

A Note About Energy Savings and Substation KVALoad Reduction Resulting From Power Factor Correction CapacitorsProton Center ExampleAbstract

A discussion of the power factors of SCR controlled power supplies is given. Power factors are generally poor ( $\sim$  PF = 0.6). Power factor correction capacitors can be installed to correct this. The Proton Center experimental area is given as an example.

The P-Center case is rather typical for experimental area loads. Power supply loading changes often. This results in changes in KVAR and P.F. To improve the power factor at a typical 1.5 MVA substation feeding mainly power supplies, to  $PF \geq 0.9$ , requires the installation of about 1000 KVAC of power factor correction capacitors, with automatic P.F. control. This equipment should be centrally located and would cost about \$60,000 per substation, installed. Annual savings in losses would be about \$2400 per bank. Released system capacity and reduction in KVA demand would be about 30% per installation. It is, at this time, not economical to install such large banks, except in cases where the KVA demand exceeds the installed capacity. It is much more economical to make a partial improvement from  $PF_1 = 0.6$  to  $PF_2 \sim 0.7$ . This can be done by installing about 120 KVAC of power factor correcting capacitors at each 500 KW and 240 KW power supply. These capacitors would be non-automatic and be connected behind the contactor of each power supply. Each installation would cost about \$2,500, and could save about \$600 per year in losses.

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### I. Power supplies and their power factors

SCR controlled power supplies cause lagging currents at the AC supply line. The value of the power factor of a rectifier unit (power supply) is less than unity for the following reasons:

1. Distortion of the current wave
2. Reactance of the rectifier transformer
3. Transformer exciting current
4. Phase control, which increases the angle of displacement between current and voltage.

Phase control, especially, can result in very low power factors. Assuming that we are not too scientific and say that reasons 1, 2, 3 do not affect the power factor, then phase control alone can result in power factors from unity to zero. Our power supplies are equipped with primary (AC) and secondary (DC) taps, so that power factors and line current draw for each specific load can be optimized. A wide range of power supply operating currents, in a short period of time, makes load matching impractical. Pulsed loads are also harder to handle, but pulsing generally reduces real power consumption about 45% (based on an 8 sec. pulse period and 2 sec. flat top time), compared to D.C. operation. Savings in installed A.C. and cooling capacity are therefore substantial.

Large experimental area magnets, operated at DC current, are good candidates for power factor correction, especially when there is a poor match between required magnet operating parameters

and available power supply taps. Some types of BM109 magnets operating at 2300 A and 120 V DC are very poorly matched to the available power supply taps, and are therefore notorious for poor power factors and large AC line currents. This can be readily seen from the tap combination of a 500 KW power supply, which is listed below.

500 KW P.S. Taps

5000A at 100 V/50 V/25 V

2500A at 200 V/100 V/50 V

1250 A at 400 V/200 V/200 V

The only tap that can be used is the 2500 A, 200 V combination and a large amount of phase control is needed to obtain the required 120 V for the BM 109 magnet.

Even when a power supply is full on (100% rated output voltage) there is already phase control. This phase control is needed for regulation at that point. The power supplies are specified to regulate well at a 10% low line voltage and the only thing that can be done is to have sufficient phase control to cover a 10% low line voltage.

The ceiling voltage (maximum output voltage at rated line voltage) of our power supplies is generally 15% higher than the rated output voltage. Power factors can therefore never be very good.

Typical power factors are about 0.77 at full load and get worse at reduced output voltage as shown in fig. 1, in which I have represented a graph of the power factors of our rectifier power supplies. This graph is applicable for 500 KW, 240 KW and 55 KW power supplies.

The power factor P.F. can be calculated from:

$$PF = \frac{KW}{KVA}$$

which can be written as:

$$PF = \frac{\text{load KW} + \text{PS internal load current KW loss} + \text{no load KW PS loss}}{3 \times \text{PS line current} \times \frac{480}{\sqrt{3}} \times 10^{-3}}$$

and estimated to be:

$$PF = \frac{1.08 \text{ KW load} + \text{no load P.S. KW loss}}{0.83 \times \text{P.S. line current}}$$

Roughly estimate:

	<u>500 KW PS</u>	<u>240 KW PS</u>
KW no load P.S. losses	5 KW	2.5 KW
Full load line current	850 A*	420 A*
No load line current	15 A?	7 A? (* Measured value)

The rated power supply AC line current depends on the selected tap setting. The operating AC line current is linearly proportional to the DC output current.

We can make the following table 1 for various power supply taps.

$KVAC_{\max}$  lists the maximum KVAR the power supply will draw with the worst load/P.S. tap match.

$$K = \left( 0.83 \frac{I_{L \text{ rated}}}{I_{DC \text{ rated}}} \right)^2 \text{ is a constant for a specific power}$$

supply tap and is used for calculating KVAR.

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TABLE 1

PS - 500 KW

<u>P.S. Tap Setting</u>	<u>Rated P.S. D.C. Current From ~ 30% to 100% Voltage Amp.</u>	<u>Worst Load Match</u>	<u>Rated P.S. Line Current Amp.</u>	<u>K <math>\times 10^{-4}</math></u>	<u>Approx. Max. KVAR <sub>MAX</sub></u>
5000A/100V	5000	5000A/50V	850	204	650
2500A/200V	2500	1500A/100V	850	796	650
1250A/400V	1250	1250A/200V	850	3185	650
5000A/50V	5000	5000A/25V	425	51	325
2500A/100V	2500	2500A/50V	425	204	325
1250A/200V	1250	1250A/100V	425	796	325
5000A/25V	5000	5000A/0V	215	13	180
2500A/50V	2500	2500A/0V	215	51	180
1250A/100V	1250	1250A/0V	215	204	180

PS - 240KW

<u>P.S. Tap Setting</u>	<u>Rated P.S. D.C. Current From ~ 30% to 100% Voltage Amp.</u>	<u>Worst Load Match</u>	<u>Rated P.S. Line Current Amp.</u>	<u>K <math>\times 10^{-4}</math></u>	<u>Approx. Max. KVAR <sub>MAX</sub></u>
1200A/200V	1200	1200A/100V	420	844	320
600A/400V	600	600A/200V	420	3376	320
300A/800V	300	300A/400V	420	13502	320
1200A/100V	1200	1200A/50V	210	211	160
600A/200V	600	600A/100V	210	844	160
300A/400V	300	300A/200V	210	3376	160
1200A/50V	1200	1200A/0V	105	53	90
600A/100V	600	600A/0V	105	211	90
300A/200V	300	300A/0V	105	844	90

TABLE 1 (cont.)PS - 55KW

<u>P.S. Tap Setting</u>	<u>Rated P.S. D.C. Current From ~ 30% to 100% Voltage Amp.</u>	<u>Worst Load Match</u>	<u>Rated P.S. Line Current Amp.</u>	<u>K <math>\times 10^{-4}</math></u>	<u>Approx. Max. KVAR KVAR<sub>MAX</sub></u>
200A/275V	200A	200A/206V	74	943	41
100A/550V	100A	100A/412V	74	3772	41
200A/206V	200A	200A/138V	56	540	36
100A/412V	100A	100A/275V	56	2160	36
200A/138V	200A	200A/69V	37	236	27
100A/275V	100A	100A/138V	37	943	27
200A/69V	200A	200A/0V	19	62	16
100A/138V	100A	100A/0V	19	249	16

How do we use all this information to calculate the P.F., P.S. line currents, etc.?

Example A

Take a load running at 2300A/120V which needs a 500KW P.S. tapped at 2500A/200V (Table 1):

$$\text{AC line current} = \frac{\text{DC Current}}{\text{P.S. rated D.C. current}} \times \text{rated line current}$$

$$I_L = \frac{2300}{2500} \times 850 = 782 \text{ Amp.}$$

$$\text{KW}_{\text{Load}} = 1.08(2300 \times 120 \times 10^{-3}) + 5 = 303 \text{ KW}$$

$$\text{Substation KVA} = 0.83 \times 782 = 649 \text{ KVA}$$

$$\text{P.F.} = \frac{303}{649} = 0.466$$

If we want to use the graph of fig. 1 we can say:

P.S. operating voltage is  $\frac{120}{200} = 60\%$  of rated and fig. 1 shows a power factor of 0.47 at that point.

II. Power Factor Correction Capacitors

The lagging A.C. line current caused by power supplies, or other loads, can be compensated (reduced) by a leading current caused by installed P.F. correction capacitors. (Fig. 2)

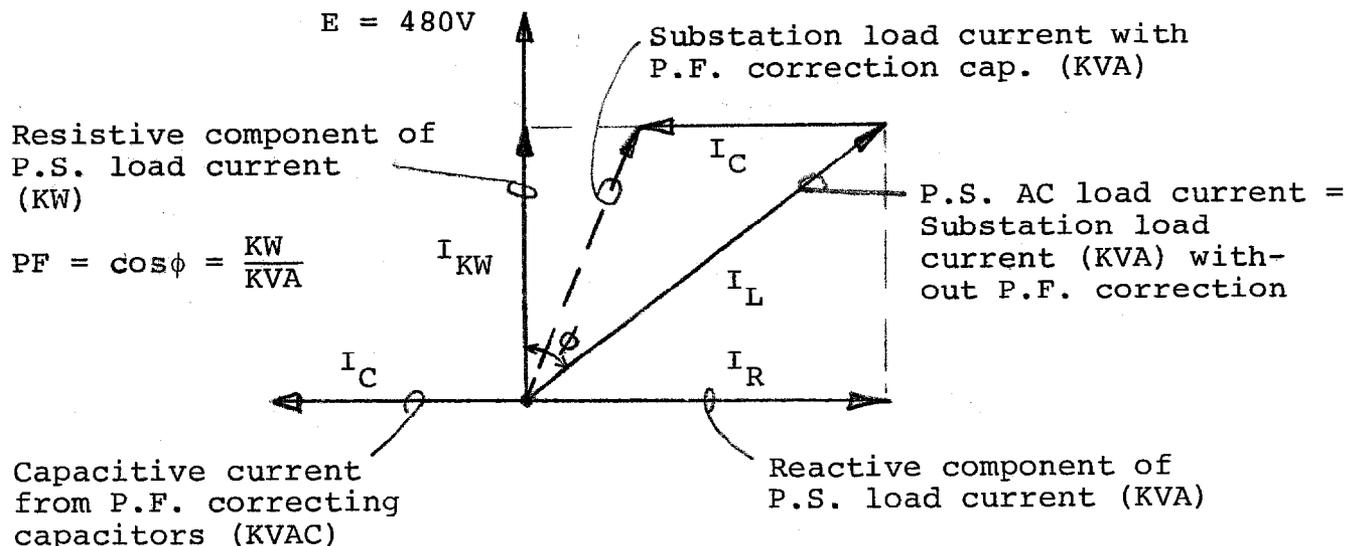


Fig. 2

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Substantial reduction in substation load current can be obtained as seen from Fig. 2.

The final power factor should be lagging and less than unity. This poses a problem for widely varying loads because experimenters generally operate their magnets over a wide range of current. Some kind of automatic capacitor switching is required. This equipment must switch capacitors on and off in blocks when the D.C. load current changes. Commercially available equipment, such as Westinghouse "Var-Pak" will keep the power factor automatically in balance.

This equipment monitors the P.F. and switches P.F. correction capacitors on and off when the power factor gets out of balance. We could use centralized outdoor equipment, which always stays in place, regardless of equipment changes in the experimental areas. Experiment change over labor cost would then be avoided as far as power factor correction equipment is concerned. This may be the most attractive and least confusing solution\*, because experimental areas are in constant turmoil, but substations stay mostly in place. It would also save experimental area floor space, and avoid possible fire code problems for oil-filled units inside buildings. A disadvantage of mounting capacitors at the substations is that the KVA loading of the secondary feeders remains unchanged.

Installed power factor correcting capacitors will have the following benefits:

1. Energy savings.
2. Substantial reduction of KVA loading at the substations and feeders, for the same experimental loads.

\* Later on we will discover that this costs too much.

3. Better AC line voltage regulation resulting in longer equipment life, especially motors.
4. AC line noise reduction and better AC current form factors.
5. Improved power factor resulting in cheaper cost per KWHR, if there is a penalty clause for low power factor in the utility-customer contract.

The following gives us some feel about the size and cost of a typical power factor correction capacitor bank:

Enclosed P.F. correction capacitor bank - 480 Vac, 60 Hz, no switching -	500 KVAC
Size -	3 ft. x 4 ft. x 3 ft.
Weight -	1100 lbs.
Cost -	\$6200 (5/81).

Attached Table 2 permits rapid selection of capacitor KVAR (= KVAC) required to improve the power factor.

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The required KVAC for a certain amount of power factor improvement can also be calculated as follows:

Let us define circuit values without power factor correction with subnumber 1 and with power factor correction with subnumber 2.

Data from Example A

$$I_{L1} = 782A$$

$$\text{Load} = 303KW$$

$$KVA_1 = 649 \text{ KVA}$$

$$PF_1 = 0.47$$

Say we want to increase the power factor to  $PF_2 = 0.9$ . The load (KW) does not change.

$$\text{Thus: } PF_2 = \frac{KW}{KVA_2} = \frac{303}{KVA_2} = 0.9$$

$$KVA_2 = 337 \text{ KVA}$$

In general we can write:

$$KVA^2 = KVAR^2 + KW^2$$

$$\text{Thus: } 649^2 = KVAR_1^2 + 303^2$$

$$KVAR_1 = 573 \text{ KVA}$$

and with  $PF_2 = 0.9$

$$337^2 = KVAR_2^2 + 303^2$$

$$KVAR_2 = 112 \text{ KVA}$$

The required KVAC =  $KVAR_1 - KVAR_2$

$$KVAC = 573 - 112$$

$$KVAC = 461 \text{ KVAC for } PF_2 = 0.9$$

$$\text{The line current } I_{L2} = \frac{KVA_2}{KVA_1} I_{L1}$$

The ratio of the losses (if this was the only load!) produced by

$I_{L1}$  and  $I_{L2}$  in the feeders and substation is:

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$$\frac{\text{Loss}_2}{\text{Loss}_1} = \frac{I_{L_2}^2 R}{I_{L_1}^2 R} = \frac{406^2}{782^2}$$

$$\text{Loss}_2 = 0.27 \text{ Loss}_1 \quad (\text{R} = \text{feeder} + \text{substation resistance})$$

Resumé of Example A:

P. Factor corr. cap.	0	461 KVAC
P. Factor	0.47	0.9
AC line current	782 A	406 A
Load	303 KW	303 KW
KVA	649	337
Substation and feeder loss	$L_1$	$0.27 L_1$

This example clearly demonstrates that substantial savings in capacity, KVA demand, and losses can be made.

Before we had concluded that the capacitors must be switched on and off in steps because the value of the reactive component of the power supply AC current changes when the DC load current changes. What is the relation between the reactive component of the AC current and the DC operating current? Once we know that, we can select a reasonable "capacitor step" size. Let us see what we can find.

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$$\text{KVAR}^2 = \text{KVA}^2 - \text{KW}^2$$

$$\text{KVAR}^2 = (0.83I_L)^2 - \text{KW}^2$$

$$I_L = \frac{I_{L \text{ rated}}}{I_{DC \text{ rated}}} I_{DC}$$

Define:  $K = \left( 0.83 \frac{I_{L \text{ rated}}}{I_{DC \text{ rated}}} \right)^2$

K is a constant for a selected power supply and tap setting and is listed in table 1.

$$\text{KVAR}^2 = KI_{DC}^2 - \text{KW}^2$$

We will neglect the no load power supply loss, thus:

$$\text{KVAR}^2 = KI_{DC}^2 - \left( 1.08I_{DC}^2 R_{\text{load}} \times 10^{-3} \right)^2$$

$$\text{KVAR}^2 = KI_{DC}^2 - 1.166 \left( I_{DC}^2 R_{\text{load}} \times 10^{-3} \right)^2$$

1)

$$I_{DC} = \text{Load Amp}$$

$$R_{\text{load}} = \text{Load Ohms}$$

From formula 1) we can plot  $\text{KVAR} = f(I_{DC})$ , for example A, and find it as shown in fig. 3. Fig. 3 also shows a graph for the best match (load requiring 2500 A at 200 V,  $80 \times 10^{-3} \Omega$ ) and the poorest match (load requiring 2500A at 100V,  $40 \times 10^{-3} \Omega$ ). Normal operation is somewhere in between these extremes, provided a proper tap setting is selected.

Fig. 4 shows the best and worst match KVAR for a 500 KW P.S. at the 5000 A/100 V tap.

Fig. 3 and Fig. 4 are identical. The "worst" case KVAR at the 2500 A/200 V tap matches the worst case KVAR of the 5000 A/100 V tap. This could be expected, since in both cases the rated P.S. line current will be obtained. For tap combinations yielding only half the line current the worst case KVAR will be half of the value for full line current. From this conclusion we can deduct easily the maximum operating KVAR for all P.S. taps for the "worst case" load match. This is listed in Table 1 under column  $KVAR_{MAX}$ .

The experimental area substations feed mostly power supplies. Looking at fig. 3 and fig. 4 and Table 1 we can conclude that it is reasonable to equip each 1.5 MVA substation, feeding mainly power supplies, with 1000 KVAC of power factor correcting capacitors. The step size should be 100 KVAC or smaller. This amount of capacitance will yield power factors of about 0.9, provided the power supply taps are reasonably matched to the load.

### III. P-Center Example

Consider only the big loads BH507, AN520, AN510 and SP508, shown for E-497 on drw. #ATV 120579. There is a lot of load switching, thus we must be able to switch power factor correcting capacitors on and off automatically. It is already confusing enough. There are three different substations bringing power to P-Center. We can go through the same exercise as in Example A and arrive at the following tables for each power supply.

Power Supply - BHS 507A (500KW) Fed from Substation PL-2

Note: 2 - 500KW P.S. in series feed one load BH507

P.S. Tap	100V/5000A	100V/5000A	
D.C. load ( $27 \times 10^{-3} \Omega$ )	3600A/97V	3600A/97V	
D.C. load KW	350	350	
P.F.	0.69	0.9	
A.C. line current	612	469	
Substation KVA	508	389	
Substation and Feeder loss	$L_1$	$0.59 L_1$	1)
P.F. correction	0	198	
Capacitor Bank KVAC			
Estimated cost of P.F. correcting bank	0	\$2,500	
Estimated cost of controls, cables	-	\$2,500	
Total est. size	-	20 ft. <sup>3</sup>	2)
Total est. installed cost (labor & mat.)	0	\$10,000	2)

- 1) Not considering other loads  
2) Includes controls

Power Supply - BHS 507B (500KW) Fed from Substation PL-5

Note: 2 - 500KW P.S. in series feed one load BH507

P.S. Tap	100V/5000A	100V/5000A	
D.C. load ( $27 \times 10^{-3} \Omega$ )	3600A/97V	3600A/97V	
D.C. load KW	350	350	
P.F.	0.69	0.9	
A.C. line current	612	469	
Substation KVA	508	389	
Substation and feeder loss	$L_1$	$0.59 L_1$	1)
P.F. correction	0	198	
Capacitor Bank KVAC			
Estimated cost of P.F. correcting bank	0	\$2,500	
Estimated cost of controls, cables	0	\$2,500	
Total est. size	-	20 ft. <sup>3</sup>	2)
Total est. installed cost (labor & mat.)	0	\$10,000	

- 1) Not considering other loads  
2) Includes controls

Power Supply - ANS 510 (500KW) Fed from Substation PL2B

(This is Example A)

P.S. Tap	200V/2500A	200A/2500A
D.C. Load ( $52 \times 10^{-3} \Omega$ )	2300A/120V	2300A/120V
D.C. load KW	303	303
P.F.	0.47	0.9
A.C. line current	782A	406A
Substation KVA	649	337
Substation and feeder loss	$L_1$	0.27 $L_1$ 1)
P.F. correction	0	461
Capacitor bank KVAC		
Estimated cost of P.F. correcting bank	0	\$6,200
Estimated cost of controls, cables	-	\$4,800
Total est. size	0	50 ft. <sup>3</sup> 2)
Total est. installed cost (labor & mat.)	0	\$22,000 2)

1) Not considering other loads

2) Includes controls

Power Supply - ANS 520 (500KW) Fed from Substation PL-2

Note: This power supply is operated beyond its rated current.

P.S. Tap	2500A/200V	2500A/200V
D.C. load ( $64 \times 10^{-3} \Omega$ )	2700A/172V	2700A/172V
D.C. load KW	506	506
P.F.	0.55	0.9
A.C. line current, A	920	677
Substation KVA	762	562
Substation and feeder loss	$L_1$	0.54 $L_1$ 1)
P.F. Correction	0	524
Capacitor bank KVAC		
Estimated cost of P.F. correcting bank	0	\$6,200
Estimated cost of controls	0	\$4,800
Total est. size	0	50 ft. <sup>3</sup> 2)
Total est. installed cost	0	\$22,000 2)

1) Not considering other loads

2) Includes controls

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Power Supply - SPS 508 (240KW) Fed from Substation PL2B

P.S. Tap	1200A/50V	1200A/50V	
D.C. load ( $16 \times 10^{-3} \Omega$ )	800A/16V	800A/16V	
D.C. load KW	16	16	
P.F.	0.28	0.9	
A.C. line current, A	70	22	
Substation KVA	58	18	
Substation and feeder loss	$L_1$	$0.01 L_1$	1)
P.F. correction	0	48	
Capacitor Bank KVAC			
Estimated cost of P.F. correcting bank	0	\$1,000	
Estimated cost of controls/cables	0	\$2,000	
Total est. size	0	8 ft. <sup>3</sup>	2)
Total est. installed cost	0	\$4,000	2)

- 1) Not considering other loads  
 2) Includes controls

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#### IV. P-Center - Conclusion

To install automatic power factor correcting capacitors at each individual power supply would roughly cost \$68,000 including controls. The required total KVAC is about 1000 KVAC, which improves the power factor from about PF = 0.5 (different for various loads) to PF = 0.9. Most locations require different size equipment. There are also space and connecting problems.

Power (feeder and transformer) loss savings are hard to estimate. We can, however, conclude that improving the power factor to P.F. = 0.9 will reduce the 480 VAC line currents about 30%. It is reasonable to say that the P-Center load draws a total 480 VAC line current of 2734A, if we add the individual currents algebraically. However, the currents are phase displaced. Say, therefore, that the total 480 VAC line current to P-Center is 2500 A without P.F. correction and  $0.7 \times 2500 \text{ A} = 1750 \text{ A}$  with power factor correction. The estimated reduction in secondary feeder current is  $\frac{1750}{2500} 100\% = 70\%$ . The estimated reduction in 480 VAC supply losses is  $\left(\frac{0.7}{1}\right)^2 100\% \approx 50\%$ . The load losses of a 1.5 MVA substation are 14.5 KW. Use the losses of two 1.5 MVA substations for P-Center. The reduction in substation losses is  $2 \times 14.5 \times 0.5 \approx 15\text{KW}$ . Primary feeder loss savings are not as much because other substations use the same feeders. I will only venture to guess that the feeder current gets reduced by 5%, resulting in 10% loss savings, or 3 KW for the P-Center case.

(4000' - 750 MCM AL per phase,  $R_{\text{feeder}}$  per phase  $\sim 0.1 \Omega$   
 estimate feeder load current  $\sim 300 \text{ A}$ . Losses without P.F. correction  
 $3 \times 300^2 \times 0.1 \times 10^{-3} = 27 \text{ KW}$ . Feeder losses saved with power factor  
 correction  $0.1 \times 27 \approx 3 \text{ KW}$ .)

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Although we have saved about 18 KW in losses by installing a 1000 KVAC bank, we have added the losses created by the newly installed power factor capacitor bank. I estimate the losses of an automatic 1000 KVAC capacitor bank to be about 3 KW. The following summary table can be made for P-Center.

P-Center Conclusion Summary of Estimates

Power factor correction cap. (Divided among three substations)	1000 KVAC
Total cost (individually mounted systems)	\$68,000
Loss savings -	18 KW
New loss from P.F. Cap. banks - <u>3 KW</u>	
Net loss savings	15 KW
Loss savings/year (100% operation)	130 MWHRS
Cost/KWHR	\$0.04
Dollars saved/year (100% operation)	\$5,300
Released system capacity	30%
Reduction in KVA demand	30%

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### V. General Conclusion

We can draw some general conclusions from the preceding discussion, for a typical 1.5 MVA experimental area substation for power supplies, equipped with an automatic P.F. correcting bank. They are listed below.

Substation	1.5 MVA
Load	SCR controlled P.S.
Recommended size of P.F. correcting cap. with automatic P.F. correction, central installation	1000 KVAC
P.F. w/out capacitors	~ 0.6
P.F. with capacitors	~>0.9
Cost - Material - \$ 40,000	
Labor & Misc. - \$ <u>20,000</u>	
Total -	\$60,000
Loss savings:	
Feeder 3 KW	
Substation 7 KW	
Losses added:	
P.F. Bank <u>(3) KW</u>	
Net loss savings	7 KW
Loss savings/yr. (100% Operation)	61 MWHRS
Cost/KWHR	\$0.04
Dollars saved/year (100% Operation)	\$2400
Released system capacity	30%
Reduction in KVA demand	30%
Improved sec. voltage regulation	5% (estimate)

Equipment maintenance and depreciation cost have been ignored in this table.

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Looking at the above numbers it becomes apparent that the installation of a large, central, automatic 1000 KVAC power factor correcting bank is not economical at this time, except in cases where the KVA demand exceeds the installed capacity. Then the question might boil down to a new substation or a capacitor bank. The real savings are in released system capacity of about 30% and about 5% better voltage regulation.

It is much more economical to make a partial power factor correction by installing 120 KVAC of power factor correcting capacitors at each 500 KW and 240 KW power supply. These capacitors would be connected at the load side of each power supply contactor. They would thus automatically switch in when the power supply comes on. A time delay of about 3 minutes must be installed before the P.S. can be restarted after a trip. This prevents connecting charged capacitors to the line. The capacitors must have discharge resistors, with a time constant of about one minute. Installing 120 KVAC per power supply would cost \$2500 each. How much would we save in losses? It will be different for each case, but let us make some realistic assumptions for a typical 1.5 MVA substation as follows:

Assumption

Substation	1.5 MVA
Load, 3 power supplies	1000 KW
$PF_1$	0.6
$KVA_1$	1666
$KVAR_1$	1333
$I_{L_1}$ Amp.	2007
Feeder and substation Loss <sub>1</sub>	20 KW (estimate)
Install (3 x 120 KVAC)	360 KVAC
Cost	\$7,500
Load, 3 power supplies	1000 KW
$PF_2$	0.72
$KVA_2$	1395
$KVAR_2$	973
$I_{L_2}$ Amp.	1680
$\frac{Loss_2}{Loss_1}$	0.7
Feeder loss <sub>2</sub>	14 KW
Loss savings (= Loss <sub>1</sub> - Loss <sub>2</sub> + Cap. Loss)	5 KW
Annual savings (Based on \$0.04 KWHR 100% operation)	\$1750

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It is obvious that installing 120 KVAC at each power supply makes much more economical sense. It also unloads the secondary feeders and switchboards. A 500 KVAC automatic bank (equipment cost \$19,000) could be added centrally in places where it is necessary.

In the future we will be running more superconducting loads. This will result (see Table 1 for lowest tap) in a reduction for the KVAR per power supply. The KVAR per substation will, however, remain the same, because we will feed more power supplies from the same substation. The way it looks now, however, most experimental loads will be conventional magnets.

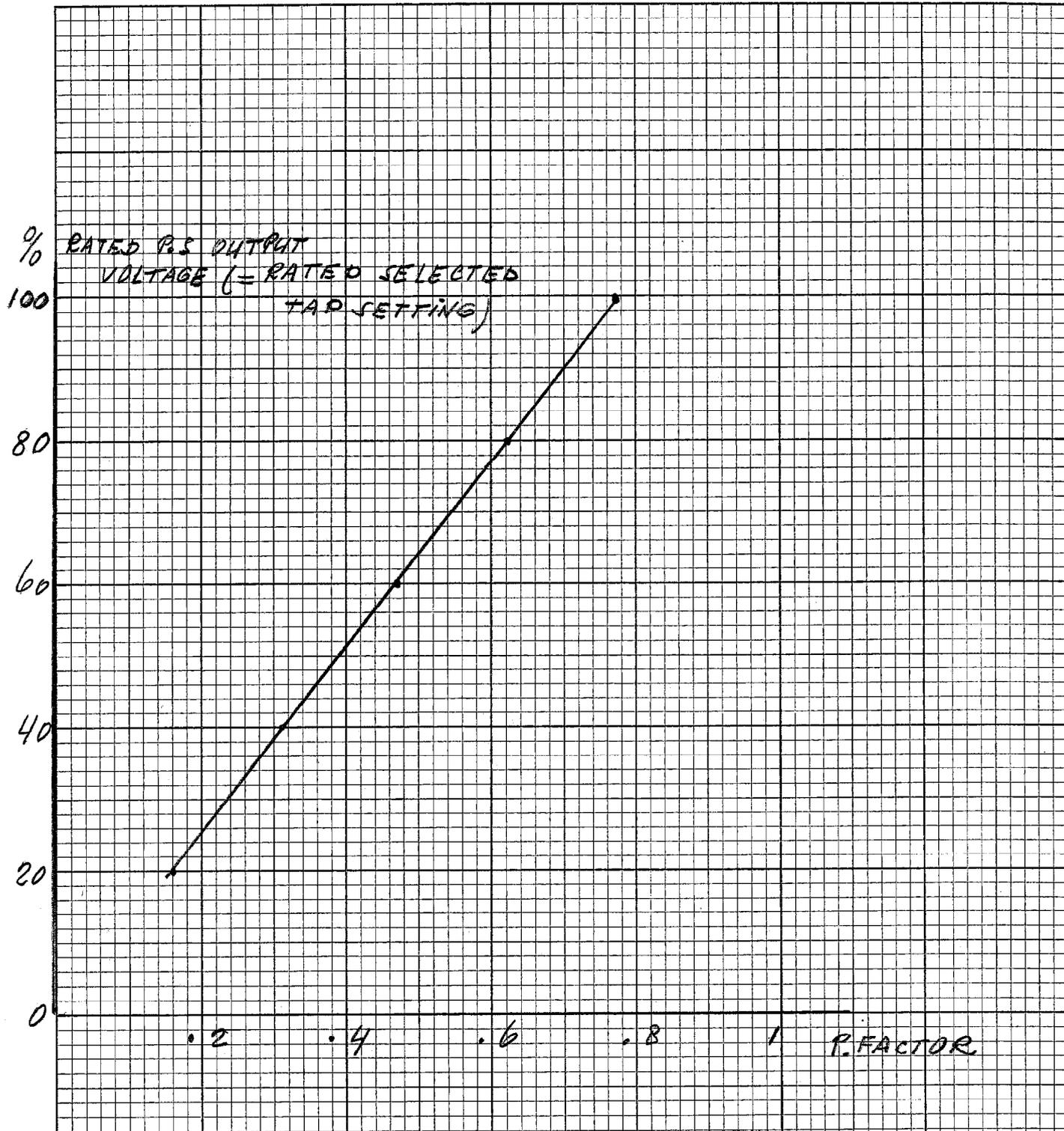


Fig. 1  
 500KW, 240KW, 55KW Power  
 Supply Power Factor as a  
 Function of Output Voltage

ATV

5/13/81

# Table for calculating necessary capacitor kvar to improve power factor

Desired power factor in percentage

Original power factor in percentage

	80%	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
50%	.982	1.008	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.303	1.337	1.369	1.402	1.441	1.481	1.529	1.590	1.732
51	.936	.962	.988	1.014	1.040	1.066	1.093	1.119	1.146	1.174	1.202	1.230	1.257	1.291	1.320	1.357	1.395	1.435	1.483	1.544	1.686
52	.894	.920	.946	.972	.998	1.024	1.051	1.077	1.104	1.132	1.160	1.188	1.215	1.249	1.281	1.315	1.353	1.393	1.441	1.502	1.644
53	.850	.876	.902	.928	.954	.980	1.007	1.033	1.060	1.088	1.116	1.144	1.171	1.205	1.237	1.271	1.309	1.349	1.397	1.458	1.600
54	.809	.835	.861	.887	.913	.939	.966	.992	1.019	1.047	1.075	1.103	1.130	1.164	1.196	1.230	1.268	1.308	1.356	1.417	1.559
55	.769	.795	.821	.847	.873	.899	.926	.952	.979	1.007	1.035	1.063	1.090	1.124	1.156	1.190	1.228	1.268	1.316	1.377	1.519
56	.730	.756	.782	.808	.834	.860	.887	.913	.940	.968	.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277	1.338	1.480
57	.692	.718	.744	.770	.796	.822	.849	.875	.902	.930	.958	.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239	1.300	1.442
58	.655	.681	.707	.733	.759	.785	.812	.838	.865	.893	.921	.949	.976	1.010	1.042	1.076	1.114	1.154	1.202	1.263	1.405
59	.618	.644	.670	.696	.722	.748	.775	.801	.828	.856	.884	.912	.939	.973	1.005	1.039	1.077	1.117	1.165	1.226	1.368
60	.584	.610	.636	.662	.688	.714	.741	.767	.794	.822	.849	.878	.905	.939	.971	1.005	1.043	1.083	1.131	1.192	1.334
61	.549	.575	.601	.627	.653	.679	.706	.732	.759	.787	.815	.843	.870	.904	.936	.970	1.008	1.048	1.096	1.157	1.299
62	.515	.541	.567	.593	.619	.645	.672	.698	.725	.753	.781	.809	.836	.870	.902	.936	.974	1.014	1.062	1.123	1.265
63	.483	.509	.535	.561	.587	.613	.640	.666	.693	.721	.749	.777	.804	.838	.870	.904	.942	.982	1.030	1.091	1.233
64	.450	.476	.502	.528	.554	.580	.607	.633	.660	.688	.716	.744	.771	.805	.837	.871	.909	.949	.997	1.058	1.200
65	.419	.445	.471	.497	.523	.549	.576	.602	.629	.657	.685	.713	.740	.774	.806	.840	.878	.918	.966	1.027	1.169
66	.388	.414	.440	.466	.492	.518	.545	.571	.598	.626	.654	.682	.709	.743	.775	.809	.847	.887	.935	.996	1.138
67	.358	.384	.410	.436	.462	.488	.515	.541	.568	.596	.624	.652	.679	.713	.745	.779	.817	.857	.905	.966	1.108
68	.329	.355	.381	.407	.433	.459	.486	.512	.539	.567	.595	.623	.650	.684	.716	.750	.788	.828	.876	.937	1.079
69	.299	.325	.351	.377	.403	.429	.456	.482	.509	.537	.565	.593	.620	.654	.686	.720	.758	.798	.840	.907	1.049
70	.270	.296	.322	.348	.374	.400	.427	.453	.480	.508	.536	.564	.591	.625	.657	.691	.729	.769	.811	.878	1.020
71	.242	.268	.294	.320	.346	.372	.399	.425	.452	.480	.508	.536	.563	.597	.629	.663	.701	.741	.783	.850	.992
72	.213	.239	.265	.291	.317	.343	.370	.396	.423	.451	.479	.507	.534	.568	.600	.634	.672	.712	.754	.821	.963
73	.186	.212	.238	.264	.290	.316	.343	.369	.396	.424	.452	.480	.507	.541	.573	.607	.645	.685	.727	.794	.936
74	.159	.185	.211	.237	.263	.289	.316	.342	.369	.397	.425	.453	.480	.514	.546	.580	.618	.658	.700	.767	.909
75	.132	.158	.184	.210	.236	.262	.289	.315	.342	.370	.398	.426	.453	.487	.519	.553	.591	.631	.673	.740	.882
76	.105	.131	.157	.183	.209	.235	.262	.288	.315	.343	.371	.399	.426	.460	.492	.526	.564	.604	.652	.713	.855
77	.079	.105	.131	.157	.183	.209	.236	.262	.289	.317	.345	.373	.400	.434	.466	.500	.538	.578	.620	.687	.829
78	.053	.079	.105	.131	.157	.183	.210	.236	.263	.291	.319	.347	.374	.408	.440	.474	.512	.552	.594	.661	.803
79	.026	.052	.078	.104	.130	.156	.183	.209	.236	.264	.292	.320	.347	.381	.413	.447	.485	.525	.567	.634	.776
80	.000	.026	.052	.078	.104	.130	.157	.183	.210	.238	.266	.294	.321	.355	.387	.421	.459	.499	.541	.608	.750
81	—	.000	.026	.052	.078	.104	.131	.157	.184	.212	.240	.268	.295	.329	.361	.395	.433	.473	.515	.582	.724
82	—	—	.000	.026	.052	.078	.105	.131	.158	.186	.214	.242	.269	.303	.335	.369	.407	.447	.489	.556	.698
83	—	—	—	.000	.026	.052	.079	.105	.132	.160	.188	.216	.243	.277	.309	.343	.381	.421	.463	.530	.672
84	—	—	—	—	.000	.026	.053	.079	.106	.134	.162	.190	.217	.251	.283	.317	.355	.395	.437	.504	.646
85	—	—	—	—	—	.000	.027	.053	.080	.108	.136	.164	.191	.225	.257	.291	.329	.369	.417	.478	.620

**EXAMPLE:**

**GIVEN:**

A circuit supplies a load that has a 100-kilowatt value (either from calculation or from a wattmeter) and operates at a power factor of 68%.

**FIND:**

What is the required capacitor kvar rating needed to raise the power factor to 96%?

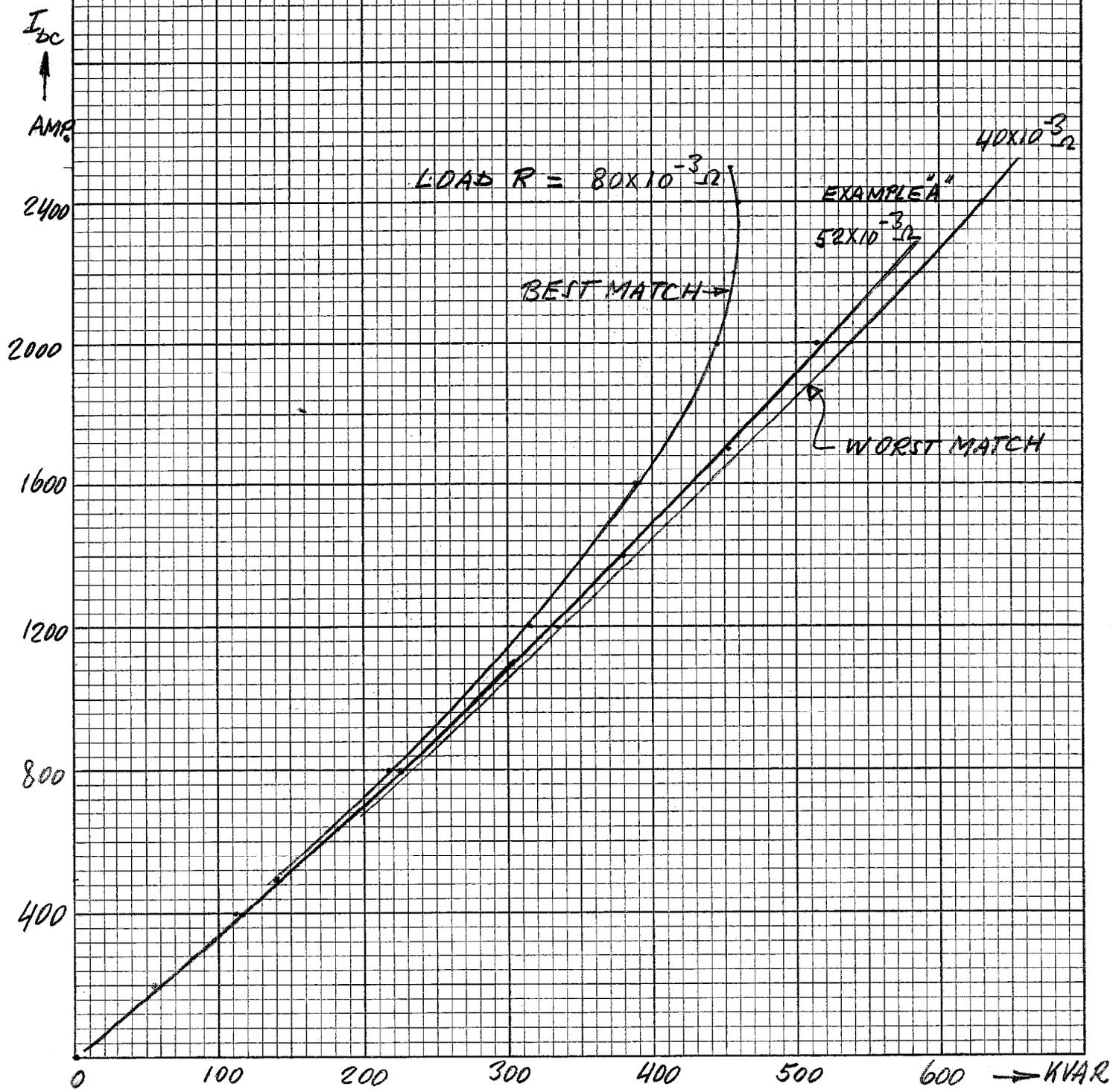
**ANSWER:**

Find the multiplier needed from the Table above by locating 68% in the vertical column at left and then moving across on that line to the multiplier listed under the top heading of 96%. The multiplier is found to be 0.788. Then—

$$100 \text{ kw} \times 0.788 = 78.8 \text{ kilovars needed}$$

500 KW P.S.  
 Tap 2500A/200V  
 $KVAR = f(I_{DC})$

Fig. 3



500 KW P.S.  
 Tap 5000A/100V  
 $KVAR = f(I_{DC})$

Fig. 4

