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Economics When Appling Shunt Capacitors

Managing your electrical loads offers many challenges. Your plant needs all the power it can muster while conserving as much energy as possible and yet maintain an efficient operation.

Looking at the power consumed it is necessary to supply two types of powers. The first is **"Active Power"** (Kilowatts); the second is "**Reactive Power"** (Kvar). The active power is supplied by the utility incoming. The reactive power can be furnished by the system, or by the use of static shunt capacitors. It has been established that shunt power capacitors are the most economical source for the reactive power (Kvar) required by the loads and lines when operating at less than unity power factor (100%).

Studies show that supply systems from the power company's lines require reactive power (Kvar) in addition to the consumer's electric load. Looking at a simple system, if the only reactive power source is the central station generation, this reactive power will have to be generated by the generators and than transmitted over the lines to the loads. If the power company has capacitor banks at the supply substation this will aid in supplying reactive power. However, if the consumer's plant has a poor power factor the substation and the lines to the plant will have to handle the additional currents required.

Coupled with the additional currents developed by poor power factor, there is also corresponding power loss (**I^2R loss**) associated with transmission and distribution of reactive power current to the plants load. These losses create an undesirable voltage reduction on the lines to the plant. Shunt capacitors affect the voltage rise when connected to the system. The addition of switched capacitors not only improves the voltage levels, but also provides an effective method of controlling the voltage levels.

The installation of power capacitors enables a utility, as well as their industrial customer, to realize savings within their systems.

The following benefits can be realized.

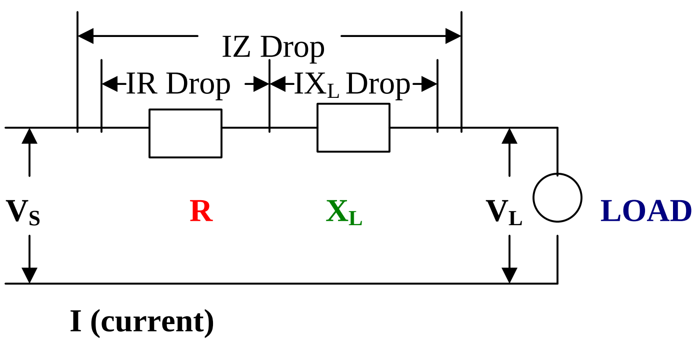
1. Raised Voltage Levels
2. Released Generation Capacity
3. Released system capacity
4. Reductions of System Loses
5. Regulations of Voltage Levels

The utility can witness benefits on their generation, EHV transmission, and sub-transmission and distribution systems with power capacitors.

1. Voltage considerations

Voltage Drop

Simply, the voltage drop is basic and is due to the impedance in the line. The impedance consists of resistance, which creates **IR** voltage drop and reactance, which creates $\mathbf{IX_L}$ voltage drop. The combination of these two drops is known as the impedance drop, or **IZ** drop.



$$V_S = V_L + IZ_T$$
$$Z_T = R + jX_L$$

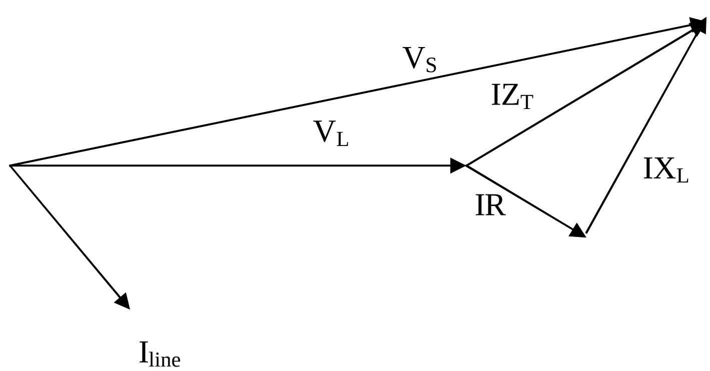


Figure 1

Table 1

Power Factor		Power Factor Angle (f)	Sin(f)	Tan(f)
cos f	%			
0.40	40	66^0	0.916	2.29
0.45	45	63^0	0.893	1.98
0.50	50	60^0	0.866	1.73
0.55	55	57^0	0.835	1.52
0.60	60	53^0	0.800	1.33
0.65	65	49^0	0.760	1.17
0.70	70	45^0	0.715	1.02
0.75	75	41^0	0.661	0.881
0.80	80	37^0	0.600	0.750
0.85	85	32^0	0.526	0.617
0.90	90	26^0	0.436	0.484
0.95	95	18^0	0.312	0.329
1.00	100	0^0	0.000	0.000

Table 2

Wire Size		Ohms Resistance Per Mile of Line	Ohms Reactance Per Mile of Line			
ACSR No.	Copper No.		Equiv. Triangle Spacing in inches			
			30	42	56	68
.6	No 8 Solid	3.47	0.776	0.817	0.852	0.876
.4	No 6 Solid	2.18	0.748	0.789	0.824	0.848
.2	No 4 Solid	1.37	0.720	0.761	0.796	0.820
1/0	No 2 Solid	0.864	0.692	0.733	0.768	0.792
2/0	No 1 solid	0.699	0.671	0.712	0.747	0.771
3/0	1/0 strand	0.555	0.657	0.698	0.733	0.757
4/0	2/0 strand	0.40	0.643	0.684	0.719	0.743
300Mcm	3/0 strand	0.278	0.714	0.655	0.690	0.714

Percent Voltage drop

% Voltage Drop = $$\frac{(KVA)*(D)*(RCOSf + XSINf)}{10*KV^2}$$

D =Line length
KV = phase to phase voltage

LET

KW = 1000
Pf = 85%
R = 0.699/mile
X_L = 0.712 Ohms
D = 10 Miles

THEN

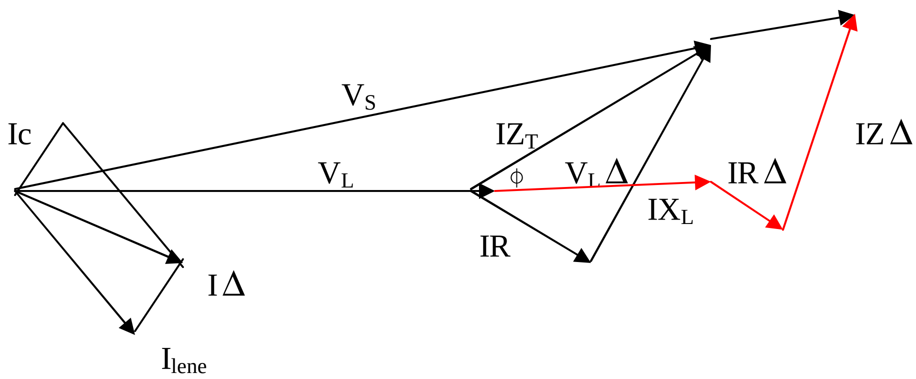
$$KVA = \frac{1000KW}{0.85PF} = 1176.5$$

KV = 12.47
ARCCOS 0.85 = 31.8^0
$\therefore$ SINf = 0.527

% Voltage Drop = $$\frac{(1176.5)*(10)*((0.699*0.85)+(0.712*0.527))}{10*(12.47)^2} = 7.33$$

With a 7.33% voltage drop the total voltage drop will be 914.57 volts. The line voltage at this point will be 11,555.43 volts. If the secondary voltage is 480 volts normally this voltage drop will be 444.8 volts.

Voltage Rise



Percent Voltage Rise

% Voltage Rise = $$\frac{(\boldsymbol{KVAR}) * (\boldsymbol{D}) * (\boldsymbol{X_L})}{10 * \boldsymbol{KV}^2}$$

D =Line length
KV = phase to phase voltage

From above

KV = 12.47
KW = 1000
Pf = 85%
X_L = 0.712 Ohms
D = 10 Miles

To correct the power factor to approximately 95% we will use 300 KVAR. This will correct this system to approximately 97%, then…

% Voltage Rise = $$\frac{(300) * (10) * (0.712\Omega)}{10 * (12.47)^2} = 1.374\%$$

With a 1.37% voltage rise, the voltage at the load V_L is increased by 159 volts. The line voltage becomes 11,714.2 volts. With the secondary voltage at 444 volts, voltage is raised to 461volts.

Percentage Voltage Drop In a Transformer

The percentage voltage drop may be calculated by the following:

$$\%Voltage - Drop = \left(\frac{Kva}{10(Kv)^2}\right)(RxfmrCos f + XxfmrSin f)$$

$$= \left(\frac{1200}{10(12.47)^2}\right)((0.699 * 0.85) + (0.712 * 0.527)) = 0.748\%$$

Voltage Rise Through Transformers

The above discussion shows the voltage drop and rises on the power line and drop in the transformers. Every transformer will also experience a voltage rise from generating source to the capacitors. This rise is independent of load or power factor and may be determined as follows:

$$PercentageVoltageRise = \left(\frac{K\,\mathrm{var}}{Kva}\right)X_t$$

Kvar =Applied Kilo-vars
Kva = Kva of the transformer
X_t = Transformer Reactance in %

Using the 300 Kvar bank given above and assuming a 1200 KVA transformer with 5.75% reactance we would have:

$$Percent - Voltage - Rise = \frac{300}{1200} * 5.75 = 1.4375\%$$

New Total Voltage Improved Drop

New net Voltage Drop =Total Drop – Total Rise

Using the values from above, the new improved voltage drop will be:

Voltage Drop in Line	= 7.33%
Voltage Drop in the Transformer	= 0.748%
Total Voltage Drop	= 8.078%

Voltage Rise in Line	= 1.374%
Voltage Rise in the Transformer	= 1.4375%
Total Voltage rise	= 2.8115%

Net Voltage Drop = 8.078% - 2.8115% = 5.2665%

Substation Capacity Released

Assuming the 1200 KVA transformer is in the customer's substation and is used with the other values used in the equations above the released substation capacity is as follows:

$$\Delta KVA_S = \left[\sqrt{1-\frac{(KVAR)^2(Cos f)^2}{(KVA_S)^2}}+\frac{Sin f(KVAR)}{KVA_S}-1\right]KVA_S$$

$$\Delta KVA_S = \left[\sqrt{1-\frac{(300)^2(0.83)^2}{(1200)^2}}+\frac{0.527(300)}{1200}-1\right]1200$$

$$\Delta KVA_S = 139KVA$$

A quick approximation of KVA increase can be as follows:

$$\approx \Delta KVA_S = (KVAR)Sin f$$

$$\approx \Delta KVA_S = (300KVAR)0.527 = 158KVA$$

Generating Capacity Released

To determine this capacity released the formula used for the **Substation Capacity Release** can also be used. We would replace the substation transformer **(KVA_S)** with the generating capacity **(KVA_G)**. Assuming the **KVA_G** is 20MVA we have the following:

$$\Delta KVA_G = \left[\sqrt{1 - \frac{(KVAR)^2 (Cos f)^2}{(KVA_S)^2}} + \frac{Sin f (KVAR)}{KVA_S} - 1 \right] KVA_S$$

$$\Delta KVA_G = \left[\sqrt{1 - \frac{(300)^2 (0.83)^2}{(20000)^2}} + \frac{0.527(300)}{20000} - 1 \right] 20000$$

$$\Delta KVA_G = 157 KVA$$

Or, by the simplified formula

$$\Delta KVA_G = KVAR(\sin f)$$

$$\Delta KVA_G = 300(0.527)$$

$$\Delta KVA_G = 158 KVA$$

Increased Feeder Capacity

Feeder capacity is limited basically by permissible voltage drop rather than thermal conditions. The application of a capacitor, as shown above, reduces the voltage drop so more KVA of load can be applied without over taxing the transformer. This may be calculated by the following formula, which does not incorporate the generating or substation capacity release.

$$\Delta KVA = \frac{X(KVAR)}{X \sin f + R \cos f}$$

$$\Delta KVA = \frac{0.712(300 KVAR)}{0.712(0.527) + 0.699(0.85)}$$

$$\Delta KVA = 570 KVA$$

The possible increase in KW due to the released feeder KVA can be obtained by multiplying ΔKVA by the corrected power factor.

Reduced Energy Losses

With the decrease in conductor losses due to the addition of capacitors, less kilowatt-hours of electrical energy are dissipated annually. The quantity of energy saved (KWH's) and resultant financial savings can be computed as:

$$E_a = \frac{R(KVAR)[2(KVA)\sin f - (KVAR)](8760)}{1000(KV)^2}$$

where:

KVAR = Three phase kilovar applied.
KVA = Uncorrected three-phase load; 24 hour value, say 720 KVA)
KV = Phase to phase voltage

$$E_a = \frac{0.699(300KVAR)[2(720KVA)(0.527) - (300KVAR)] * 8760}{1000(12.47)^2}$$

$$E_a = 5420.7kw - hr$$

The value of the energy savings can be obtained by multiplying the energy saved by the cost per kw-hr assigned in the utility rate schedule.

Consolidation of Formulas

1. Power Factor Relation

$$pf = \frac{kw}{kva}$$

$$kw = kva(pf)$$

$$kva = \frac{kw}{pf}$$

Where

Kw = kilowatt load
Kva = kilovolt-amperes
Pf = power factor

2. Ratio of I^2R Losses

$$\frac{loss\ @\ pf\,1}{loss\ @\ pf\,2} = \frac{(pf_2)^2}{(pf_1)^2}$$

3. Voltage Drop in A Line

$$Percent-drop = \frac{(kva)(L)(R\cos f + X\sin f)}{10(kv)^2}$$

Where

Kva	=	three phase kva
L	=	Line length in miles (1 wire only)
R	=	Ohms resistance per mile (table 2)
X	**=**	Ohms reactance per mile (table 2)
$\cos f$	=	Uncorrected power factor
$\sin f$	=	Sine of power factor angle (table 1)
kv	=	Phase to phase kilovolts

4. Voltage Rise in A Line

$$PERCENTAGE-RISE = \frac{(KVA)(X)(L)}{10(kv)^2}$$

Where

Kvar = three-phase kilovars applied

See Formula 3 for other units

5. Voltage Rise in A Transformer

$$Percent - rise = \frac{k\,\text{var}}{kva_T}(X_T)$$

Where

Kvar = Three-phase kilovars applied
Kva_T = kva of transformer
X_T = Transformer Reactance in percent.

6. Increase in feeder Capacity

$$\Delta kva = \frac{X(k\,\text{var})}{X \sin f + R \cos f}$$

Where

Δkva = Increase in kva capacity
See Formula 3 for other units

7. Reduced Energy Losses in A Line

$$E_a = \frac{R(k\,\text{var})[2(kva)\sin f - k\,\text{var}]8760}{1000(kv)^2}$$

Where

E_a = Annual conserved energy in kw-hrs.
R = Resistance to load center in Ohms.
Kva = Uncorrected 3-phase kva (24-hour rms value)
Kvar = here phase kilovars applied.
See Formula 3 for other units

8. Increased Revenue Due to Voltage Improvement.

V_2 / V_1	1.00	1.05	1.10	1.15	1.20	1.25	1.30
% Increased	0	8	16	25	34	43	52

Where

V_2 = Average voltage after adding capacitors.
V_1 = Average voltage before adding capacitors.

9. Reduced Substation Capacity

$$\Delta kva_s = (k\,\mathrm{var})\sin f$$ **(When kvar is small compared to kva_S)**

***9a** $$\Delta kva_s = 1 - \left[\frac{(k\,\mathrm{var})^2 (\cos f)^2}{(kva_s)^2} + \frac{(k\,\mathrm{var})\sin f}{kva_s} - 1 \right] * kva_s$$

* When kvar is more than 10% of kva_S

Where

Δkva_s = Released kva of the substation capacity at original PF.
Kva_S = Substation kva capacity
Kvar = Three phase kilovars applied.

See Formula 3 for other units

10. Reduced Substation Capacity

$$\Delta kva_G = (k\,\text{var})\sin f$$ **(When kvar is small compared to kva_G)**

$$*10a = \Delta kva_G = 1 - \left[\frac{(k\,\text{var})^2 (\cos f)^2}{(kva_G)^2} + \frac{(k\,\text{var})\sin f}{kva_G} - 1 \right] * kva_G$$

Where

Δkva_G = Released kva beyond maximum generating capacity at original power factor.

kva_G **=** Generating station kva capacity

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