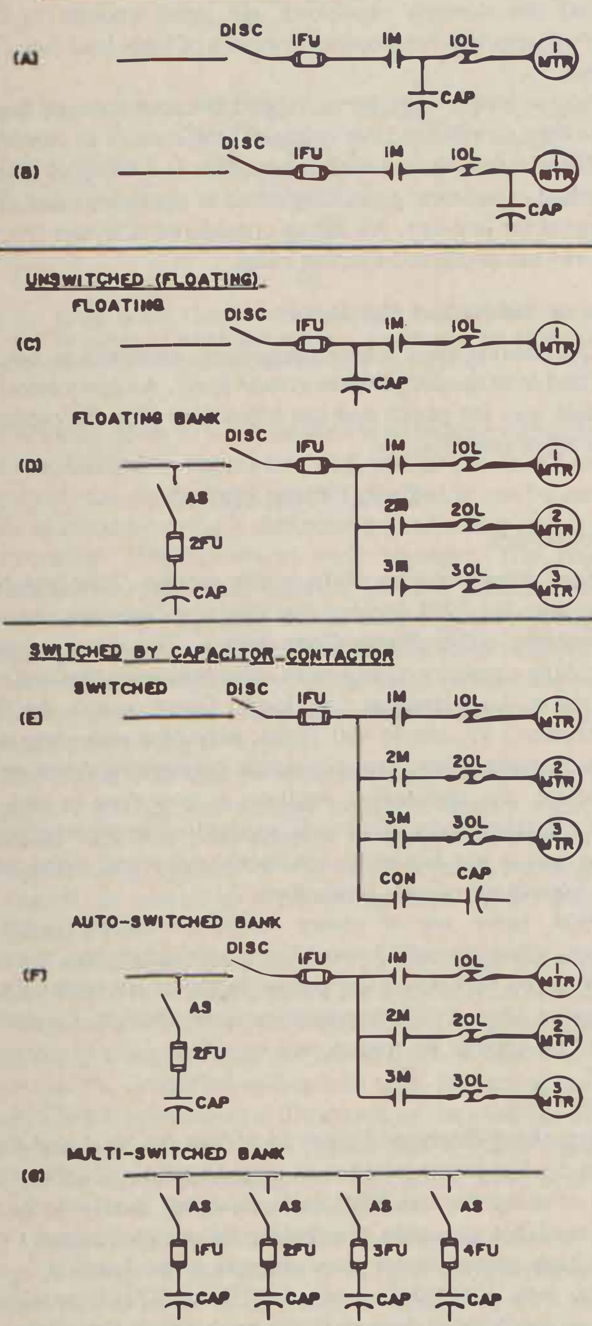
TABLE I
OPTIONAL CAPACITOR CONNECTIONS



Circuit	Name	Elementary	Accessory required for capacitor: Dis-connect switch	Contactor	Control	Capacitor kvar limited by: Motor	Contactor motor	Capaci
	Switched by motor's starter							
(A)								
(B)			NO	NO	NO	YES	NO	N
	Unswitched (floating)							
(C)	Floating		NO	NO	NO	NO	—	
(D)	Floating bank		YES	NO	NO	NO	NO	
	Switched by capacitor contactor							
(E)	Switched		NO	YES	YES	NO	NO	
(F)	Auto-switched bank		YES	YES	YES	NO	NO	
(G)	Multi-switched bank		YES	YES	YES	NO	NO	

Preferred Circuitry: Circuit (A) in Table I is preferred. In those contactors where there is no place to connect capacitor leads ahead of the overcurrent devices ("heaters"), circuit (B) may be used, in which case the size of the heater should be adjusted for the reduced current going through it.

The heater current rating I_H for motor plus capacitor, in terms of

I_M	heater rating for motor alone,
PF_1	power factor for motor alone, on which I_M is based,
c var	capacitor vars in parallel with the motor, and
E_{LL}	line-to-line voltage on a three-phase system,

is

$$I_H = \frac{I_M \cdot PF_1}{\cos \tan^{-1}\left(\dfrac{\sin \cos^{-1} PF_1 - \dfrac{c \text{ var}}{\sqrt{3}\, E_{LL}}}{PF_1}\right)},$$

a formula not nearly as formidable in use as it appears.

Major Motor Correction

One of our customers developed a most economical and satisfactory method for a battery of machines, each of which was dominated by a hydraulic-pump motor. As each machine goes through its cycle, small motors routinely do their jobs after the hydraulic pressure has been developed. One capacitor on the pump motor serves the whole machine.

To save money, the engineer decided that engineering took precedence over blind code-following. He wanted each machine to take power at a good factor without spending dollars for "correcting" each small motor. Testing under operating conditions with increasing amounts of capacitance on the hydraulic pumps, it was found that the power factor of the machine as a whole reached satisfactory levels with *no rise* in terminal voltage when the machine was deenergized. This dismissed one reason for limiting capacitor vars. The other reason—that surges can occur if the motor is reenergized quickly while still generating voltage as an induction generator—was eliminated by interlocking controls so that the motor could not be put back on the line immediately.

Pump motors range from 2 to 40 hp. Smaller motors on each machine aggregate about the same. Capacitors of two to five times pump-motor horsepower were applied. This equipment has operated for 12 years so far, with no fuse-blowing or cell or motor failures.

Advanced Machines or Sequences

Economies can be made in applying capacitors to programmed motors such as those used in machine tools, by treating each group of motors as a single load. A capacitor large enough for each load is switched on and off by its own contactor in accordance with the sequencing signals. Circuits (E), (F), or (G) of Table I are used. The cost of contactor plus larger capacitor may be less than that of the smaller capacitors used in "one-on-one." The same may be said of space requirements, but more engineering and controls are required.

This method allows more engineering freedom if people are addicted to the old NEC capacitor limitations, since capacitor size may be chosen with regard to actual loads rather than motor size alone. Also, it can ease the jogging transient problem.

Further dollars may be cut by "floating" capacitors as shown in circuits (C) and (D). However, the savings may be lost if the floating capacitors are great enough to cause overvoltages and harmonics at periods of light load (see "Side Effects").

Pullout torque may be sacrificed if capacitors are floated, since they do not hold the voltage at the motors as constant as do capacitors switched with loads. This is a factor in favor of switched capacitors, especially noted in operations that have a potential for jam-ups. All things considered, Circuits (A), (B), (D)–(F) are preferred in most cases.

Line or Substation Capacitors

Applications exist where capacitors, switched or not, are best tied in to the distribution system itself. An economical and flexible way for plants that use a bus is to plug the capacitors right there (see Fig. 3).

CAPACITOR SIZING

Introductory

Three points will be made in this section. First, the NEC Committee for 1984 decided that selecting capacitor vars is an engineering rather than a Code matter. Therefore, it ceased publishing capacitor-sizing rules. The principles that had been used in its long-standing "no-load" limits, and in the 1981 "exception" [9, article 460-7] that permitted exceeding these limits in some cases, are still worth engineering attention.

Second, the application engineer is now free to seek the most effective economical safe method of improving power factor and is not bound by traditional rules and tables when they impose unrealistic limitations.

Third, there are so many variables—characteristics of motors, plant operating conditions and schedules, the way electrical utilities determine power factor (if not peak kVA)—that close accuracy in computation is an illusion. Capacitors should be applied by reason, not by rote.

One on One

Furnishing Reactive Power to Motor by No-Load Rule: Based on historical experience (see Appendix I), there is a habit of using the old NEC rule: capacitor kvar is to be the next available capacitor size below the no-load motor kVA. With high power factor thus attained at no load, it is still usually well over 90 percent at full load. This is because it takes so much more capacitance to raise power factor from 95 to 96 percent (0.37 times kW) than to raise it one point (0.27 times kW) if it is below 87 percent; because it takes only half again as much reactive to excite a typical 1800-r/min Design B squirrel-cage motor at full load as at no load.

An example makes this clear (see Fig. 1). As noted before, the motor is well cared for over the full range of load.

One method of applying this principle is to connect no-load-sized capacitors to all eligible motors, starting with the largest

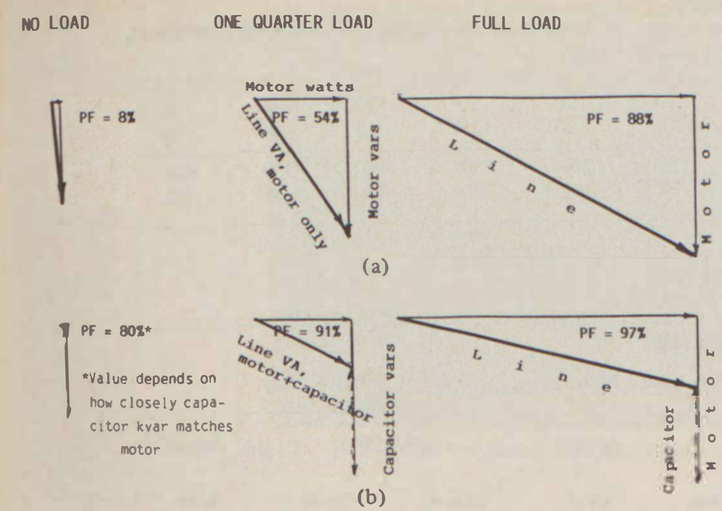


Fig. 1. Single motor. Current at no load, light load, and full load showing total composed of active and reactive components. (a) Motor only, no capacitors. (b) Motor plus capacitors per no-load rule.

and working down to some minimum horsepower size that has been established by experience with similar plants or sections. However, the number and cost of installation can be substantially reduced by using a different way of sizing capacitors.

Potential Simplification and Savings: The engineer should not be misled into thinking s/he has done the best job for the *plant* by following the no-load capacitor-sizing rule. S/he is spending too much money and has missed an opportunity to compensate inexpensively for the small motors, the ineligible motors, and other low power factor loads and still have automatic switching at no cost!

How? The cost can be reduced safely by placing larger capacitors on big motors and none on smaller ones. This heretical view has been adopted by important users. It was recognized in [9, article 460-7], which permits, *under proper restraints,* on motors up to 50 hp capacitors of half the motor *full-load* kVA.

This was adapted from the "50/50 way" that we proposed in the 1960's. It is recommended for simplicity, economy, and good operations provided the restraints are observed. Table II, reproduced from privately published *CALMANUAL*, is one form that the simplified method can take. Reduction in cost of materials and installation is illustrated by the example in Table III based on an actual case, given that a certain group of motors should be supplemented with 250 *c* kvar in order to bring the power factor to a desired level.

Buildup of capacitance for a group of motors: A plot (Fig. 2) brings out the similarity of results when planning the circuit power factor of a group of motors by two possible methods. The simplification by the 50/50 way comes from the ability to use a single value of capacitor kvar for each motor horsepower rather than having to look through many tables or address the manufacturer to get the no-load data (if, indeed, the manufacturer of the motor is known at the time). The savings come from use of fewer larger capacitors and from less engineering time.

Incidental Comments on 50/50 Way:

Extending range of 50-percent way: Once an engineer has profited by use of the 50/50 way, s/he may ask why it is not extended to larger motors. The answer is simply caution. We introduced the 50/50 idea after comprehensive laboratory type testing in two plants detected no overvoltages worthy of concern. The number of motors over 50 hp is relatively small, so there was less incentive to spend the extra money and run possible risks to test the 100–500-hp range.

The years of trouble-free operation in many plants, plus the experience related later regarding major motor correction, develop a feeling that the range of more-than-no-load correction may be safely extended. If anyone has already done this, the experience will be welcomed by the industry.

What happens at partial loads? The magnetizing vars of some motors will be considerably less than half the horsepower, at some fractional load. In such cases a motor–capacitor combination drawing less than that fraction will have a leading power factor. Despite a traditional rule of thumb that this should be avoided, no harm is done as long as the supply line to a group of motors does not lead excessively. Perhaps the possibility of leading power factor will encourage the growing practice of turning off motors when they are not producing.

When motor no-load vars are more than half of hp rating: Most commonly used motors have magnetizing (no-load) var demands less than half their horsepower rating, but for a considerable number of motors this is not so. Of course, capacitors connected to such motors may exceed the 50/50 way (see Table IV).

Major Motor Correction

The concentration of capacitance on the major motor in a group, already discussed under "Schemes," is an extension of the 50/50 way. It yields important savings but must, of course, be carefully studied. In the case cited, ratings were as follows:

hp	c kvar
1–5	10
7½–10	15
15	20
20–40	equal to hp

Conditions were favorable for such techniques. Oscillographic tests showed no rise in voltage as the motor was disconnected from the line (motor stopped typically in 2 s). Interlocking prevented restart until the motor stopped. At the recommendation of motor-started manufacturers, an oversize starter was used.

Advanced Machines or Sequences

As mentioned earlier, the use of capacitors under their own contactors on multimotored machines or other loads eliminates the problems related to motor excitation. Capacitor kvars are selected simply to raise the power factor of the load to the desired value. Contactor should be sized by the manufacturer's recommendation (e.g., NEMA standard size 2 can carry 26 kvar at 480/3/60; size 3, 52½ kvar), and where offered, the lighting contactor version should be selected. Capacitors

TABLE II
CAPACITOR kvar FOR ELIGIBLE INDUCTION MOTORS—VALUES BASED ON 50/50 WAY THAT MERGES WITH CONVENTIONAL NO-LOAD RULE ABOVE 50 hp

Motor horsepower	3	5	7½	10	15	20	25	30	40	50
Capacitor kvar	1½	2½	4	5	7½	10	12½	15	20	25
Motor horsepower	60	75	100	125	150	200	250	300	350	400
Capacitor kvar	27	30	32	35	38	42	50	60	65	70

TABLE III
SAVINGS BY 50/50 WAY[a]

Motor			Capacitor Size: Conventional "No-Load" Rule — CAL per		Accum	"50/50" Way — CAL per		Accum
hp	r/min	number	Motor	Group	kVar	Motor	Group	kvar
200	1200	1	45	45	45	42	42	42
100	1800	2	21	42	87	32	64	106
50	3600	1	12	12	99			
	1800	1	11	11	110	25	100	206
	1200	2	13	26	136			
25	1800	5	6	30	166			
	1200	4	7½	30	196	12½	125	331
	720	1	11	11	207	This is more than enough: CAL is needed on only six 25-hp motors, none on 10 hp.		
10	3600	4	3	12	219			
	1800	10	3	30	249			

[a] Allocation of 250 kvar to existing mots comparing results of sizing CAL by conventional no-load and 50/50 ways.

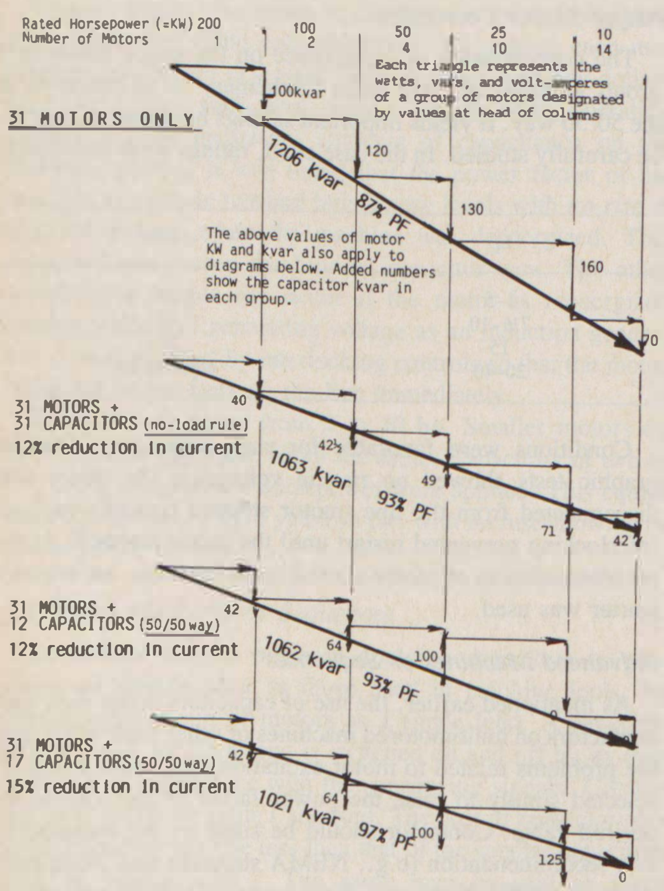


Fig. 2. Options to improve power factor with no switchgear cost on group of motors totaling 990 hp about fully loaded (1 kW/rated hp).

TABLE IV
RATIO OF CAPACITOR kvar TO MOTOR HORSEPOWER BY NO-LOAD RULE[a]

Motor (hp)	Nominal r/min: 3600	1800	1200	900	720	600
3	0.50	0.50	0.50	0.67	0.72	1.18
5	0.40	0.40	0.49	0.60	0.80	0.90
7½	0.33	0.33	0.40	0.53	0.73	0.80
10	0.30	0.30	0.35	0.50	0.65	0.75
15	0.27	0.27	0.33	0.48	0.53	0.63
20	0.25	0.25	0.32	0.37	0.45	0.60
25	0.24	0.24	0.30	0.36	0.44	0.56
30	0.23	0.23	0.30	0.33	0.40	0.51
40	0.23	0.23	0.28	0.30	0.38	0.50
50	0.24	0.22	0.26	In this range all ratios are below 0.50.		
60	0.23	0.23	0.30			
75	0.23	0.21	0.24			
100	0.22	0.21	0.25			
125	0.22	0.21	0.24			
150	0.22	0.20	0.23			
200	0.20	0.19	0.22			

[a] These numbers are derived from a commonly published table that is frequently used in lieu of values for specific motor make, horsepower, speed, type, series, construction, etc.

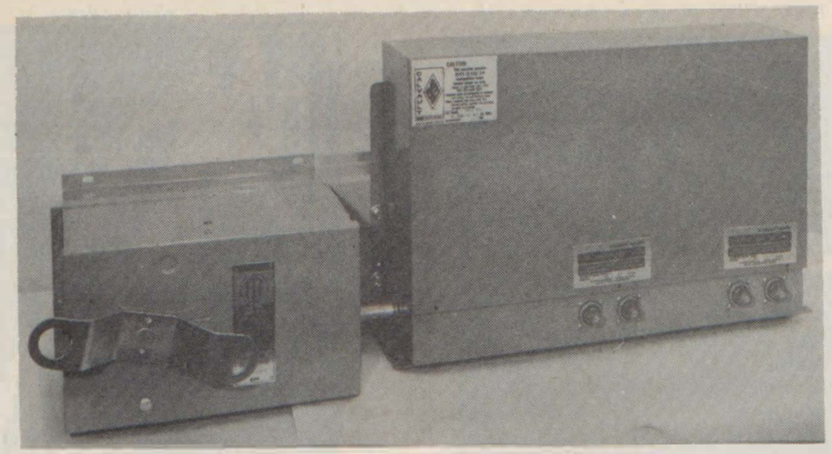


Fig. 3. 30-kvar 480-V capacitor with integrated electrical and mechanical bus mounting details.

should not be connected to the load side of phase-controlled devices, of course.

In deciding what scheme and how much capacitance should be applied, remember that the purpose is not to correct a motor or other load but to decrease the reactive load (improve power factor) on the supply lines.

Line or Substation Capacitors

We add only a few points to the already extensive literature on this subject.

1) The required amount of kvar can be figured, if the kW are known, by using multipliers from published tables or, if both PF's <90 percent, approximated within ten percent for most combinations by the simple formula:

$$c\ \text{kvar} = 0.3 \times \text{ percent change in PF } \times \text{ kW}.$$

Greater apparent accuracy is usually unwarranted or a sham (see Appendix II).

2) Whether to switch or "float" capacitors depends on conditions. A number of plants that have apparently economized by using fixed capacitors have had problems because of harmonics, overvoltages, or leading power factors. They have changed to switched units even when they had to buy switchgear to do so rather than connecting capacitors to loads. Some utilities, because of stability problems, discourage customer's from floating capacitors.

3) To attain very high power factors (93–99 percent), as encouraged by some utilities, it is usually better to install banks of medium-voltage capacitors.

SOME PRACTICAL THOUGHTS

Fusing

Much can be written about capacitor fusing, but we will cover only fundamentals relating to "unit cell" type of capacitors that have become prevalent in the small-var field. First, requirements for *line* fusing should be distinguished from those for *device* fusing. The former follow NEC rules to protect against circuit faults. The equipment engineer follows them almost by instinct. Three-line fusing is mandatory.

Device fuses depend on the characteristics of the equipment. One important respect in which capacitor fuses differ from motor fuses, for instance, is that the latter must allow many times rated current to flow for several seconds without harming the fuses. Capacitors do not have such variable current demands except for small fractions of a second.

Foil Capacitors:

Purpose of fusing: The purpose of capacitor device fuses has been to prevent case rupture under the pressure created when a cell short circuits, which is the normal mode of failure. A failure in the insulating film of the foil type capacitor gives a catastrophic short circuit between adjacent foils. Fuses of the fast-acting current-limiting type are designed and put into the capacitor leads by the manufacturer, not because the NEC requires them (it does not), because the user needs them.

Sizing: Fuse sizing practices have been changing since nuisance failures have become more common as power line voltages become distorted by harmonics, spikes, and notches. Capacitor engineers who once fused at 1.67 times steady-state current now use higher values. A factor of 2.2 has become common. Note that this does not mean that the fuse is carrying more 60-Hz current than usual: it simply has a greater tolerance for the millisecond or microsecond currents that capacitors are being called upon to withstand more persistently than they used to be.

Our experience shows that these overampere fuses still prevent rupture of the capacitor cell. In some cases the distortion of voltage, and therefore of capacitor current, is so bad (see Fig. 4) that even with the overampered fuses nuisance fuse-blowing is a problem. We anticipate obtaining a fuse that has normal steady-state ampere rating but also an added ability to hold against spikes.

Indicators: Since we introduced blown-fuse indicators in 1967, they have become indispensable to many users. They tell not only when a cell has failed, but when too many transients are on the line, causing nuisance fuse openings, and sometimes that serious system faults exist.

For instance, arcing grounds have blown capacitor fuses when they gave no other indication. Misadjusted switches or motor starters that close two points appreciably sooner than the third, have been discovered: they set up a bad unbalance that causes high capacitor currents, blowing fuses.

Maintenance: Considering all the forces that blow fuses,

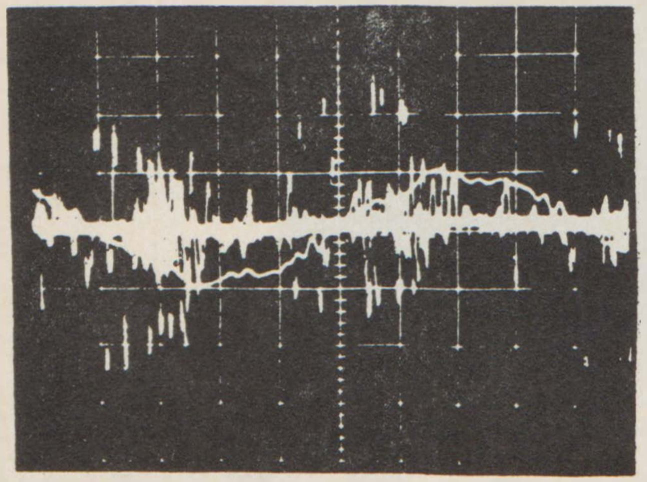


Fig. 4. Line voltage and capacitor current during start of machine with four motors. Ragged spikes show current; near-sine shows voltage.

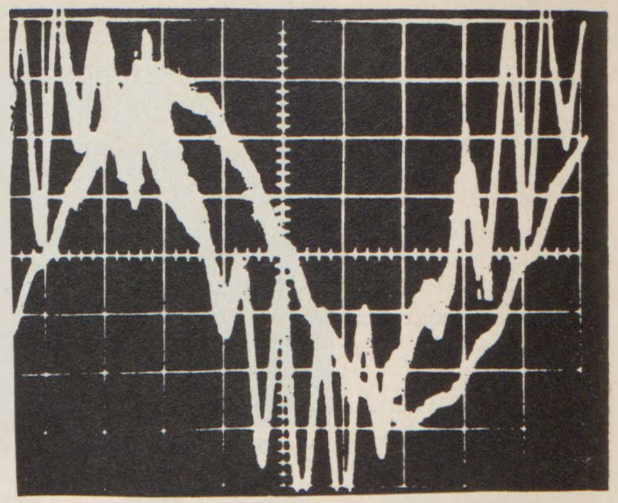


Fig. 5. Capacitor in circuit with moderate amount of harmonic. Rippled sine wave is voltage, other is capacitor current.

there is no reason to think that nuisance blowing will stop despite efforts made to minimize them. Besides the transients already shown, lightning strikes, plant short circuits, emergency throw-overs, etc., may blow capacitor fuses, not to mention transients from outside the plant such as utilities throwing on large banks of capacitors nearby at odd hours. Many users have found that a newer design of fuse-holder that permits fuse changing without entering the capacitor enclosure helps them keep capacitors in service.

Metallized Capacitors: The fusing technique for metallized capacitors has not been firmly established (see Appendix III). In summary, although most metallized capacitors in the nonindustrial service that has provided background so far, fail open circuit, a fraction of short-circuit failures exists. Although this may be small, we will not assume it is negligible until proved so; we will continue to furnish "device" fuses. This will prevent shutdown of motor, etc., if a capacitors should short.

The fuses will be supplemented by pressure interrupters that should adequately take care of the relatively slow failure mechanisms. (We have not yet gotten assurances from the cell manufacturers that these interrupters will be 100-percent dependable.)

Mechanical-Thermal

Obviously, capacitors should be located with thought. Too often they are packed too tightly: ventilation is poor, lids are not removable, blown-fuse lights are hidden. The installation of capacitors requires the same good judgment as is used for all electrical components.

Side Effects

Everyone with field experience knows that capacitors can be active parts of the plant system: they do not just sit there and improve power factor. We will cover some (by no means all) of the effects that should be kept in mind.

Voltage Buildup: Motors running at certain fractions of normal speed will generate voltage if a certain amount of capacitance is attached to the winding. This fact is often used to furnish excitation for utility or cogeneration generators. It is, incidentally, a factor in stability studies of interconnected systems. This action, discussed further in Appendix I and Fig. 6, was the basis for the original NEC limitation on capacitor kvar switched with motors. Excessive voltages are rarely encountered in today's motors.

Voltage Retention: When a motor is disconnected from the line, its capacitor will both decelerate it faster and make it retain its internally generated voltage longer (see Appendix I and Fig. 7). This leads to two precautions. First, as stated in [9, article 460-7] and later editions, capacitors should not be switched with motors that (regularly) are quickly reclosed after being taken off the line. Two-speed motors are perhaps the best example of "ineligible" ones. Reduced-voltage start should be avoided likewise, even when closed-transition circuits are used: the simultaneity of contact closing is not sufficiently reliable.

It is remarkable that when customers tell an engineer that he is too conservative in telling them that they should not switch capacitors with multispeed motors (the question usually arises when the customer has questions about how much kvar to put on the various windings), they say they have been doing it for years. Yes, if the combination of speed, magnitude, and phase relationship is just *off* the critical values, transients will be bearable, but once the right combination hits, damage results. The second point to watch is that if other functions, such as setting brakes on presses, depend on loss of voltage, the designer had better take the capacitor off the motor before disconnecting it from the line.

Harmonics, Resonance: Resonating between capacitors and the impedance of the supply circuit may show up as overloading of transformers or as overheating of capacitors, or even as less-than-expected improvement of power factor. Most commonly, harmonic resonance has to do with chopped-wave (SCR) loads. Some *very crude* thumb-guides (not good enough to be called rules) indicating that conditions are favorable for resonance are

1) chopped-wave load is more than 40 percent of substation load;
2) ratio (SCR kW/short-circuit kVA at load) is more than 0.05;

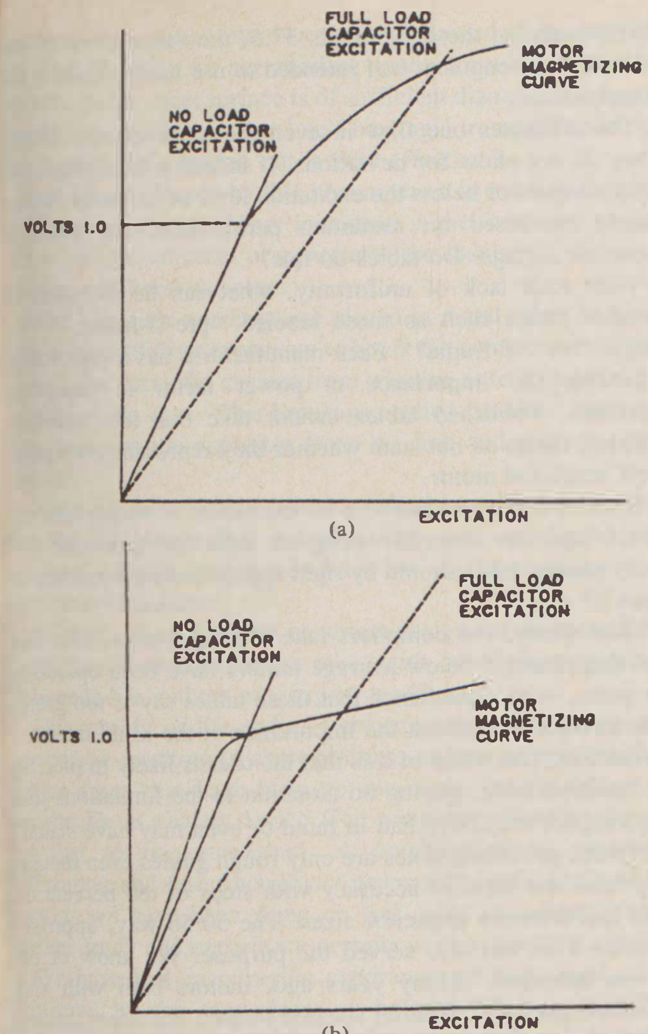


Fig. 6. (a) Pre-U-frame motors. (b) U-frame and T-frame motors.

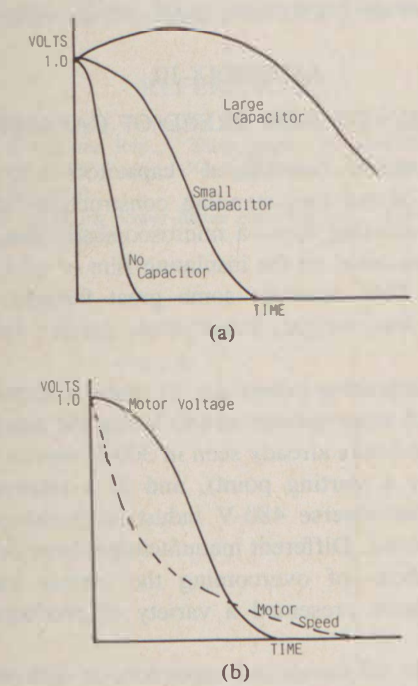


Fig. 7. (a) Typical voltage trace of squirrel-cage motor with high inertia load. (b) Motor/capacitor characteristics during stopping.

3) capacitor kvar is more than 25 percent of transformer kVA rating;
4) ratio (capacitor kvar/short-circuit kVA at the load) is more than 0.014.

Items 2) and 4) are adapted from Stratford [8]. Item 1) is more important if there are a few large drives rather than many small ones. Item 3) is particularly important at light loads.

Solution *is* a plant engineering problem, although a modification of capacitor-at-the-load standards may be desirable. A simple fifth harmonic trap may be the answer.

Spikes: Switching operations are the primary cause of spikes. These operations include capacitor switching, especially if near other capacitors, and all forms of commutation. Fig. 4 shows one type of spike that is not uncommon in factories. This causes nuisance fuse-blowing and may cause capacitor failure, especially in nonindustrial-grade capacitors.

APPENDIX I
HISTORY OF CAPACITORS AT LOADS

One-on-One Method, 60-Hz Induction Motors

The pinpoint accuracy in sizing capacitors that is sought by many users has been fostered in part by the historical development, which we therefore now summarize.

1930's: In the early days of capacitor switching with motors, the aim was to get maximum power factor at full load. Capacitor kvars were matched to motor demands, but incidents of motor damage led the AIEE and NEC to recognize that these were caused by overvoltage.

Motors driving high-inertia loads, when taken off the line, would generate voltage several times normal if excited by large enough capacitors. In those days, motors did not protect themselves by saturation. NEC adoption of the rule that limited capacitor vars to motor no-load requirements which are practically equal to excitation vars, prevented such overvoltages.

Although this rule drastically reduced the amount of capacitance applied to many motors, the practice was still quite economical, as indicated by the increased acceptance of the concept. Power factor was typically brought to 90–95 percent at full load.

Tables were published, even in the NEC for a while, showing "permissible" value of capacitance for various horsepower and speed ratings. They were adopted "wholesale" in some industries such as machine tools, process equipment, and many building facility drives. The economies were welcomed.

1950's: Further economies came from the decrease in cost of small capacitors by the introduction of the "unit cell" concept plus packaging that cut the cost of installation and maintenance. However, the no-load limitation made it impossible to get the power factor of many whole plants up to the desired levels unless capacitors were applied to many small motors where they are expensive.

1960's: A chance to add capacitance was at first overlooked when U-frame and then T-frame motors became prevalent. These motors, using materials more intensively, saturate at low enough levels (Fig. 6(b)) so that voltage developed at induction generator is usually acceptable.

Thus the need for limited capacitance was not the same. Instead, the problem was transferred to another phenomenon that had been indirectly covered by the rule.

This effect is the fast-reclosure transient—created by putting a motor on the line when its internally generated voltage is not in synchronism with the line voltage. High transient currents and shaft torques up to 15–20 times rating (two or three times the normal starting torque for which the shaft is designed) are created.

Since capacitors lengthen the decay period of generated voltage (see Fig. 7(a)), they increase the probability that this will happen. It should be recognized, however, that reducing or even eliminating capacitors does not guarantee that no shafts will shear on reclosure. There have been only a few cases where this has happened with capacitors, and some where there were none.

1980's: Retention of the var-limiting rule masked the true nature of the solution which was recognized in [9]. Capacitors are not to be used on motors that regularly have the fast-reclosing routine (two-speed motors, for instance, where capacitors are to be put on the line side of the motor starter).

The unlikelihood of factors leading to the shaft-shearing coinciding is indicated by the many users who tell us that they ignore the rule. We still advocate that they abide by it.

Compilations

As more and more types of induction motors came into use—U frame, T-frame, designs A–D, and then some, various codes, high efficiency, etc.—various manufacturers issued tables showing maximum or recommended capacitor vars to use with each horsepower and speed for each class (open, totally enclosed, etc.) motor of its own make.

Capacitor manufacturers compiled composites using their best judgments but not telling how the figures were obtained. IEEE issued some "guides." Large users have stated their own specifications for sizing.

Few, if any, engineers have the tables for all the motors they may use in their plants. It is not stretching too far to believe that most of them pick up the table that is handiest.

The result of all this is that the basic principle of matching capacitor to the no-load vars of the motor to which it is to be attached is seldom followed in fact. The 50/50 way used by some plants recognizes this fact, gives practical values that permit economies if properly applied, and has had over ten years of unblemished field use.

APPENDIX II

PRETENSIONS OF ACCURACY

The engineer who chooses to abide by the no-load rule had better work from data for the particular motor he has in mind. Design numbers are not as accurate as could be desired, as indicated by the no-load var tests on six motors that were bought from two manufacturers using the same specifications:

manufacturer A		manufacturer B	
motor 1	52 kvar	motor 1	27 kv..r
2	32	2	35
3	44	3	30.

The average of these figures is 37.5, the value given on the table that the engineer had intended to use before making the actual tests.

This indicates one flaw in even the most specific tables. They do not allow for deviations. If indeed it is important to keep a capacitor below the excitation level of its motor, tables should be based on minimum permissible, not average, capacitor sizings. Do tables do this?

With such lack of uniformity, what can be expected of broader tables such as those labeled "pre-U-frame," "U-frame," or "T-frame?" Each manufacturer has a philosophy regarding the importance of power factor in designing machines. Published tables cannot take this into account. Besides, tables do not state whether they represent average or most restricted motor.

Since the avowed purpose of the tables is to prevent the motor/capacitor from becoming an induction generator set, every general table should by right approximate the minimum. Does it?

More likely, the compilers take average values. The fact that thousands of below-average motors have been operating for years, with capacitance that these tables say is too great, tells its own story about the importance of the usual intended precaution. The worst of it is that the user is likely to pick up the handiest table, paying no attention to the limitations that the compiler may have had in mind or even may have stated.

In sum, published tables are only rough guides even though they have the form of accuracy with steps of ten percent or even less between capacitor sizes. The 50/50 way, approximate as it is, has also served the purpose. We know of no motors damaged. (Many years ago, motors both with and without capacitors did suffer sheared shafts.) Therefore, rather than pretended accuracy of no-load rules as generally applied, we recommend that engineers take advantage of the simplicity and economy of the 50/50 way, used with discretion.

APPENDIX III

TRANSITION TO NEW BREED OF CAPACITORS

Widespread use of "metallized" capacitors is in sight. In these, instead of the long-standing construction—aluminum foil between insulating film—a microscopically thin layer of aluminum is deposited on the insulating film or on a separate carrier tissue. This develops some great features: smaller power losses, less weight, lower cost, greater volumetric efficiency.

The counterbalancing points are 1) more susceptibility to corona (so much more serious at 480 V that the astronomical number of farad-hours already seen in 300-V service must be considered only a starting point), and 2) a relatively slim record under the adverse 480-V industrial punishment that they must withstand. Different manufacturers have developed their own methods of overcoming the corona and other problems and have presented a variety of products to the market.

The life cycle of metallized capacitors is different. The catastrophic failure that is typical of the foil cells occurs infrequently in metalized cells. Instead, continual minor

deterioration occurs: microscopic breakdowns of the insulating sheet vaporize the surrounding conductor until an insulating area on the sheet surface is of sufficient diameter to quench the arc (erroneously called "self-healing" in most literature, this is only self-*clearing* but is very effective.)

Loss of capacitance by this phenomenon is small (estimated at ½ percent a year). More important is the formation of gas where the arc contacts or penetrates the insulation. In time, this gas will burst the case.

Most capacitor windings are placed in metal cases. Advantage is taken of their expansion to break the connections of thin "tabs" that carry the current from winding to terminals on the outside of the case. This breakage, called pressure interruption, removes the capacitor from the line and prevents case rupture.

Other means are taken when windings are placed in cases that do not bulge. For instance, they are surrounded and enclosed in still larger structures so that the products of rupture are contained.

Another cause of failure in certain designs of the metallized capacitors is erosion of the tabs, with subsequent opening. This ends life without any exposive effects.

This variety of life-ending performances, with only some percentage resulting in short circuits, makes the quick-acting device fuses that have been so successful in foil cells less dependable as a safety device. The complete protection system has yet to be established. A combination of pressure-interrupter and fuse (though not necessarily as sophisticated a fuse as we have been using on foil cells) is indicated until further study and experience permits a more positive answer.

We have had encouraging experience with the new cells, protected by the same fuses as before. "Torture tests"—repeated frequent switching—have produced no failures, whereas there was a 16-percent failure rate in foil cells tested simultaneously. This is encouraging but not conclusive.

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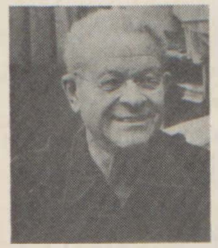

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