

Substation Department, Riyadh  
Protection Division, Riyadh

# *Power factor correction capacitors*

## *Theory & applications*



*Prepared by*  
**Engr. Samir zamzam**  
*Senior Protection Engineer*

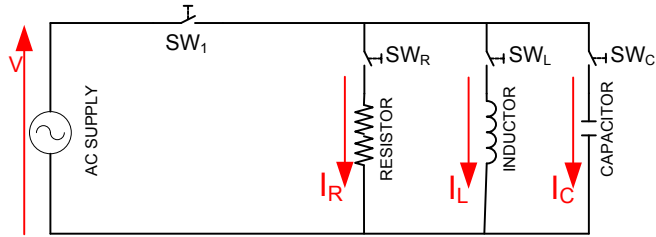
*Approved by*  
**Engr. Nasser M. Al-Enazi**  
*Manager, Protection Division, Riyadh*

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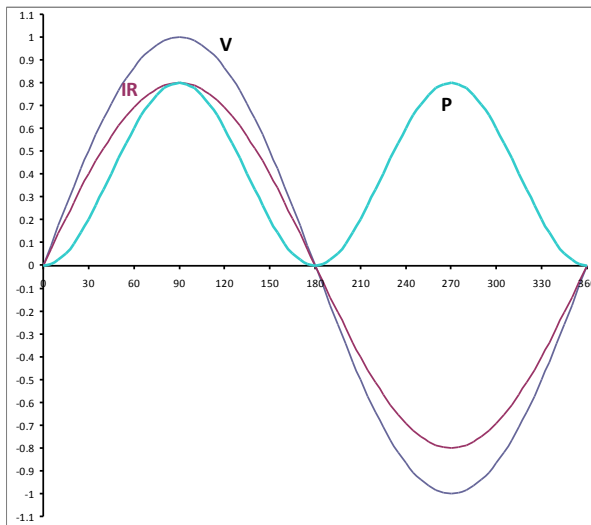
## Introduction

### Voltage & Current Relations for Different Electric Elements



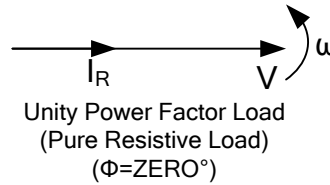
The resistor, inductor & capacitor are the three basic electric elements. Any linear load can be represented by any one of them or by a combination of more than one of them.

**Figure 1: AC supply feeding Resistor, Inductor & Capacitor**

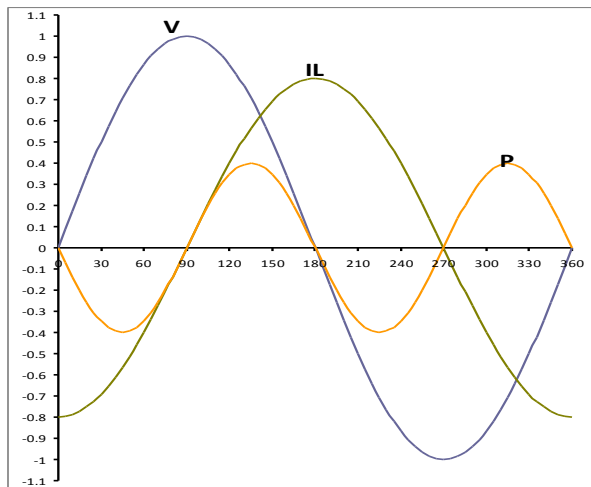


$$v(t) = R \times i(t)$$

i.e. voltage and current are in-phase

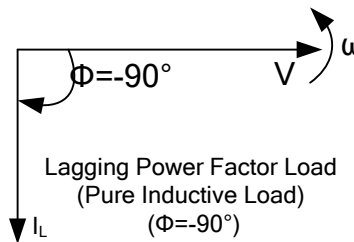


**Figure 2: Voltage, Current & Power in a pure resistive load**



$$v(t) = L \times \frac{di(t)}{dt}$$

i.e. current lags voltage by  $90^\circ$   
if the AC supply is sine wave



**Figure 3: Voltage, Current & Power in a pure inductive load**

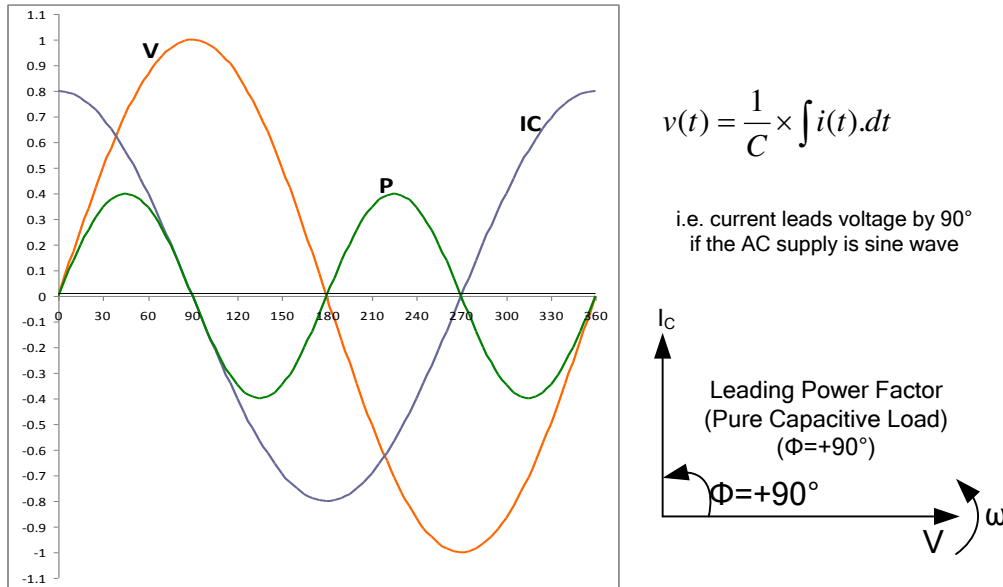


Figure 4: Voltage, Current & Power in a pure capacitive load

**Note:**

The electric current is established in a conductor when a net charge "q" passes through it in a certain time "t":

$$i(t) = \frac{dq(t)}{dt}$$

The capacitance "C" is the accumulated charge "Q" per unit voltage "V":  $C = \frac{Q}{V}$

$$Q = C \times V$$

$$q(t) = C \times v(t)$$

$$i(t) = \frac{dC \times v(t)}{dt}$$

$$i(t) = C \times \frac{dv(t)}{dt}$$

$$\int i(t)dt = \int C \times \frac{dv(t)}{dt} dt$$

$$v(t) = \frac{1}{C} \int i(t)dt$$

## What is Power Factor?

### Introduction:

- Most plant loads are Inductive and require a magnetic field to operate: \*\*Motors \*\*Transformer \*\*Florescent lighting
- The magnetic field is necessary, but produces no useful work
- The utility must supply the reactive power "Q" to produce the magnetic field and the active power "P" to produce the useful work. You pay for all of it.
- You pay for "P" in the form of power consumption.
- You pay for "Q" in the form of low power factor penalty.
- These two types of current are the active and reactive components

### Power Factor Definition

The power factor of a load is given by ratio of the active power to the apparent power of this load .i.e. KW divided by KVA at any given particular moment.

$$\text{POWER FACTOR} = \frac{\text{ACTIVE POWER [KW]}}{\text{APPARENT POWER [KVA]}} = \cos \phi$$

### Power Triangle

The power triangle shown in figure (5) indicates that the power factor is the cosine value of the angular displacement between the KW vector & the KVA vector (the angle  $\phi$ ). The power factor ranges from zero to one.

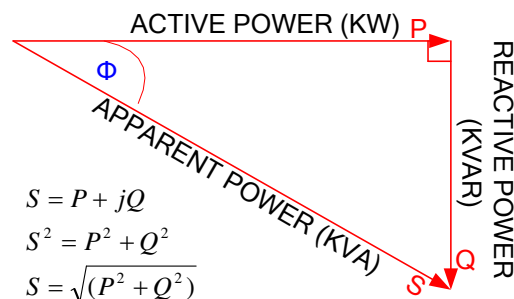


Figure 5:Power Triangle

**What we will learn:**

- Most industrial loads require both real power and reactive power to produce useful work.
- You pay for BOTH types of power (active power as power consumption & apparent power as low power factor penalty). See examples 1 & 2.
- Capacitors can supply the REACTIVE power thus the utility does not need to supply it.
- Capacitors save your money!

**Example 1:**

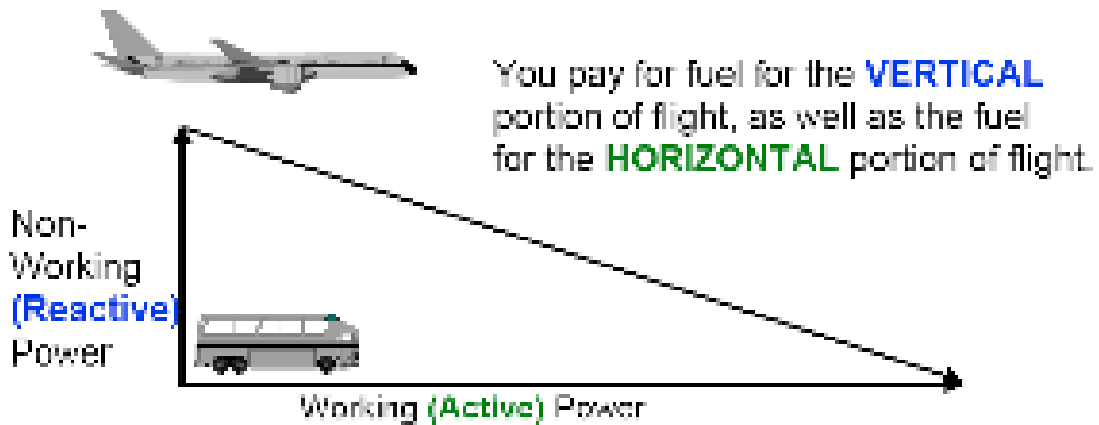


Figure 6: Example 1 for the reactive power role & meaning

Similarly, motors require REACTIVE power to set up the magnetic field while the ACTIVE power produces the useful work (shaft horsepower). Total power is the vector sum of the two & represents what you pay for. See figure (7).

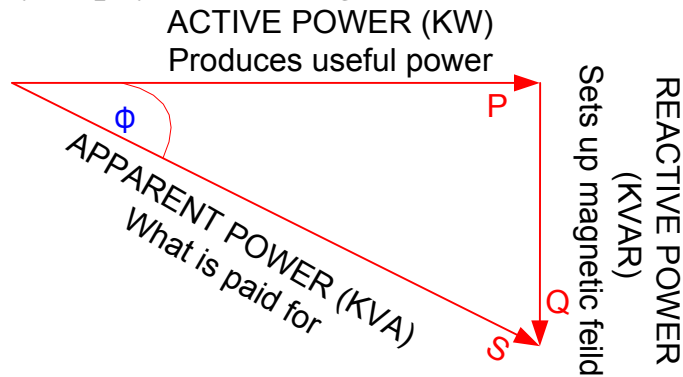


Figure 7: Example 1 power triangle

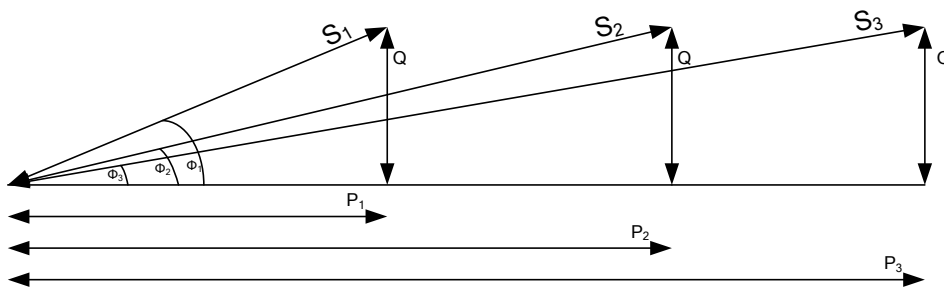
**Example 2:**



**Figure 8: Example 2 for the reactive power role & meaning**

Consider a canal boat being pulled by a horse as shown in fig.(8). If the horse could walk on water then the angle (Phi)  $\emptyset$  would be zero and  $\text{Cosine } \emptyset = \text{one}$ . This Means that all the horsepower is being used to pull the load.

However, the relative position of the horse influences the power. As the horse gets closer to the barge, angle  $\emptyset_1$  increases and power is wasted, but as the horse is positioned further away, then angle  $\emptyset_2$  gets closer to zero and less power is wasted as shown in fig.(9).



$$PF_1 = \text{COS } \Phi_1 = P_1 / S_1$$

$$PF_2 = \text{COS } \Phi_2 = P_2 / S_2$$

$$PF_3 = \text{COS } \Phi_3 = P_3 / S_3$$

$$\left. \begin{array}{l} PF_1 = \text{COS } \Phi_1 = P_1 / S_1 \\ PF_2 = \text{COS } \Phi_2 = P_2 / S_2 \\ PF_3 = \text{COS } \Phi_3 = P_3 / S_3 \end{array} \right\} \longrightarrow PF_1 < PF_2 < PF_3$$

**Figure 9: Equations for the power factors in example 2**

**Typical un-improved Power Factor by Industry**

<b><i>Industry</i></b>	<b><i>Power Factor</i></b>
Auto Parts	75-80
Brewery	75-80
Cement	80-85
Chemical	65-75
Coal Mine	65-80
Clothing	35-60
Electroplating	65-70
Foundry	75-80
Forging	70-80
Hospital	75-80
Machine Manufacturing	60-65
Metalworking	65-70
Office Building	80-90
Oil Filled Pumping	40-60
Paint Manufacturing	65-70
Plastic	75-80
Stamping	60-70
Steel Works	65-80
Tool, Dies, Jigs Industry	65-75

**Typical un-improved Power Factor by Equipment**

<b><i>Equipment</i></b>	<b><i>Power Factor</i></b>
Air Compressors & Pumps (External Motors)	75-80
Hermetic Motors	50-80
Arc Welding	35-60
Resistance Welding	40-60
Machining	40-65
Arc Furnaces	75-90
Induction Furnaces (60HZ)	100
Standard Stamping	60-70
High Speed Stamping	45-60
Spraying	60-65

	<b>Equipment</b>	<b>Billing for</b>	<b>P.F.</b>	<b>Generation needed</b>
1	60 Watts incandescent lamp	60W	1.0	60VA
2	15 Watts fluorescent lamp electronic ballast normal power factor	15W	0.6	25VA
3	15 Watts fluorescent lamp electronic ballast high power factor	15W	0.95	15.8VA
4	16 Watts magnetic adaptor unit	16W	0.25	64VA

From the above table, the utility generates certain amount of power and can refund easily the costs if the load power factor is high (as near as to the unity (1.0)). For the low power factor loads, the utility has to introduce certain rules to increase the energy unit price as a function of power factor.

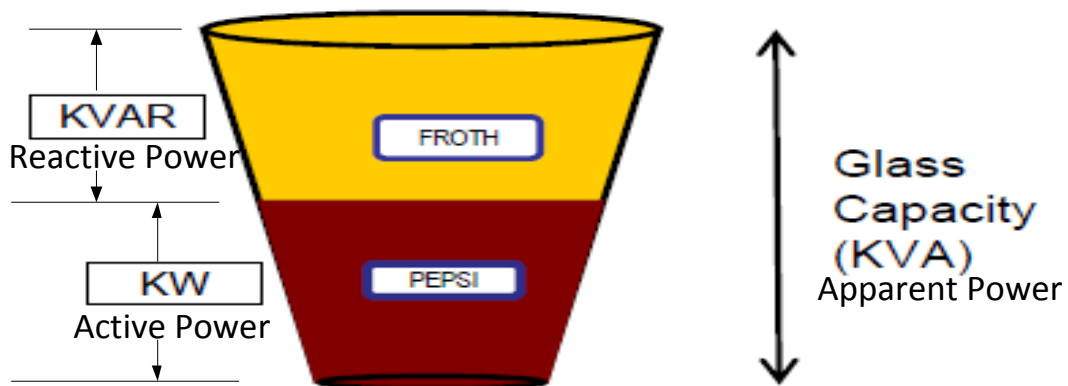


Figure 10: Active , Reactive & Apparent powers Example

It is clear that, the amount of the froth is blocking the usage of the whole available space for Pepsi.

## Why apply Power Factor Correction?

- ✓ Saves money  
(Line Current Reduction=Conductors Cross Section Reduction)
- ✓ Reduces power bills  
(Improving Power Factor= Avoid Low Power Factor Penalty)
- ✓ Reduces  $I^2R$  losses  
(Line Current Reduction= Power Losses Reduction)
- ✓ Improves voltage drop  
(Line Current Reduction= Voltage Drop Reduction)

### Example

Since  $P = S \times \cos \phi$

Then, for an installation (Load) which requires 800KW (P), the transformer apparent Power (S) should be:

- 800KVA for power factor = 100%
- 1000 KVA for power factor = 80%
- 1600 KVA for power factor = 50%

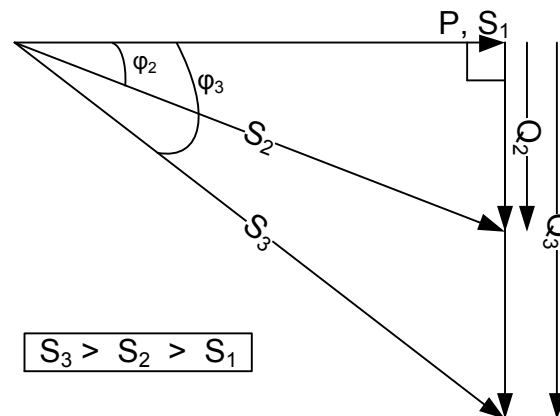


Figure 11: Apparent power increases as the power factor decreases for constant active power

## Benefits of power factor correction capacitors

### 1. Reduction of apparent power demand

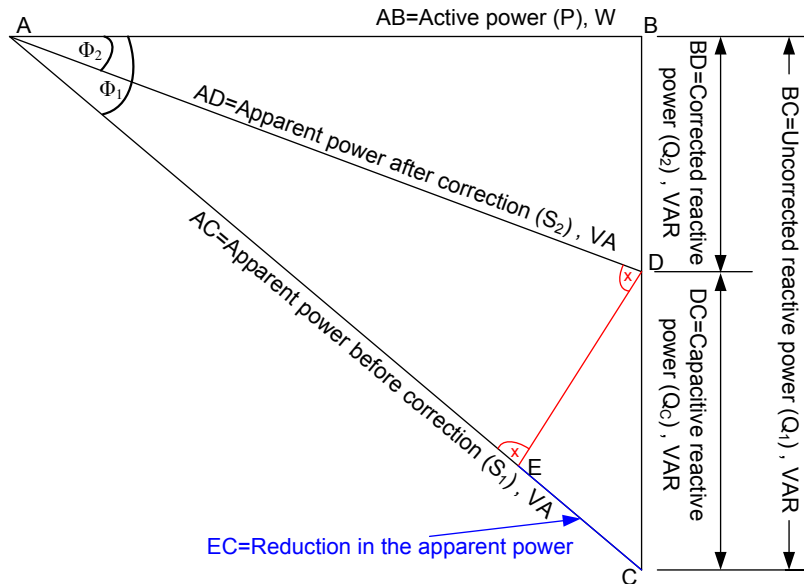


Figure 12: Reactive power compensation triangles

The new KVA demand from the utility side can be calculated from the following equation:

$$KVA = \sqrt{(KW)^2 + (KVAR \text{ inductive} - KVAR \text{ capacitive})^2}$$

Where

- KW : is the load active power,
- KVAR inductive : is the load reactive power,
- KVAR capacitive : is the added capacitor reactive power.

The reduction in the apparent power can be calculated from the following equations:

$$\Delta S = S1 - S2 = \frac{P}{\cos \phi1} - \frac{P}{\cos \phi2} = \frac{P(\cos \phi2 - \cos \phi1)}{\cos \phi1 \times \cos \phi2}$$

$$\% \Delta S = \frac{S1 - S2}{S1} \times 100 = \frac{P(\cos \phi2 - \cos \phi1)}{\cos \phi1 \times \cos \phi2} \times \frac{\cos \phi1}{P} \times 100 = \frac{\cos \phi2 - \cos \phi1}{\cos \phi2} \times 100$$

## 2. Line current reduction

The percentage line current reduction can be approximated from the following equation:

$$\Delta I\% = \left[ 1 - \frac{PF \text{ original}}{PF \text{ corrected}} \right] \times 100$$

As the current reduces by installing capacitors, the drawn current is reduced. Thus the existing conductor cross section can be reduced or the same conductor can be used to handle more power. The following diagram shows the decreasing size of the conductor required to carry the same 100MW at power factors from 70% to 100%.

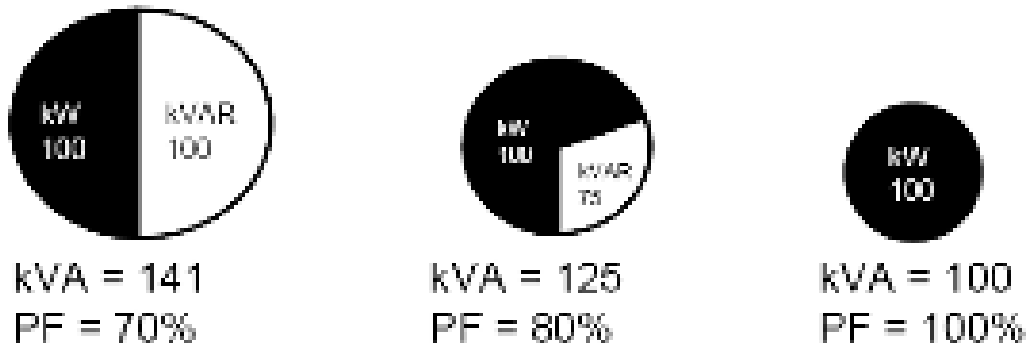


Figure 13: Line current reduction due to power factor correction

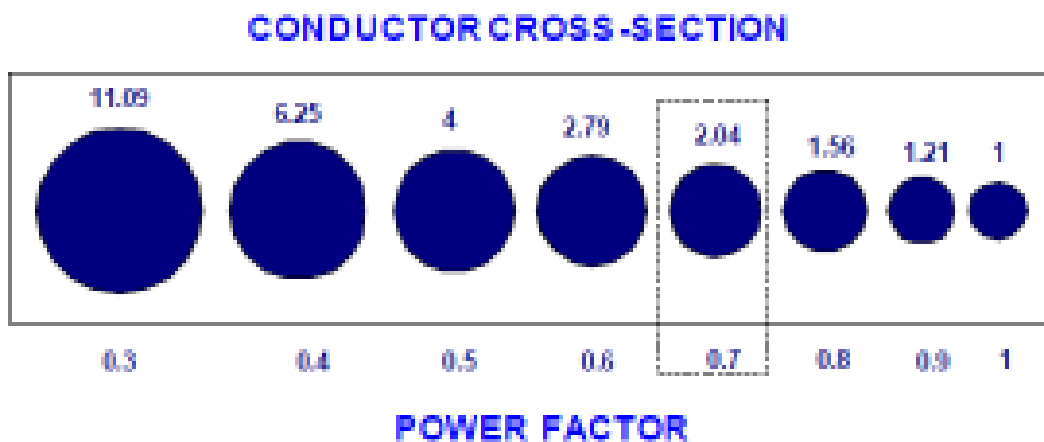


Figure 14: Conductor cross section decreases as the power factor increases

**Note:**

$$PF_1 = \cos \phi_1 = \frac{P_1}{S_1} \quad , \quad PF_2 = \cos \phi_2 = \frac{P_1}{S_2}$$

$$I_1 = \frac{S_1}{V_1} = \frac{P_1}{V_1 \times PF_1} \quad , \quad I_2 = \frac{S_2}{V_2} = \frac{P_1}{V_1 \times PF_2}$$

$$I_1 - I_2 = \frac{P_1}{V_1 \times PF_1} - \frac{P_1}{V_1 \times PF_2} = \frac{P_1}{V_1} \left[ \frac{1}{PF_1} - \frac{1}{PF_2} \right] = \frac{P_1}{V_1} \left[ \frac{PF_2 - PF_1}{PF_1 \times PF_2} \right]$$

$$\Delta I \% = \frac{I_1 - I_2}{I_1} \times 100 = \frac{\frac{P_1}{V_1} \left[ \frac{PF_2 - PF_1}{PF_1 \times PF_2} \right]}{\frac{P_1}{V_1} \times \frac{1}{PF_1}} \times 100 = \frac{PF_2 - PF_1}{PF_2} \times 100 = \left[ 1 - \frac{PF_1}{PF_2} \right] \times 100$$

**3. Voltage rise**

The voltage rise realized with the installation of capacitors can be approximated from the following equation:

$$\Delta V \% = \frac{\text{KVAR capacitor} \times \%Z \text{ transformer}}{\text{KVA transformer}}$$

Where

% Z transformer : is the percentage impedance of the transformer,

KVA transformer: is the nominal rating of the transformer.

### 4. Gaining active power

Assuming keeping the apparent power (S) constant (capacity of the feeding cables/overhead lines and transformers), an additional active power can be fed by the system in place of the compensated reactive power according to the following equation:

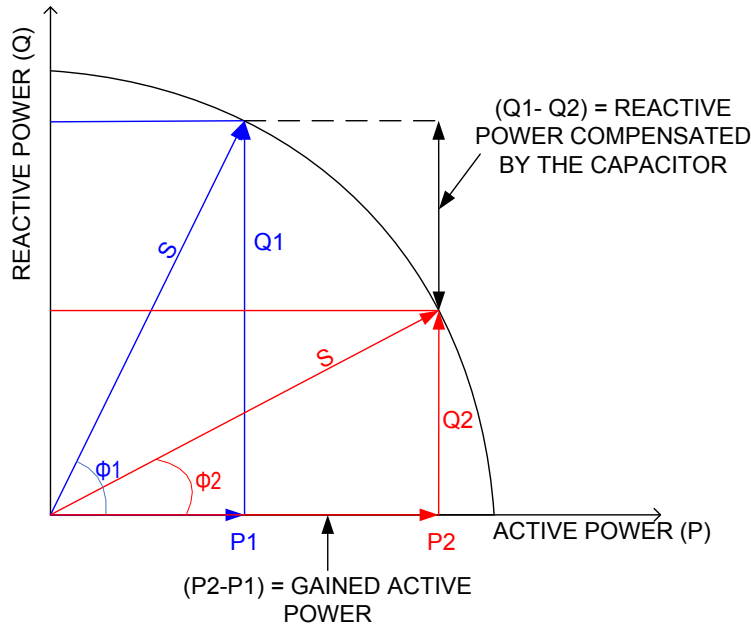


Figure 15: Gained active power due to power factor correction

**Note:**

$$\Delta P = P2 - P1 = S \times (\cos \phi2 - \cos \phi1)$$

$$\% \Delta P = \frac{P2 - P1}{P1} \times 100 = \frac{S \times (\cos \phi2 - \cos \phi1)}{S \times \cos \phi1} \times 100 = \frac{(\cos \phi2 - \cos \phi1)}{\cos \phi1} \times 100$$

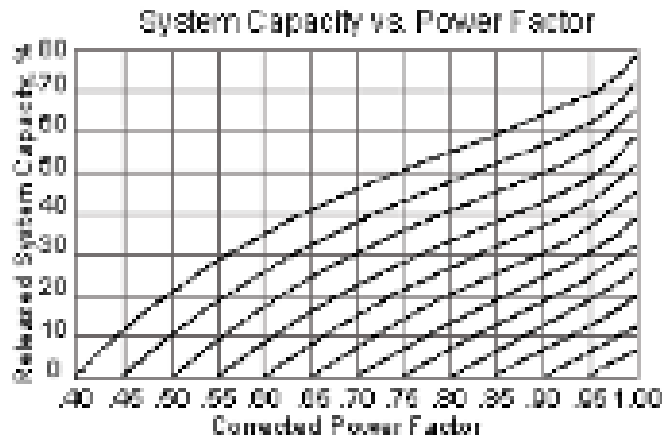


Figure 16: Released system capacity increases as power factor increases

## 5. Power losses reduction

The losses  $I^2R$  decrease since capacitor applications reduce the line current. The reduction in the power losses can be estimated from the following equation:

$$\Delta P_{\text{losses}} = \left[ 1 - \left( \frac{PF_{\text{original}}}{PF_{\text{corrected}}} \right)^2 \right] \times 100$$

### Note:

Reduction in current magnitude and losses is realized only upstream from the capacitor connection point up to the utility side. While, Current magnitude & losses remain unchanged between capacitor connection point & the load.

### Note:

$$P_{\text{losses } 1} = I_1^2 \times R, \quad P_{\text{losses } 2} = I_2^2 \times R$$

$$\Delta P_{\text{losses}} \% = \frac{P_{\text{losses } 1} - P_{\text{losses } 2}}{P_{\text{losses } 1}} \times 100 = \frac{I_1^2 \times R - I_2^2 \times R}{I_1^2 \times R} \times 100 = \frac{I_1^2 - I_2^2}{I_1^2} \times 100 = \left[ 1 - \frac{I_2^2}{I_1^2} \right] \times 100$$

$$\Delta P_{\text{losses}} \% = \left[ 1 - \left( \frac{PF_1^2}{PF_2^2} \right) \right] \times 100 = \left[ 1 - \left( \frac{PF_1}{PF_2} \right)^2 \right] \times 100$$

## Practical effect of power factor correction capacitors

<b>S/S 8119 GT1</b>	Before energizing the capacitor	After energizing the capacitor
<b>132 KV current</b>	185 A	170 A
<b>13.8 KV current</b>	1640 A	1580 A
<b>MW reading</b>	38 MW	38 MW
<b>MVAR reading</b>	14.1 MVAR	8.4 MVAR
<b>13.8 KV reading</b>	13.39 KV	13.77 KV
<b>Tap #</b>	11	11

Table 1: different values measured before and after energizing the capacitor for GT1

<b>S/S 8119 GT2</b>	Before energizing the capacitor	After energizing the capacitor
<b>132 KV current</b>	165 A	155 A
<b>13.8 KV current</b>	1550 A	1470 A
<b>MW reading</b>	38 MW	38 MW
<b>MVAR reading</b>	18.0 MVAR	11.0 MVAR
<b>13.8 KV reading</b>	13.42 KV	13.91 KV
<b>Tap #</b>	10	10

Table 2: different values measured before and after energizing the capacitor for GT2

<b>S/S 8119 GT3</b>	Before energizing the capacitor	After energizing the capacitor
<b>132 KV current</b>	190 A	180 A
<b>13.8 KV current</b>	1820 A	1720 A
<b>MW reading</b>	41 MW	41 MW
<b>MVAR reading</b>	22.5 MVAR	16.0 MVAR
<b>13.8 KV reading</b>	13.25 KV	13.62 KV
<b>Tap #</b>	10	10

Table 3: different values measured before and after energizing the capacitor for GT3



## Capacitors in the electric circuits

### 1. Normal circuit (not compensated)

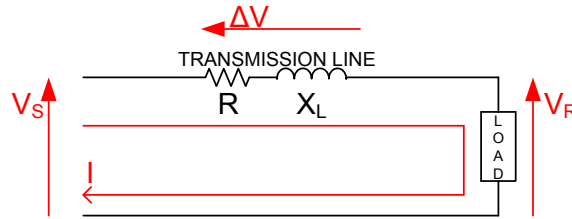


Figure 18: Circuit diagram before improving the power factor

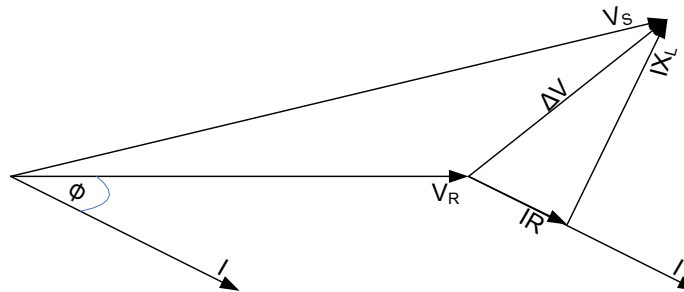


Figure 19: Phasor diagram before improving the power factor

### 2. Parallel capacitor compensated circuit

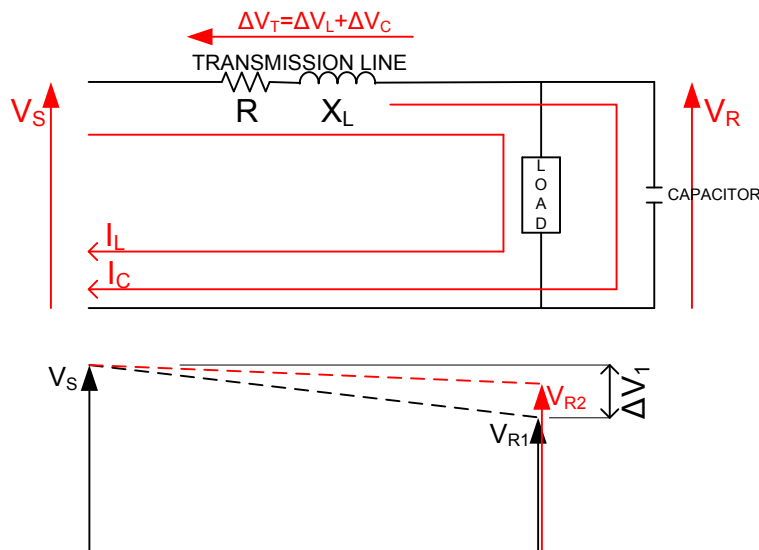


Figure 20: Circuit diagram after improving the power factor with a parallel capacitor

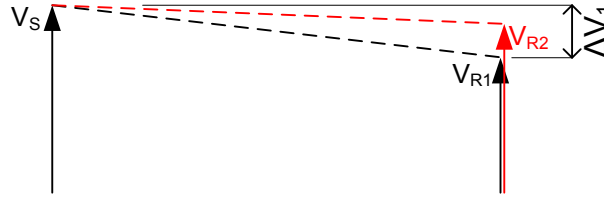


Figure 21: Voltage drop across the transmission line decreases as the load power factor increases

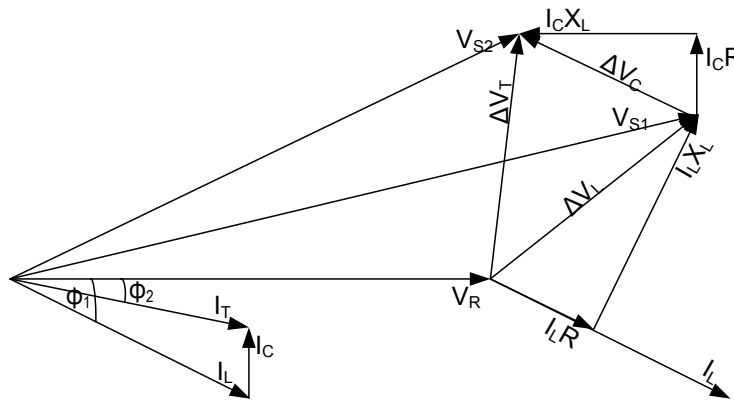


Figure 22: Phasor diagram after improving the power factor with a parallel capacitor  
 It can be noticed from figure (22) that  $|V_{S1}| > |V_{S2}|$   
 Then, for the same  $|V_{S1}|$ , receiving voltage can be higher.  
 Or For the same  $|V_R|$ , Sending voltage can be lower.

### 3. Series capacitor compensated circuit

The power transfer through a transmission line is given by the following equation:

$$P = \frac{V_S \times V_R \times \sin \delta}{X_L}$$

Where  $\delta$  is the angle between the sending end voltage  $V_S$  and the receiving end voltage  $V_R$ . While  $X_L$  is the transmission line series reactance.

If the transmission line is series compensated by a capacitor, the power transfer equation will be as follows:

$$P = \frac{V_S \times V_R \times \sin \delta}{X_L - X_C}$$

Therefore, for a given phase angle difference between the voltages, the power transfer is greater with a series capacitor.

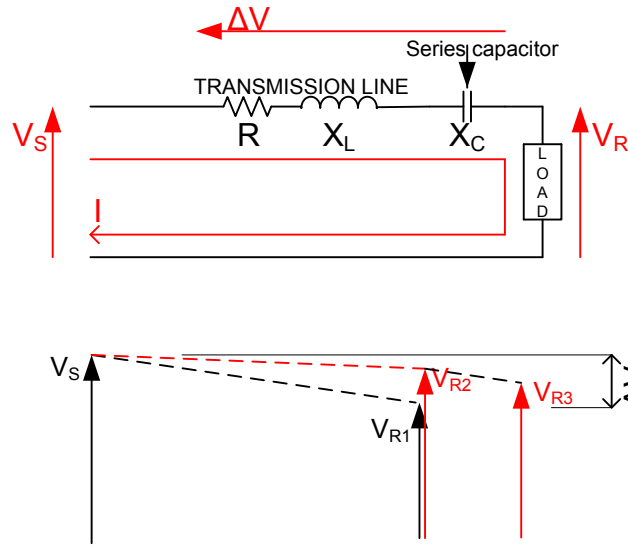


Figure 23: Circuit diagram after adding a series capacitor

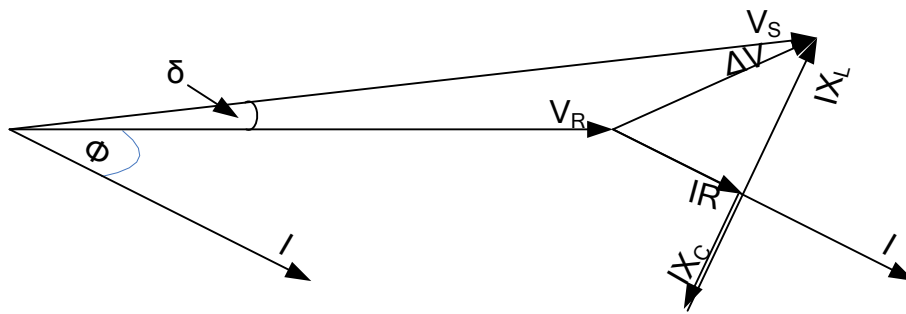


Figure 24: Phasor diagram after adding a series capacitor

#### 4. Effect of Parallel capacitor modified circuit

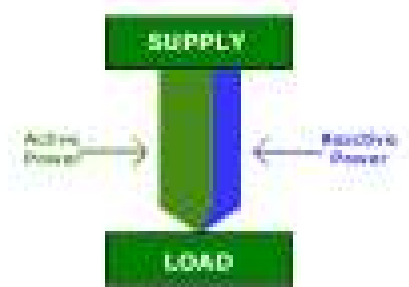


Figure 25: Active & Reactive power flow without capacitor

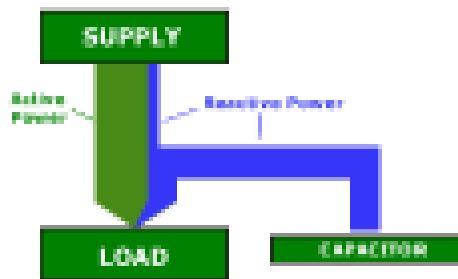


Figure 26: Active & Reactive power flow with a capacitor added

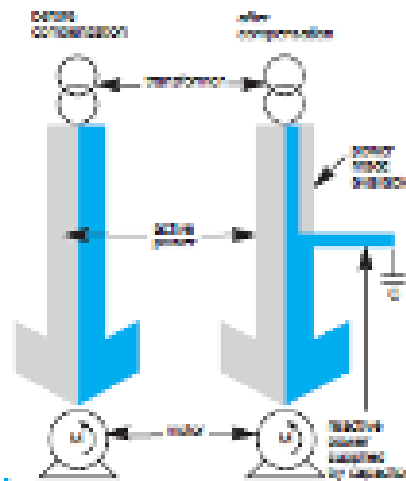


Figure 27: Another presentation for the active and reactive power flow before and after adding a power factor correction capacitor

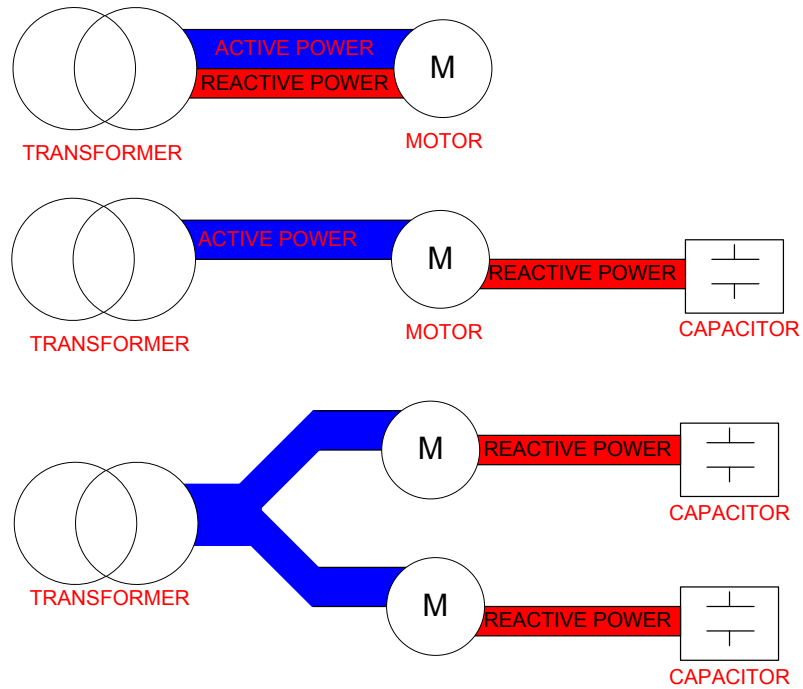


Figure 28: Another motor can be added to the same transformer without overloading it , if the reactive power is compensated locally

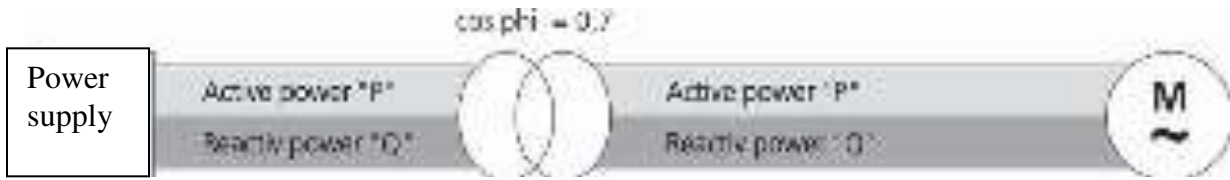


Figure 29: Practical example for power factor correction

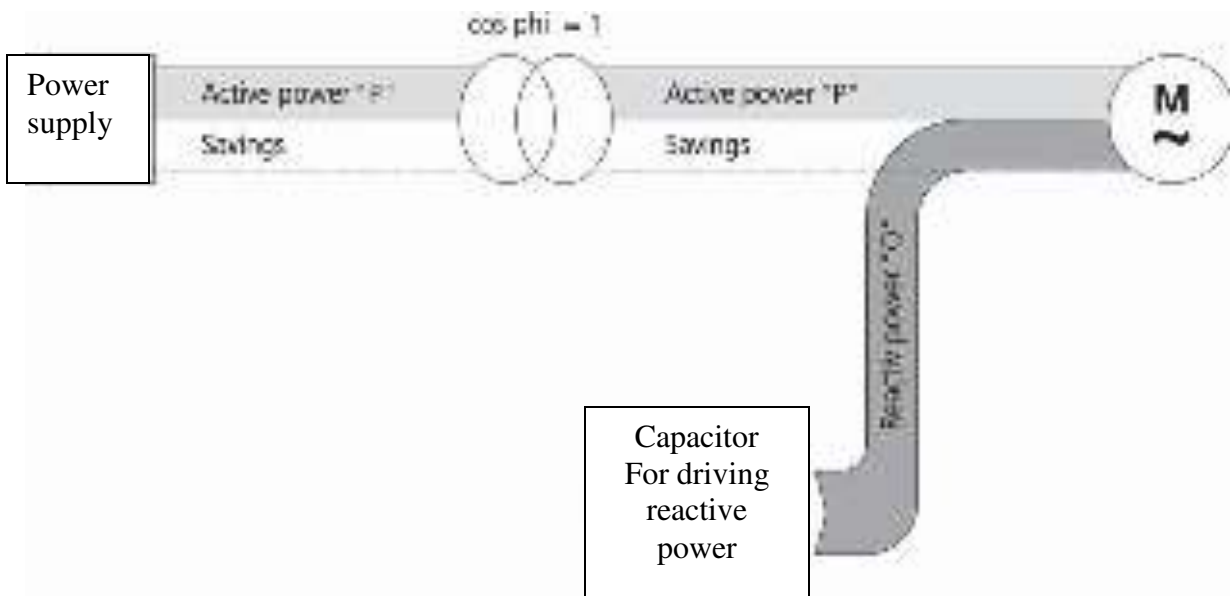


Figure 30: Saving in the supply and transformer in case of reactive power compensation locally

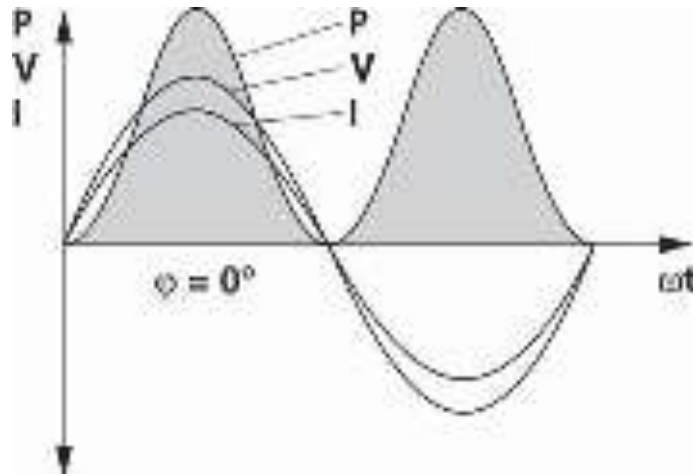


Figure 31: Voltage, Current & Power in case of unity power factor load

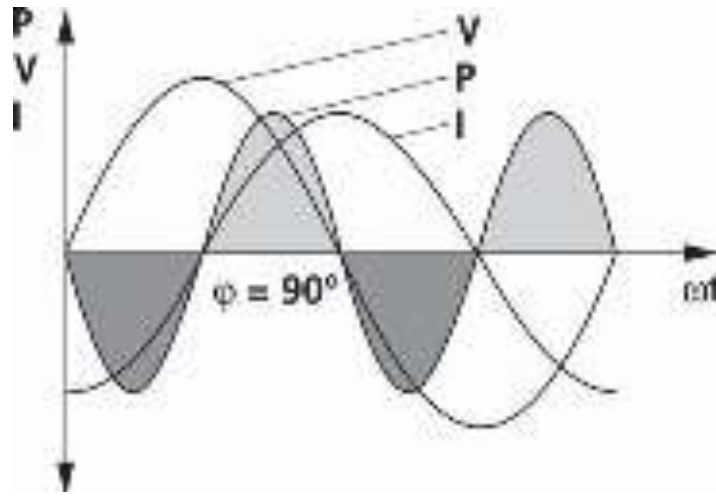


Figure 32: Voltage, Current & Power for pure inductive load

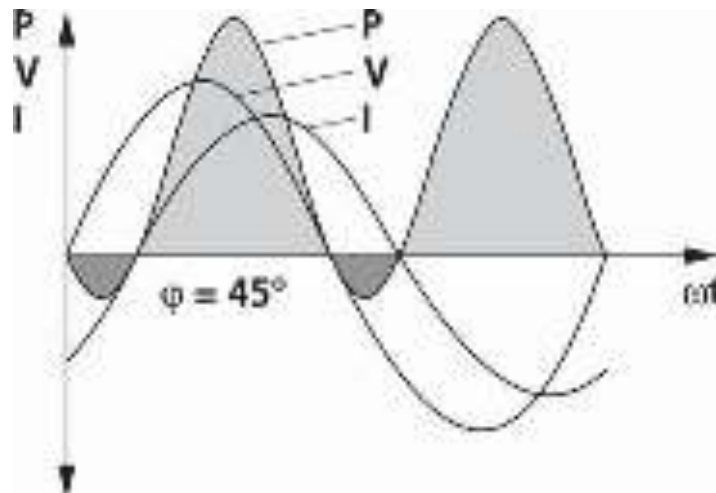
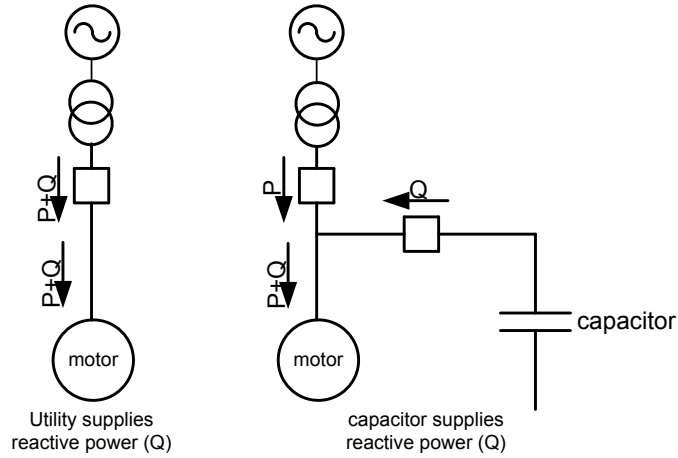
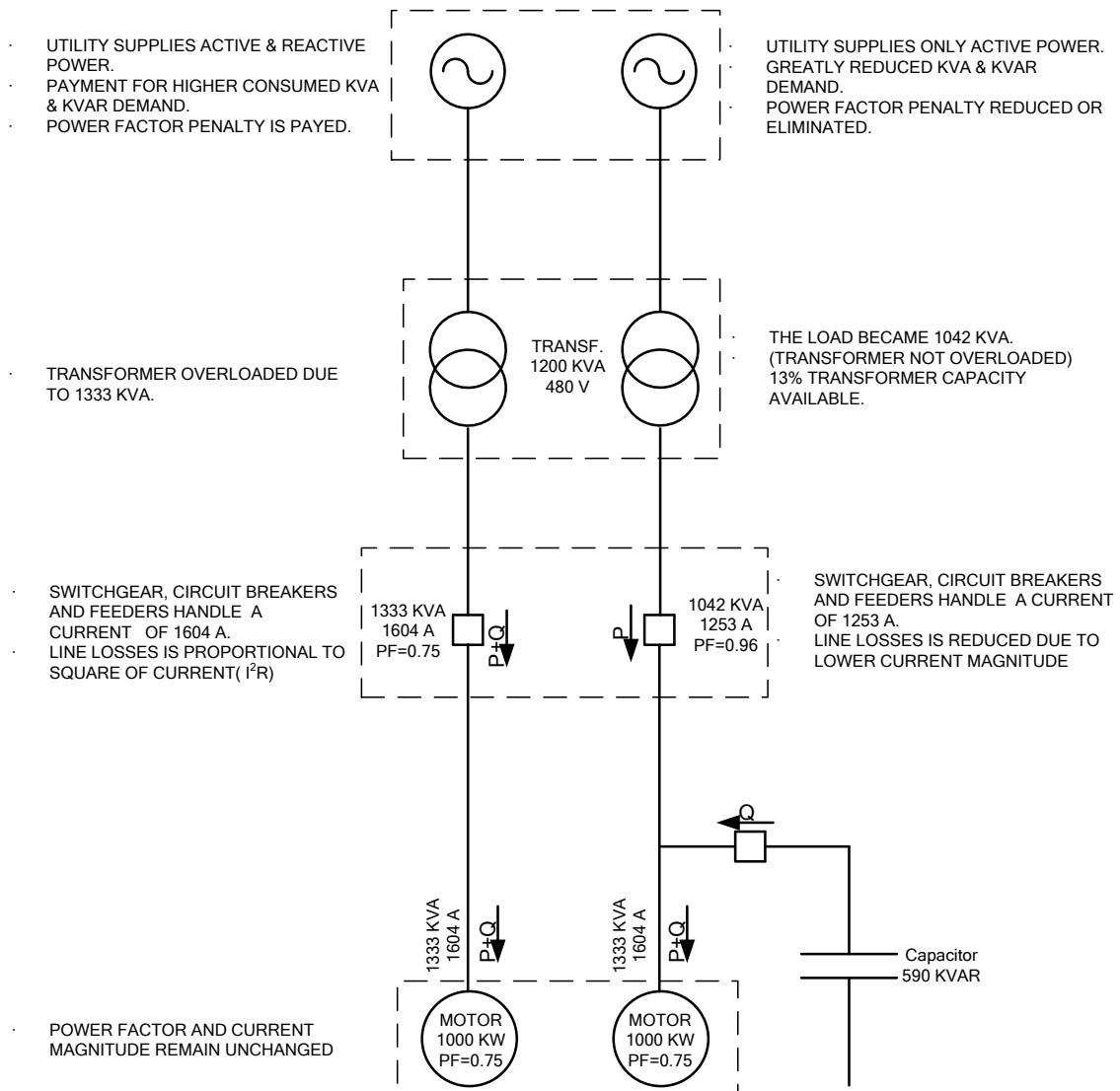


Figure 33: Voltage, Current & Power for load of 0.707 power factor (load angle  $45^\circ$ )

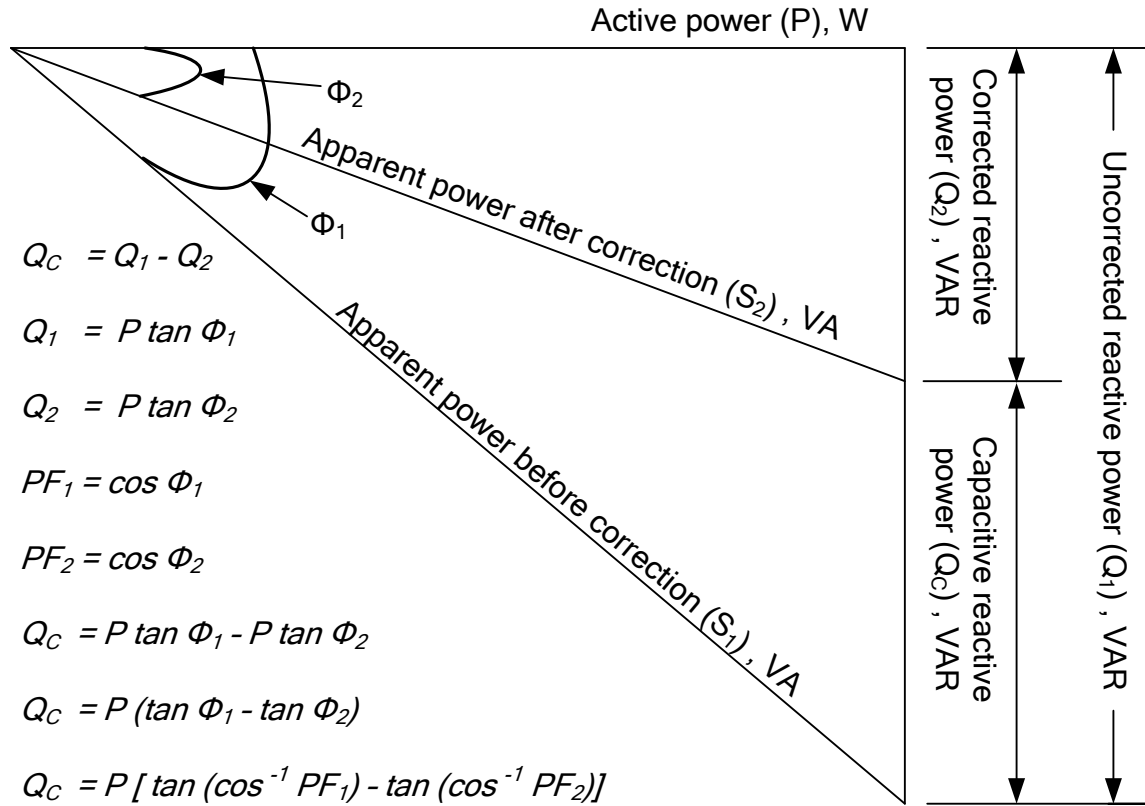


**Figure 34: Active and Reactive power flow before and after capacitor adding**



**Figure 35: Numerical example for the capacitor adding effect on the network**

## Calculation of the Required Reactive Power Compensation



**Figure 36: Calculation principle of the reactive power compensation**

Thus, for a certain load ( $P$  &  $Q_1$ ), if it is required to improve the power factor from the original uncorrected  $PF_1$  to the desired  $PF_2$ , a reactive power  $Q_C$  should be installed according to the equation:

$$Q_C = P [\tan (\cos^{-1} PF_1) - \tan (\cos^{-1} PF_2)] = K \times P$$

Where  $K$  is a constant =  $\tan (\cos^{-1} PF_1) - \tan (\cos^{-1} PF_2)$

The next table is filled up from this equation and it is used always in the reactive power compensation calculations everywhere.

For example:

1. For a load of 0.65 power factor, a reactive power of 0.685 of its active power is required to improve the power factor to be 0.90 as it is indicated on the table below.
2. For a 100 MW load and power factor 0.77, 0.5 of the 100 MW (50 MVAR) is required to improve the power factor to 0.95 as given by the tables below.

**Desired PF in Percent**

	00	01	02	03	04	05	06	07	08	09	90	91	92	93	94	95	96	97	98	99	100
50	0.902	1.000	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.305	1.337	1.369	1.403	1.440	1.481	1.529	1.580	1.733
51	0.927	0.963	0.989	1.015	1.041	1.067	1.093	1.120	1.147	1.174	1.202	1.231	1.261	1.291	1.324	1.358	1.395	1.436	1.484	1.544	1.607
52	0.950	0.979	0.995	0.971	0.997	1.023	1.049	1.076	1.103	1.130	1.158	1.187	1.217	1.247	1.280	1.314	1.351	1.392	1.440	1.500	1.643
53	0.950	0.978	0.992	0.970	0.994	0.990	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271	1.308	1.349	1.397	1.458	1.600
54	0.969	0.935	0.951	0.977	0.913	0.939	0.965	0.992	1.019	1.048	1.074	1.103	1.133	1.163	1.194	1.230	1.267	1.308	1.356	1.416	1.559
55	0.780	0.794	0.820	0.848	0.873	0.899	0.925	0.952	0.979	1.008	1.034	1.063	1.092	1.123	1.154	1.190	1.227	1.268	1.315	1.376	1.518
56	0.729	0.755	0.781	0.807	0.834	0.860	0.888	0.913	0.940	0.967	0.995	1.024	1.053	1.084	1.116	1.151	1.188	1.229	1.276	1.337	1.479
57	0.691	0.717	0.743	0.769	0.796	0.822	0.848	0.875	0.902	0.929	0.957	0.986	1.015	1.046	1.079	1.113	1.150	1.191	1.238	1.299	1.441
58	0.655	0.681	0.707	0.733	0.759	0.785	0.811	0.838	0.865	0.892	0.920	0.949	0.979	1.009	1.042	1.076	1.113	1.154	1.201	1.262	1.405
59	0.618	0.644	0.670	0.696	0.723	0.749	0.775	0.802	0.829	0.856	0.884	0.913	0.942	0.973	1.006	1.040	1.077	1.118	1.165	1.226	1.368
60	0.583	0.609	0.635	0.661	0.687	0.714	0.740	0.767	0.794	0.821	0.849	0.878	0.907	0.938	0.970	1.005	1.042	1.083	1.130	1.191	1.333
61	0.549	0.575	0.601	0.627	0.653	0.679	0.706	0.732	0.759	0.787	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.157	1.299
62	0.515	0.541	0.567	0.593	0.620	0.646	0.672	0.699	0.726	0.753	0.781	0.810	0.839	0.870	0.903	0.937	0.974	1.015	1.062	1.123	1.265
63	0.483	0.509	0.535	0.561	0.587	0.613	0.639	0.666	0.693	0.720	0.748	0.777	0.807	0.837	0.870	0.904	0.941	0.982	1.030	1.090	1.233
64	0.451	0.477	0.503	0.529	0.555	0.581	0.607	0.634	0.661	0.688	0.716	0.745	0.775	0.805	0.838	0.873	0.909	0.950	0.998	1.058	1.201
65	0.419	0.445	0.471	0.497	0.523	0.549	0.576	0.602	0.629	0.657	0.685	0.714	0.743	0.774	0.808	0.844	0.877	0.919	0.968	1.027	1.169
66	0.388	0.414	0.440	0.466	0.492	0.519	0.545	0.572	0.599	0.626	0.654	0.683	0.712	0.743	0.775	0.810	0.847	0.888	0.935	0.994	1.136
67	0.358	0.384	0.410	0.436	0.462	0.488	0.515	0.541	0.568	0.596	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.964	1.106
68	0.328	0.354	0.380	0.406	0.432	0.459	0.485	0.512	0.539	0.566	0.594	0.623	0.652	0.683	0.715	0.750	0.787	0.828	0.875	0.934	1.076
69	0.299	0.325	0.351	0.377	0.403	0.429	0.456	0.482	0.509	0.537	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.907	1.049
70	0.270	0.296	0.322	0.348	0.374	0.400	0.427	0.453	0.480	0.508	0.536	0.565	0.594	0.625	0.657	0.692	0.729	0.770	0.817	0.878	1.020
71	0.242	0.268	0.294	0.320	0.346	0.372	0.398	0.425	0.452	0.480	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
72	0.214	0.240	0.266	0.292	0.318	0.344	0.370	0.397	0.424	0.452	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
73	0.188	0.212	0.238	0.264	0.290	0.316	0.343	0.370	0.398	0.424	0.452	0.481	0.510	0.541	0.573	0.608	0.645	0.686	0.733	0.794	0.936
74	0.169	0.195	0.211	0.237	0.263	0.289	0.316	0.342	0.369	0.397	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
75	0.152	0.158	0.184	0.210	0.236	0.262	0.289	0.315	0.342	0.370	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
76	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.288	0.315	0.343	0.371	0.400	0.429	0.460	0.492	0.526	0.563	0.605	0.652	0.713	0.855
77	0.079	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.289	0.316	0.344	0.373	0.403	0.433	0.466	0.500	0.537	0.579	0.626	0.686	0.829
78	0.052	0.078	0.104	0.130	0.156	0.183	0.209	0.236	0.263	0.290	0.318	0.347	0.376	0.407	0.439	0.474	0.511	0.552	0.599	0.660	0.802
79	0.026	0.052	0.078	0.104	0.130	0.156	0.183	0.209	0.236	0.264	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.634	0.776
80	0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.238	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.608	0.750
81		0.000	0.026	0.052	0.078	0.104	0.131	0.157	0.184	0.212	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
82			0.000	0.026	0.052	0.078	0.105	0.131	0.158	0.186	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.556	0.698
83				0.000	0.026	0.052	0.079	0.105	0.132	0.160	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.530	0.672
84					0.000	0.026	0.053	0.079	0.106	0.134	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.645
85						0.000	0.026	0.053	0.080	0.107	0.135	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
86							0.000	0.027	0.054	0.081	0.109	0.138	0.167	0.198	0.230	0.265	0.302	0.343	0.390	0.451	0.593
87								0.000	0.027	0.054	0.082	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
88									0.000	0.027	0.055	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
89										0.000	0.028	0.057	0.086	0.117	0.149	0.184	0.221	0.262	0.309	0.370	0.512
90											0.000	0.029	0.058	0.089	0.121	0.156	0.193	0.234	0.281	0.342	0.484
91												0.000	0.030	0.060	0.093	0.127	0.164	0.205	0.253	0.313	0.455
92													0.000	0.031	0.063	0.097	0.134	0.175	0.223	0.284	0.426
93														0.000	0.032	0.067	0.104	0.145	0.192	0.253	0.395
94															0.000	0.034	0.071	0.112	0.160	0.220	0.363
95																0.000	0.037	0.075	0.120	0.180	0.320
96																	0.000	0.041	0.080	0.140	0.202
97																		0.000	0.048	0.108	0.251
98																			0.000	0.051	0.203
99																				0.000	0.142
100																					0.000

Table 4: Power factor correction table usage

Power factor Cos $\phi_2$ after improvement													
	1.0	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90	0.85	0.80
0.9	1.73	1.59	1.53	1.48	1.44	1.40	1.37	1.34	1.30	1.28	1.25	1.11	0.98
0.92	1.64	1.50	1.44	1.39	1.35	1.32	1.28	1.25	1.22	1.19	1.16	1.02	0.89
0.95	1.52	1.38	1.32	1.27	1.23	1.19	1.16	1.12	1.09	1.06	1.04	0.90	0.77
0.97	1.44	1.30	1.24	1.19	1.15	1.11	1.08	1.05	1.01	0.99	0.96	0.82	0.69
0.98	1.33	1.19	1.13	1.08	1.04	1.01	0.97	0.94	0.91	0.88	0.85	0.71	0.58
0.99	1.027	1.23	1.06	1.01	0.97	0.94	0.90	0.87	0.84	0.81	0.78	0.65	0.52
0.95	1.77	1.63	1.57	1.52	1.48	1.44	1.41	1.37	1.34	1.31	1.28	1.14	1.01
0.97	1.11	0.97	0.91	0.86	0.82	0.79	0.75	0.71	0.68	0.65	0.62	0.49	0.36
0.7	1.02	0.88	0.81	0.77	0.73	0.69	0.66	0.62	0.59	0.56	0.54	0.40	0.27
0.72	0.96	0.82	0.75	0.71	0.67	0.63	0.60	0.57	0.53	0.51	0.48	0.34	0.21
0.75	0.88	0.74	0.67	0.63	0.59	0.55	0.52	0.49	0.45	0.43	0.40	0.26	0.13
0.77	0.83	0.69	0.62	0.58	0.54	0.50	0.47	0.43	0.40	0.37	0.35	0.21	0.08
0.8	0.75	0.61	0.54	0.50	0.46	0.42	0.39	0.35	0.32	0.29	0.27	0.13	
0.82	0.70	0.56	0.49	0.45	0.41	0.37	0.34	0.30	0.27	0.24	0.21	0.08	
0.85	0.62	0.48	0.42	0.37	0.33	0.29	0.26	0.22	0.19	0.16	0.14		
0.87	0.57	0.42	0.36	0.32	0.28	0.24	0.20	0.17	0.14	0.11	0.08		
0.90	0.48	0.34	0.28	0.23	0.19	0.16	0.12	0.09	0.06	0.02			
0.94	0.45	0.31	0.25	0.21	0.16	0.13	0.09	0.06	0.02				
0.92	0.43	0.29	0.22	0.18	0.13	0.10	0.06	0.03					
0.93	0.40	0.25	0.19	0.15	0.10	0.07	0.03						
0.94	0.36	0.22	0.16	0.11	0.07	0.04							
0.95	0.33	0.18	0.12	0.08	0.04								
0.96	0.29	0.15	0.09	0.04									
0.97	0.25	0.11	0.05										
0.98	0.20	0.06											
0.99	0.14												

Table 5 : Calculation of the reactive power required for improving the power factor.

To calculate the required capacitive MVAR for improving the power factor of certain load from old value Cos  $\phi_1$  to new value Cos  $\phi_2$ , follow the next steps:

1. Determine the existing active power P in KW or MW and the existing power factor.
2. On the above table start from the most left column with the existing power factor and move horizontally up to the column corresponding to the desired power factor.
3. The value picked from this location is the factor (multiplier) which should be multiplied into the existing active power to obtain the required reactive power Q in KVAR or MVAR.

The following graph can be used also to determine the factor (multiplier) which should be multiplied into the existing active power to obtain the required reactive power Q in KVAR or MVAR.

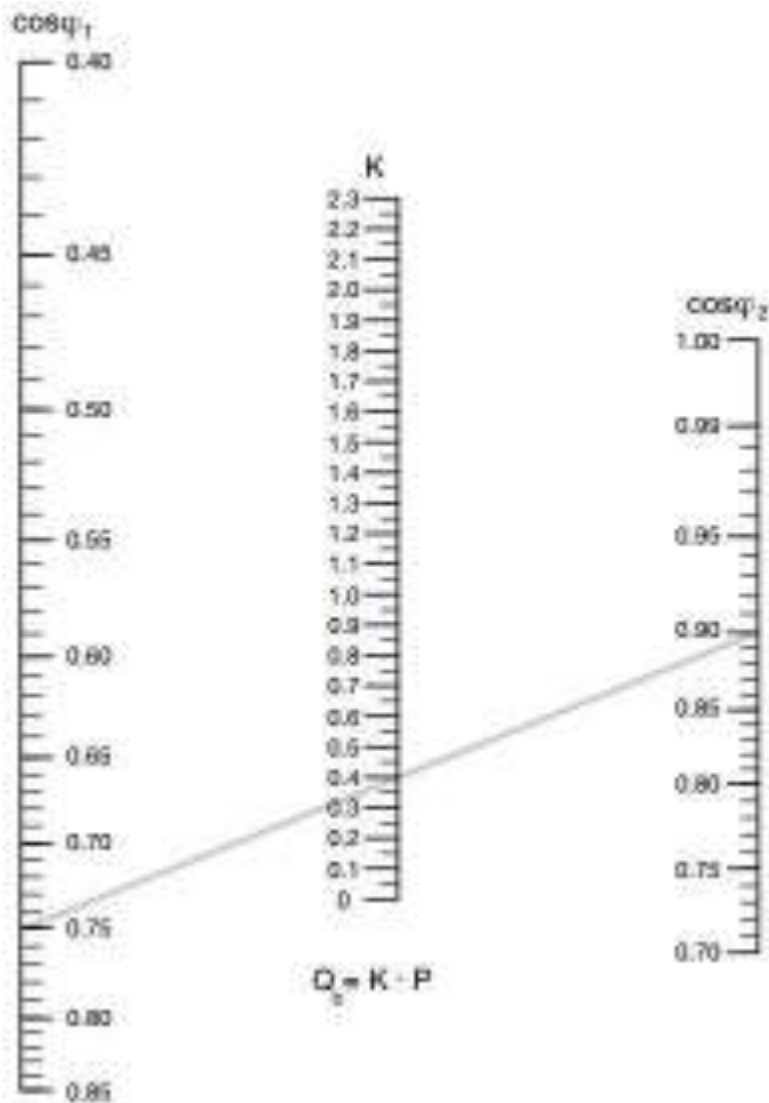


Figure 37: The capacitive power needed to improve the power factor from certain value  $\cos \phi_1$  to a better one  $\cos \phi_2$

## Optimal Capacitor bank location

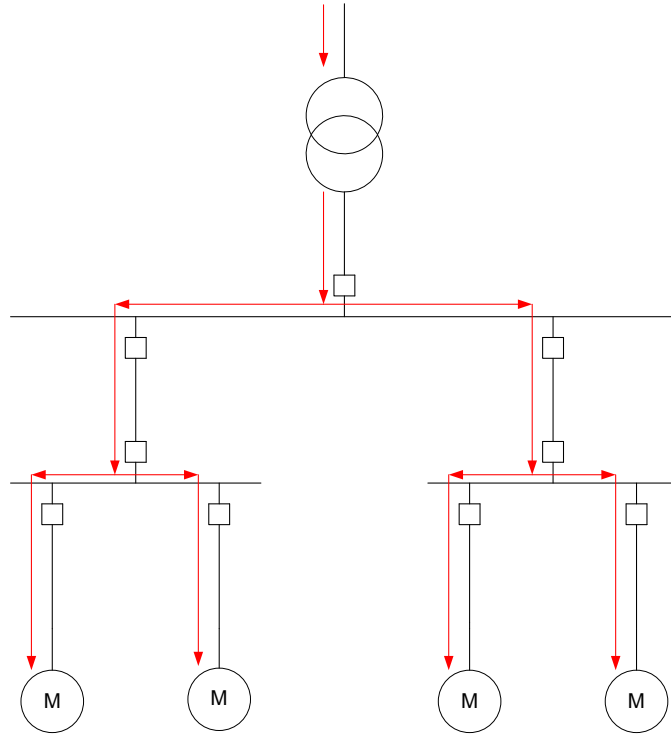


Figure 38: Reactive power flow without capacitors

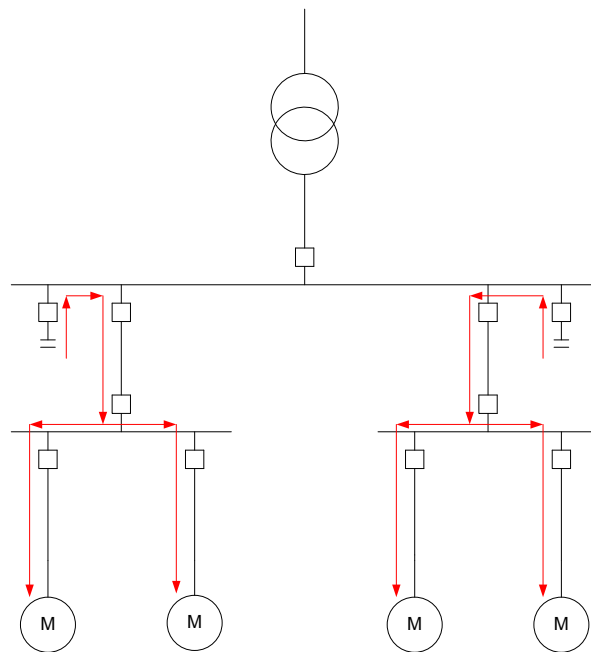
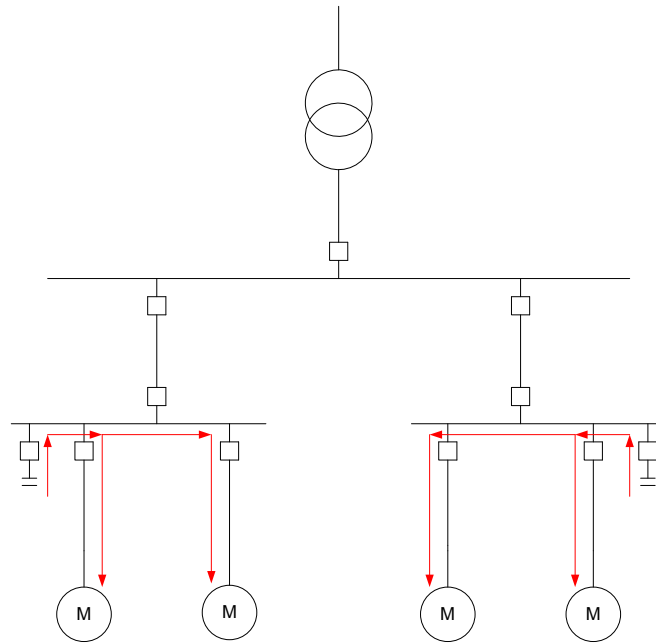


Figure 39: Reactive power flow with an upstream capacitor installed

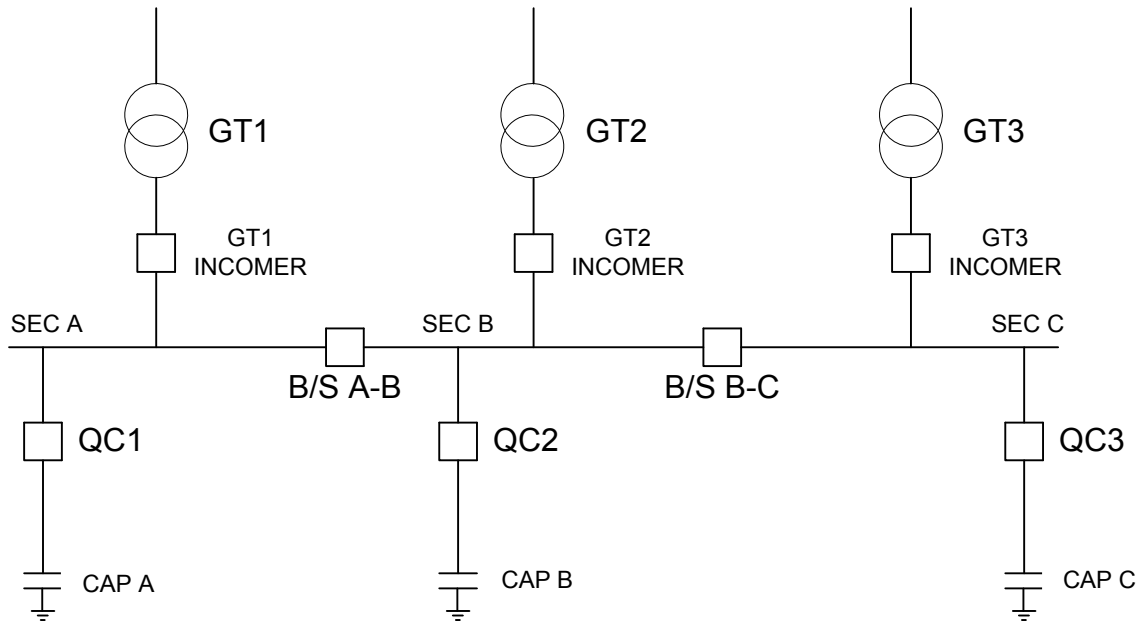


**Figure 40: Reactive power flow with a down stream capacitor installed**

Figure Number	Capacitor Location	Equipment that reactive power is passing through	Remarks
38	No Capacitor	All system equipment up to load	Not recommended
39	Upstream Bus Bar	From upstream bus bar up to load	Preferability 2
40	Downstream Bus Bar	From downstream bus bar up to load	Preferability 1

## Automatic capacitor control system (ACCS)

### Automatic capacitor control system (ACCS) operational logic



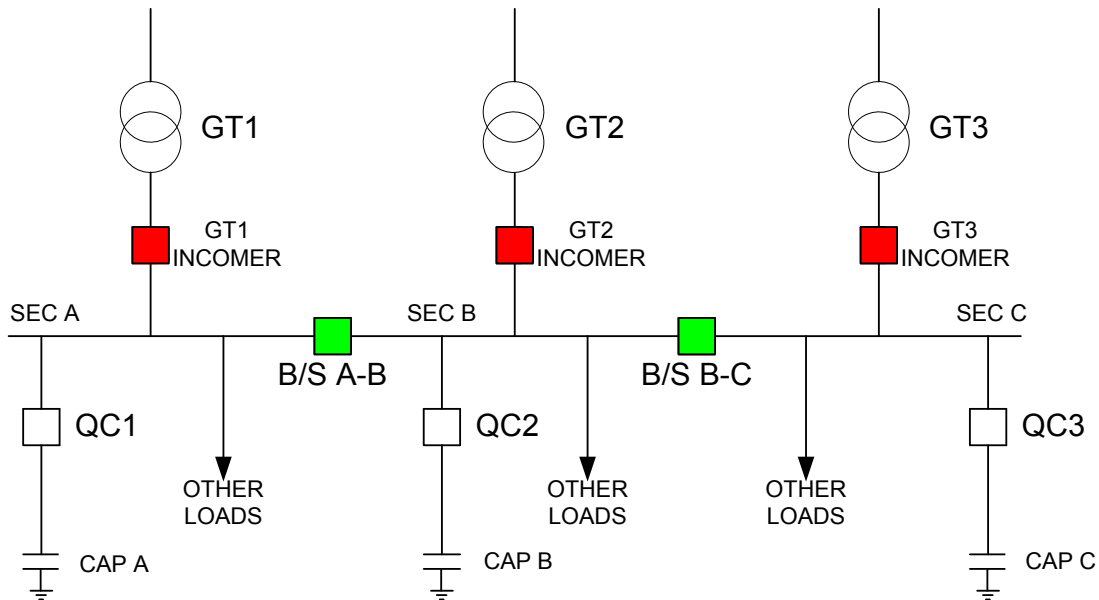
**Figure 41: 13.8 KV substation operational single line diagram**

**CASE 1: all three incomers are ON & both bus sectionalizers are OFF:**

Capacitor A circuit breaker shall be switched ON if the reactive power demand of GT1 exceeds 9 MVAR for a time more than 5 minutes.

Capacitor A circuit breaker shall be switched OFF if the reactive power demand of GT1 comes below 1 MVAR for a time more than 5 minutes.

Similarly, capacitors B & C shall follow the same sequence & settings as capacitor A.



**Figure 42: Case 1 operational single line diagram**

**CASE 2: all three incomers are ON, bus sectionalizer A-B is OFF & the bus sectionalizer B-C is ON:**

Capacitor A circuit breaker shall be switched ON if the reactive power demand of GT1 exceeds 9 MVAR for a time more than 5 minutes.

Capacitor A circuit breaker shall be switched OFF if the reactive power demand of GT1 comes below 1 MVAR for a time more than 5 minutes.

Capacitor B circuit breaker shall be switched ON if the total reactive power demand of GT2 +GT3 exceeds 10 MVAR for a time more than 5 minutes.

Capacitor B circuit breaker shall be switched OFF if the total reactive power demand of GT2+GT3 comes below 2 MVAR for a time more than 5 minutes.

Capacitor C circuit breaker shall be switched ON if the total reactive power demand of GT2 +GT3 exceeds 11 MVAR for a time more than 10 minutes.

Capacitor C circuit breaker shall be switched OFF if the total reactive power demand of GT2+GT3 comes below 3 MVAR for a time more than 5 minutes.

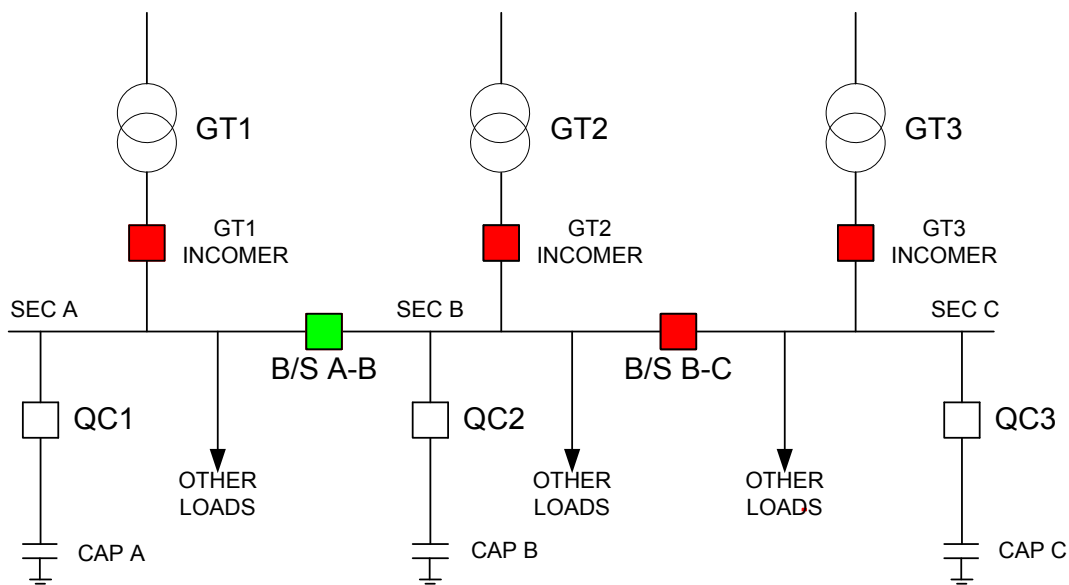


Figure 43: Case 2 operational single line diagram

### CASE 3: all three incomers are ON, bus sectionalizer A-B is ON & the bus sectionalizer B-C is OFF:

Capacitor C circuit breaker shall be switched ON if the reactive power demand of GT3 exceeds 9 MVAR for a time more than 5 minutes.

Capacitor C circuit breaker shall be switched OFF if the reactive power demand of GT3 comes below 1 MVAR for a time more than 5 minutes.

Capacitor A circuit breaker shall be switched ON if the total reactive power demand of GT1 +GT2 exceeds 10 MVAR for a time more than 5 minutes.

Capacitor A circuit breaker shall be switched OFF if the total reactive power demand of GT1+GT2 comes below 2 MVAR for a time more than 5 minutes.

Capacitor B circuit breaker shall be switched ON if the total reactive power demand of GT1 +GT2 exceeds 11 MVAR for a time more than 10 minutes.

Capacitor B circuit breaker shall be switched OFF if the total reactive power demand of GT1+GT2 comes below 3 MVAR for a time more than 5 minutes.

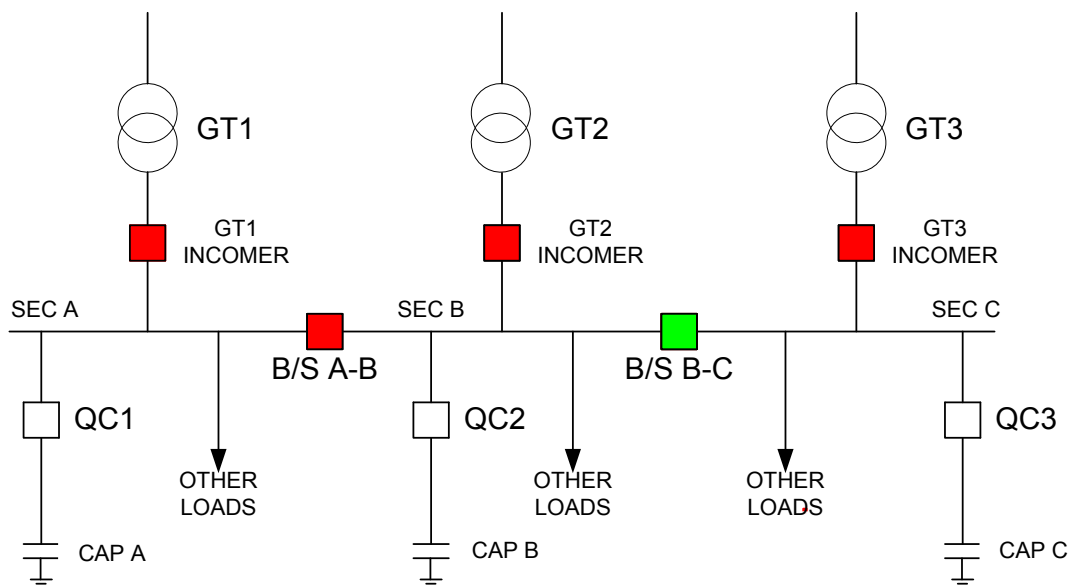


Figure 44: Case 3 operational single line diagram

### CASE 4: two incomers only are ON & both bus sectionalizers are ON:

The capacitor C.B. of the incomer which is in OFF position shall not come into service until its incomer becomes ON.

The other two capacitors C.B.s shall come into service according to the sequence ABC in the following conditions:

Capacitor A circuit breaker shall be switched ON if the total reactive power demand of GT1 +GT2 exceeds 10 MVAR for a time more than 5 minutes.

Capacitor A circuit breaker shall be switched OFF if the total reactive power demand of GT1+GT2 comes below 2 MVAR for a time more than 5 minutes.

Capacitor B circuit breaker shall be switched ON if the total reactive power demand of GT1 +GT2 exceeds 11 MVAR for a time more than 10 minutes.

Capacitor B circuit breaker shall be switched OFF if the total reactive power demand of GT1+GT2 comes below 3 MVAR for a time more than 5 minutes.

Similarly, the other two conditions shall follow the same sequence & settings.

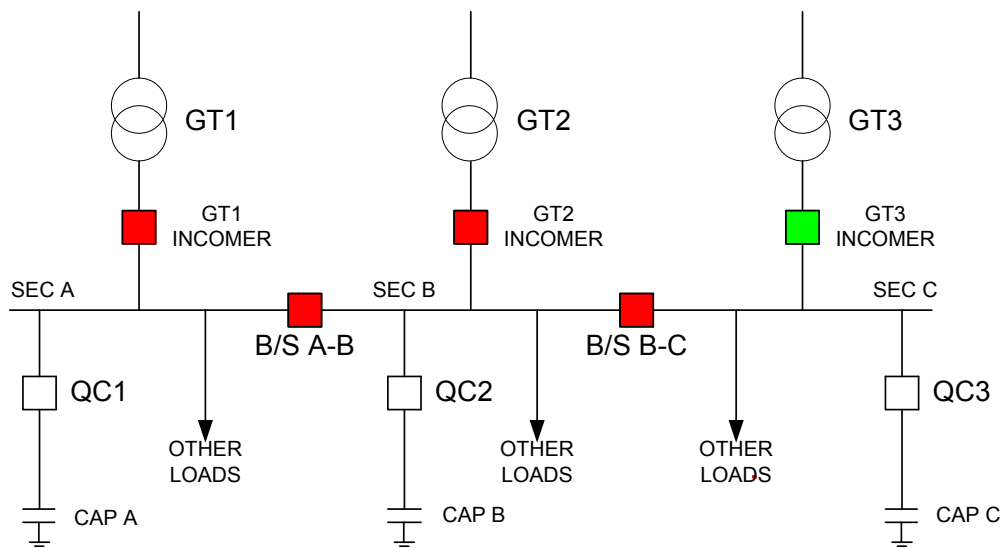


Figure 45: Case 4 operational single line diagram with GT3 in hot standby mode

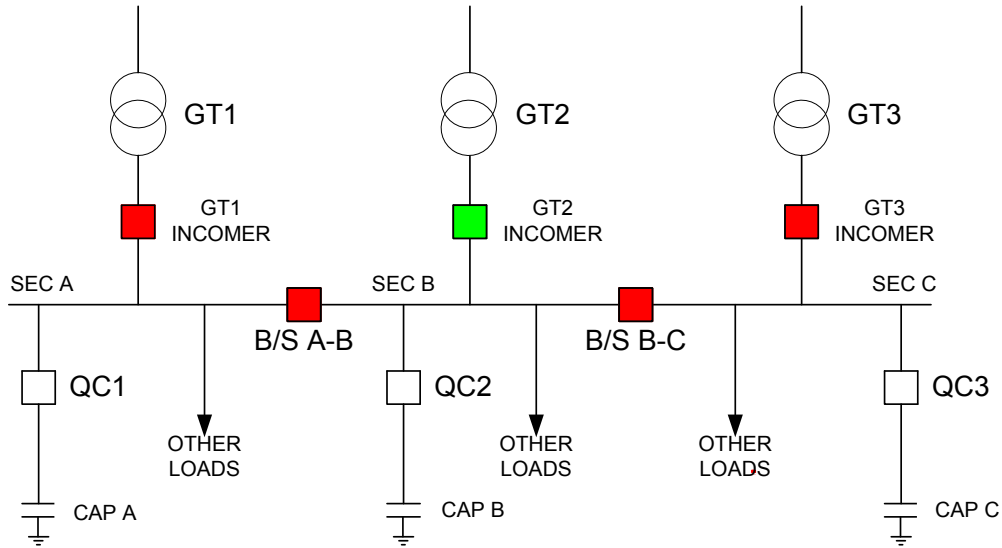


Figure 46: Case 4 operational single line diagram with GT2 in hot standby mode

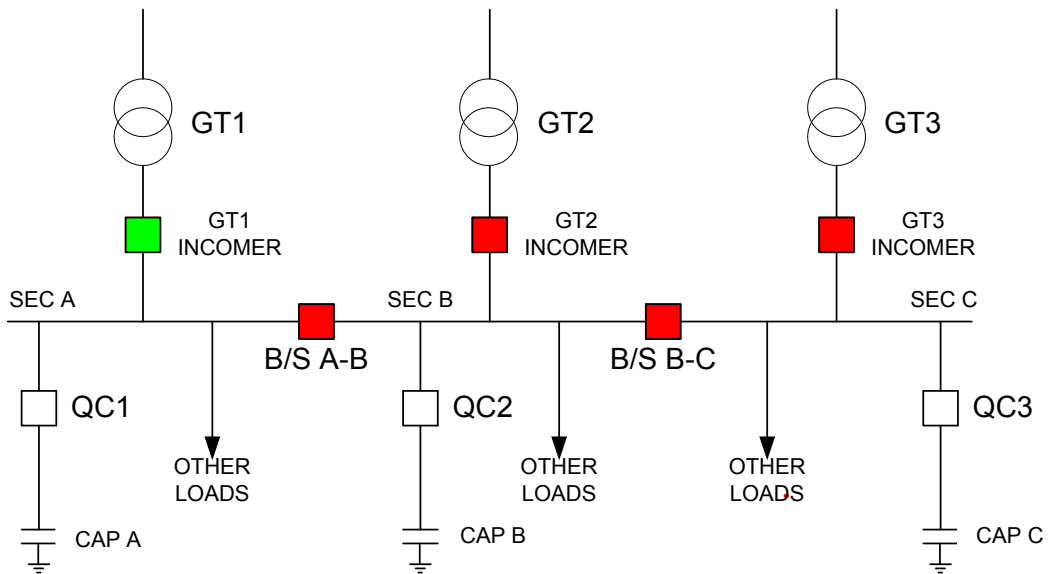


Figure 47: Case 4 operational single line diagram with GT1 in hot standby mode

**Case 5: over voltage condition:**

The circuit breaker of a certain capacitor shall be switched OFF (regardless of the load MVAR demand) if the respective bus bar voltage becomes more than 14.6 KV(106% of  $U_{base}$ ) for 120 seconds.

**Case 6: under voltage condition:**

The circuit breaker of a certain capacitor shall be switched ON (regardless of the load MVAR demand) if the respective bus bar voltage becomes less than 12.14 KV(88% of  $U_{base}$ )for 5 seconds.

## ***Automatic capacitor control system (ACCS) inputs & outputs***

### **Controller inputs**

#### **Analogue inputs**

1. The incomers' currents on the three phases.
2. The 13.8 KV bus bar voltages.

#### **Digital inputs**

1. The status of the incomers & bus sections circuit breakers.

### **Controller outputs**

1. ON & OFF Commands to the capacitors circuit breakers.
2. Back indications to the HMI unit, to the mimic panel & to ECC.
3. Readings to the HMI unit, to the mimic panel & to ECC.
4. Alarms to local control panel & to ECC.

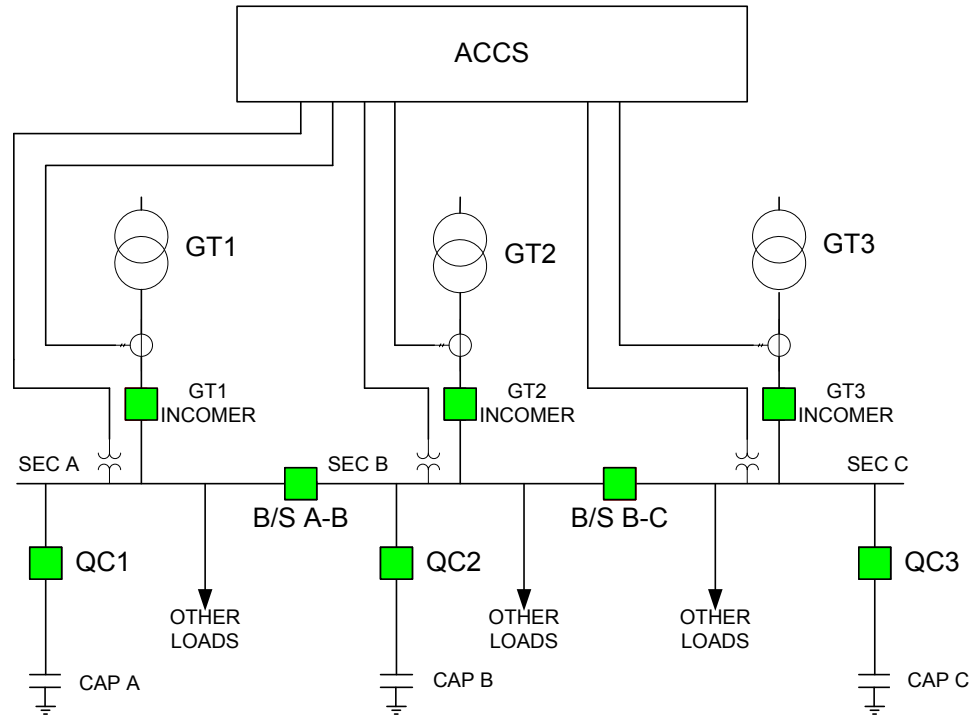


Figure 48: ACCS analogue inputs

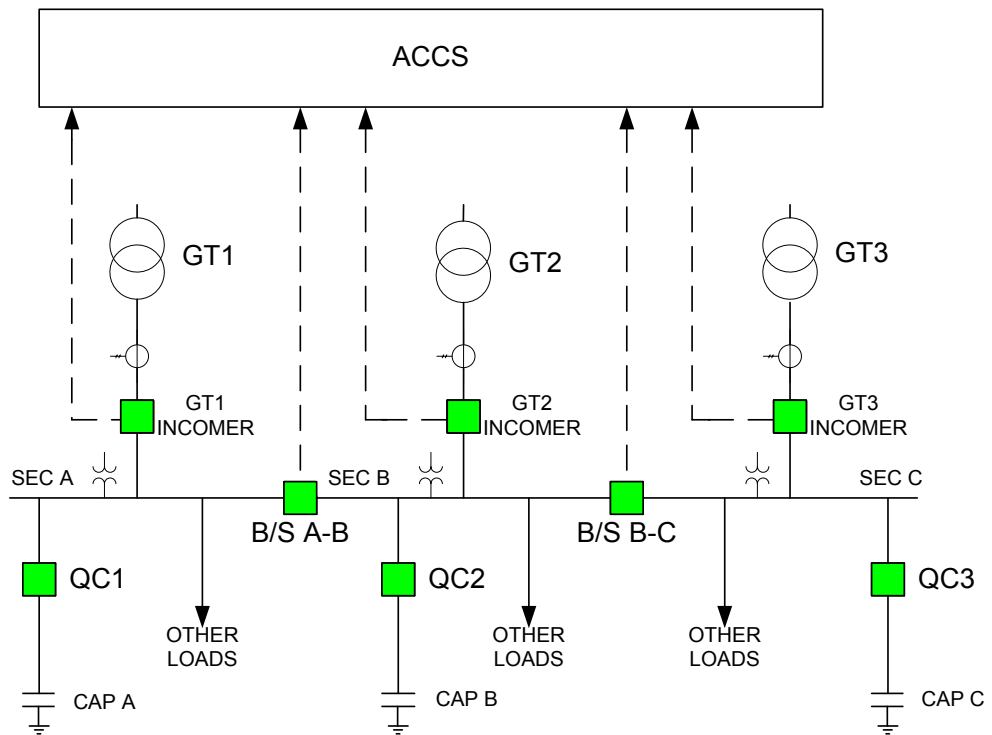


Figure 49: ACCS digital inputs

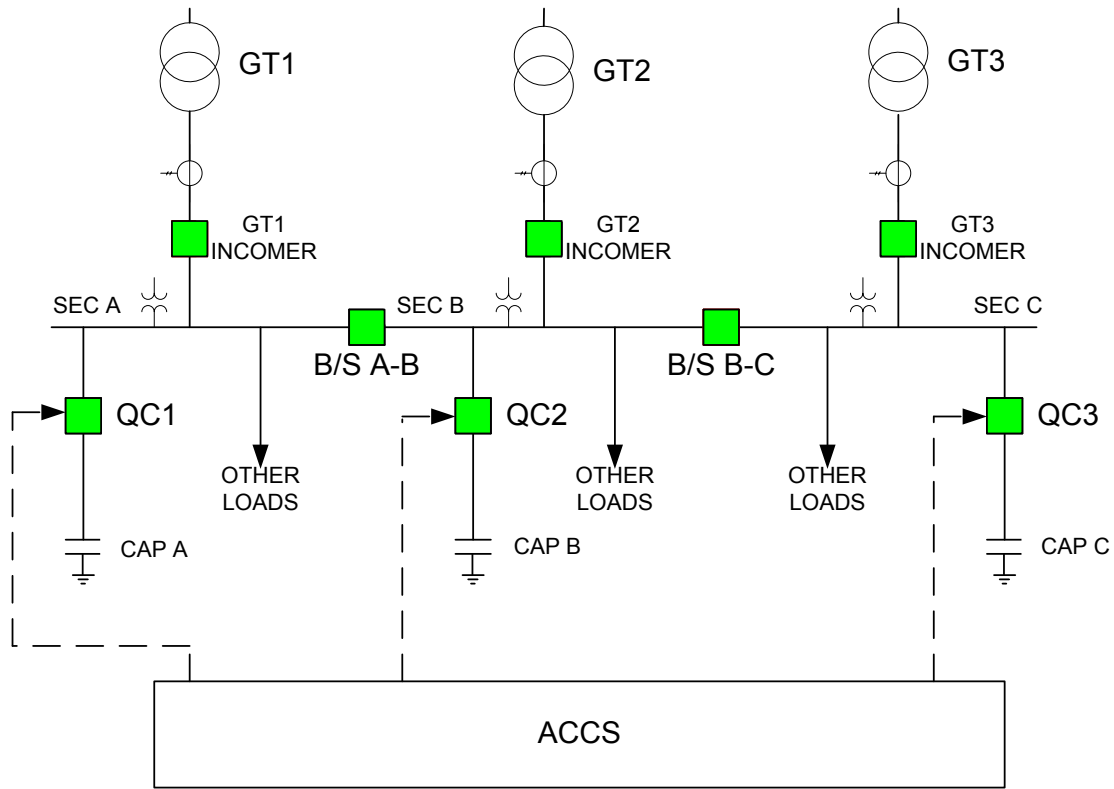


Figure 50: ACCS digital outputs

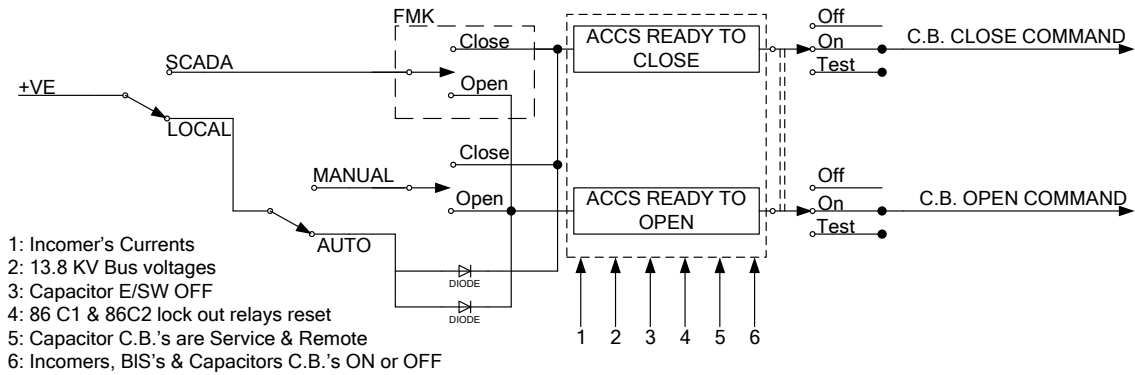


Figure 51: ACCS control circuit of ABB capacitor project

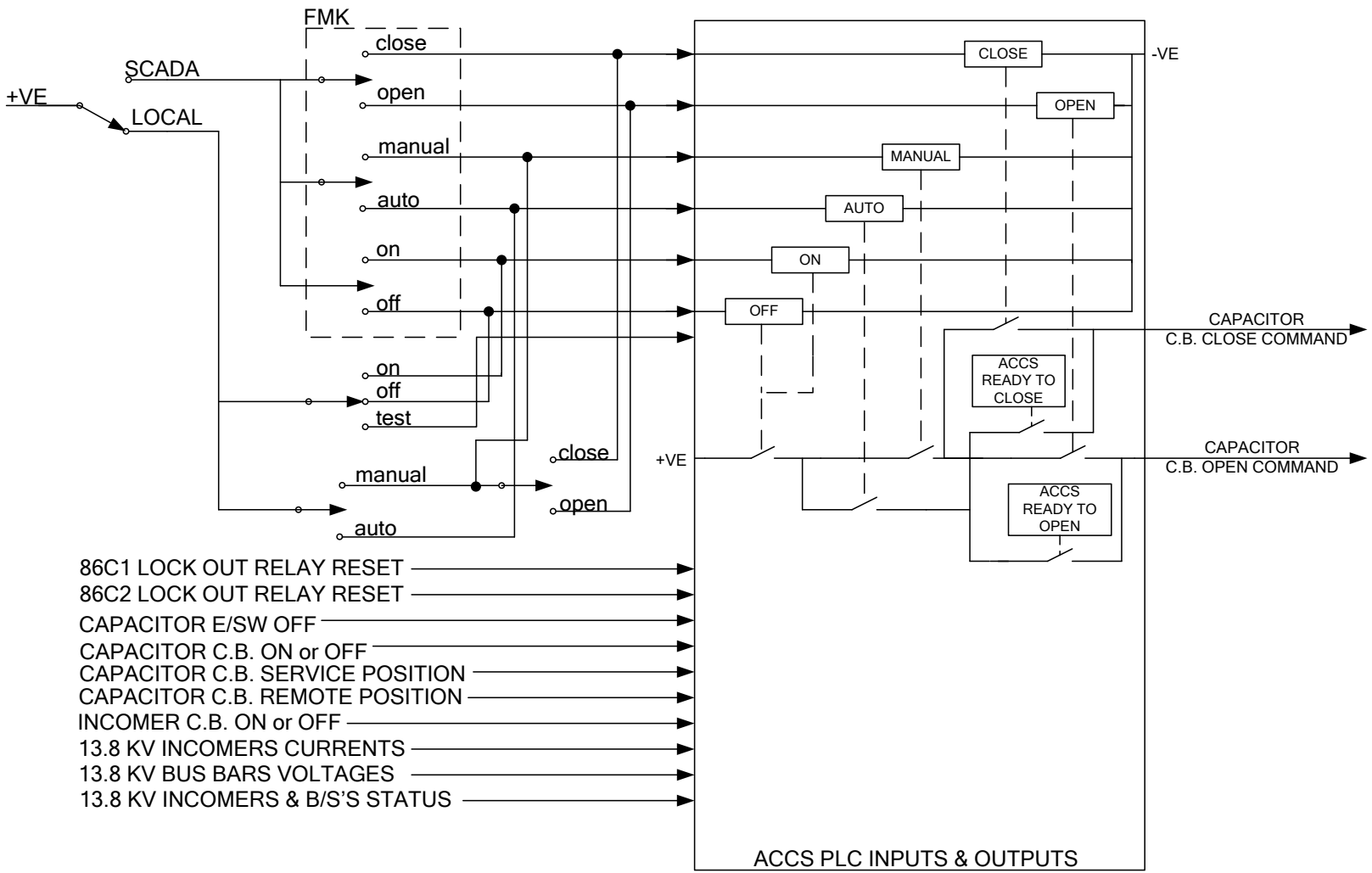


Figure 52: ACCS controller of the SSEM capacitor projects

## Capacitor bank protection

### 1. Over current & earth fault (50/51/51N)

The over current element shall be peak detectors including the harmonics but supervised by the positive sequence directional sensor. The purpose of the directional feature is to keep the capacitor supplying the MVAR to the network while clearing the faults on any of the adjacent feeders.

Over current (51) settings = 135% of the rated capacitor current with short time inverse (STI) characteristics TMS=0.28.

(Tripping time =0.5 seconds @ 2 times the current settings)

The earth fault element shall be peak detectors supervised by directional ground. The purpose of the directional feature is to keep the capacitor supplying the MVAR to the network while clearing the faults on any of the adjacent feeders.

Earth fault (51N) settings = 40% of the rated capacitor current with short time inverse (STI) characteristics TMS=0.28.

(Tripping time =0.5 seconds @ 2 times the current settings)

(STI) equation is:  $t = TMS \times \frac{0.05}{I^{0.04} - 1}$

Where t is the tripping time, TMS is the time multiplier setting &  $I = I_{\text{fault}}/I_{\text{setting}}$

The high set instantaneous (50) settings = 3 to 4 times (or lower) of the rated current with time delay of 100 milliseconds.

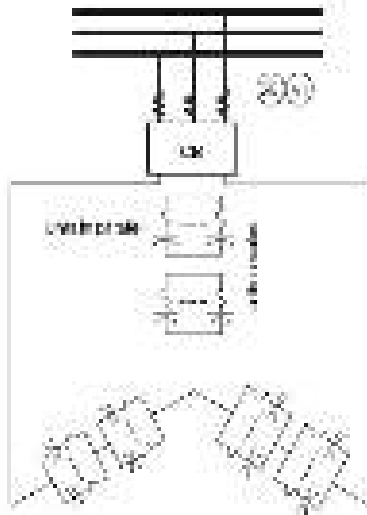


Figure 53: Over current relays connection for the capacitor bank

## 2. Thermal overload (49)

120% of the rated capacitor current will be considered as over load & tripping time = 10 seconds.

## 3. Neutral unbalance (46UB)

With all capacitor elements fuses intact (no fault), no current flows between the two star points. Current will be detected by the neutral CT in case of any loss of capacitance in any section (one capacitor open or short circuited).

The relay is able to detect (identify) the short circuiting of one percent of the capacitor bank.

Alarm stage: 1.49 Amperes & time = 1 second.

Trip stage: 2.32 Amperes & time = 0.5 seconds.

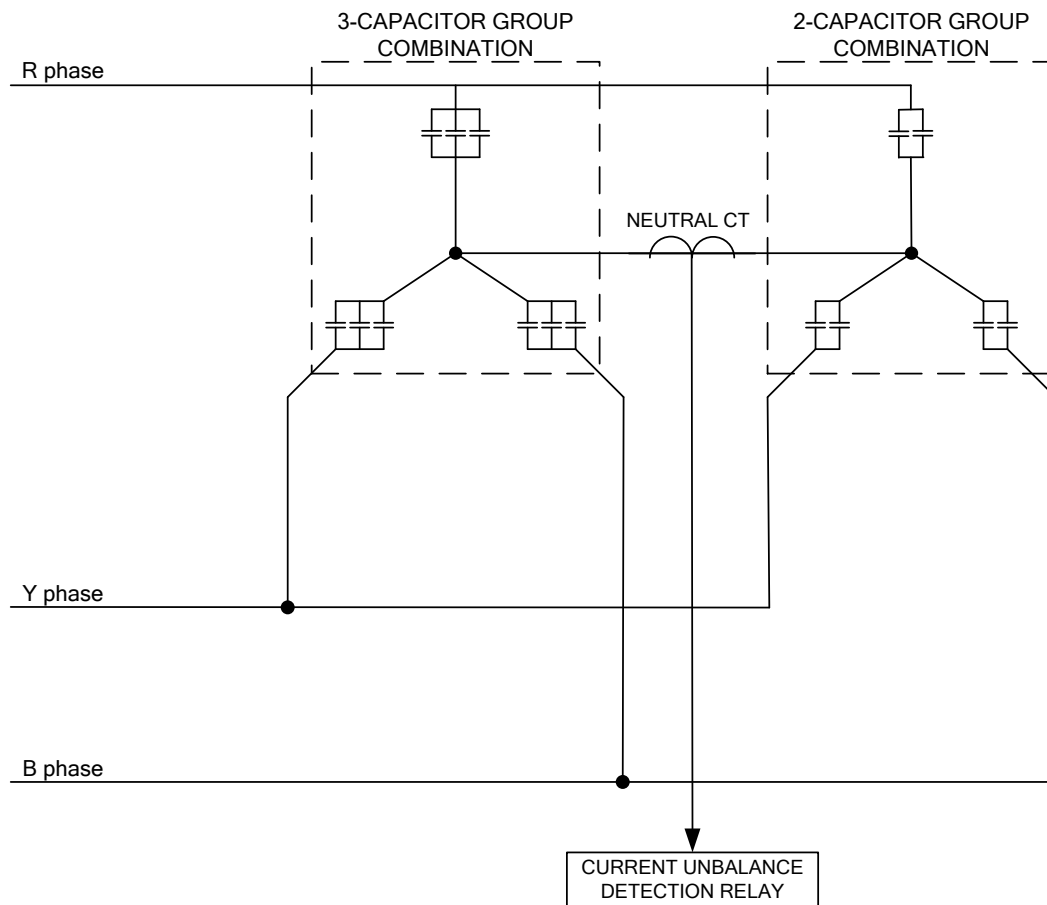


Figure 54: Neutral unbalance detection relay connections

#### 4. Directional negative sequence(46 –VE)

The directional negative sequence sensor is applied to detect (identify) only the inter phase faults within the capacitor bank while it shall block upon the fault condition on the parallel feeders.

#### 5. Over voltage (59)

The voltage is sensed as a fundamental frequency signal.

Alarm stage: 112%  $U_{base}$  & time = 120 seconds.

Trip stage: 115%  $U_{base}$  & time = 5 seconds.

#### 6. Under voltage (27)

The voltage is sensed as a fundamental frequency signal.

Alarm stage: 90%  $U_{base}$  & time = 5 seconds.

Trip stage: 70%  $U_{base}$  & time = 10 seconds.

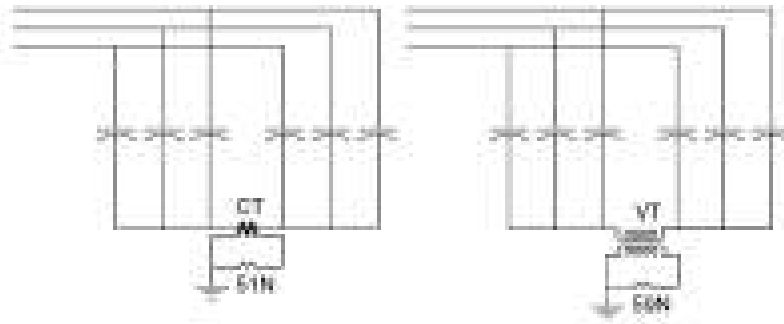
#### 7. Under current (37)

Tripping stage (for identifying the open circuit of the capacitor string) at 50% of the rated current with time delay of 2 seconds.

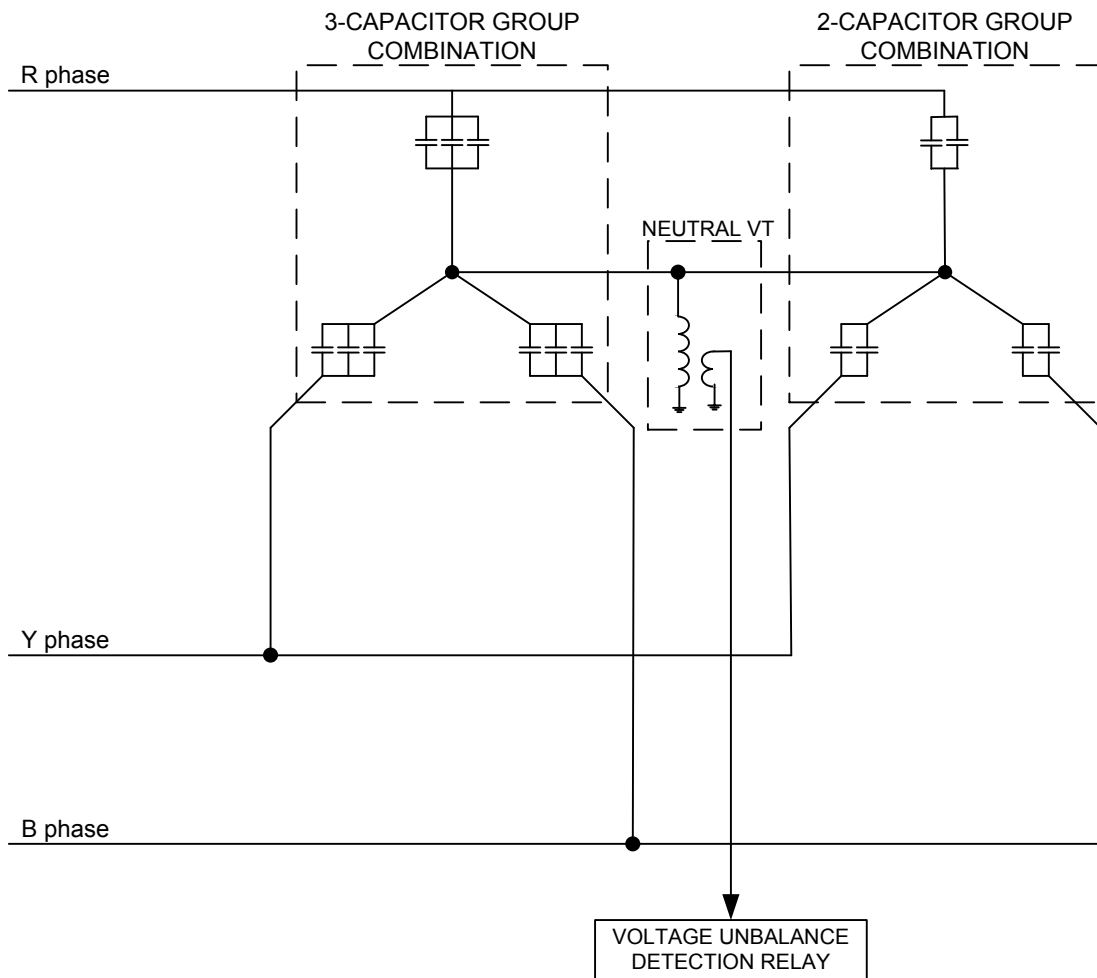
This function will be blocked if the current comes below 20% of the rated current for a time delay period of 2 seconds.

#### 8. Fuse failure (98)

The settings are applied to confirm the fuse failure conditions as a function of both zero sequence current & voltage with certain magnitudes and angles.



**Figure 49: Neutral current / voltage unbalance detection principles**



**Figure 50: Connection of the Voltage unbalance detection relay to the neutral point of the capacitors**

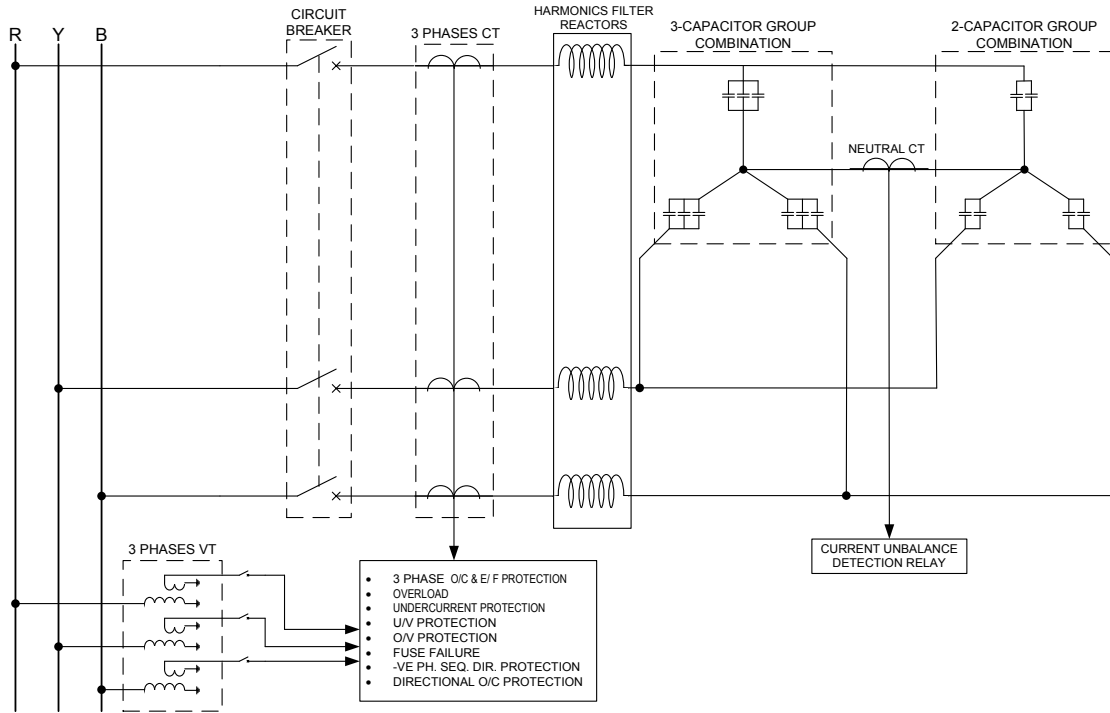


Figure 51: Connections of the Multifunction relay and the current unbalance detection relay

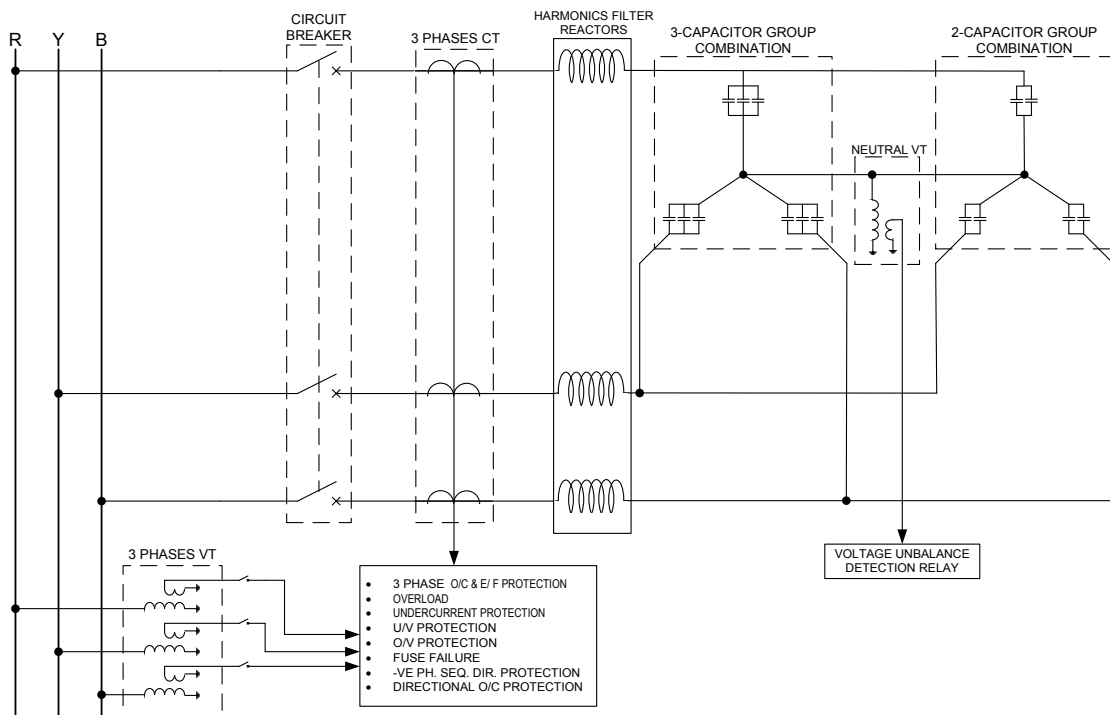
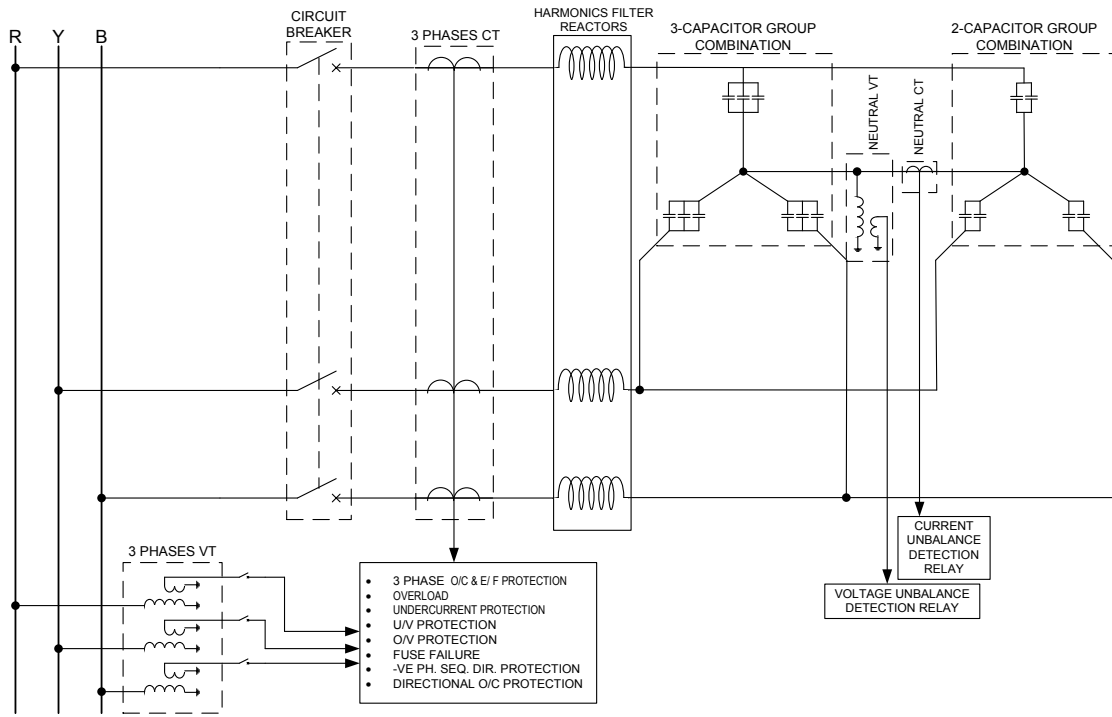


Figure 52: Connection of the multifunction relay and the voltage unbalance detection relay



**Figure 53: connections of the multifunction relay, voltage unbalance relay and current unbalance relay**

## SEC Specifications for capacitor protection & control

It is recommended to have two independent sets of protection for the 33 & 13.8 KV capacitors. Each set should be fed by:

1. Independent current transformer
2. Independent voltage signal from the voltage transformer
3. Independent DC supply.

The first set (called also group 1) has the following functions:

1. Directional O/C protection (67)
2. Under current protection (37)
3. Negative phase sequence directional protection (46)
4. Non-directional over current protection (50/51).
5. Non-directional earth fault protection (51N)
6. Overload protection (26OL)
7. Under voltage protection (27)
8. Over voltage protection (59)
9. Fuse failure protection (98)

The second set (called also group 2) has the following functions:

1. Directional O/C protection (67)
2. Under current protection (37)
3. Negative phase sequence directional protection (46)
4. Neutral unbalance current protection (46UB)
5. Non-directional over current protection (50/51).
6. Non-directional earth fault protection (51N)
7. Overload protection (26OL)
8. Under voltage protection (27)
9. Over voltage protection (59)
10. Breaker failure protection (50BF)
11. Fuse failure protection (98)

Each set is operating the following relays:

1. One trip relay (94) from the functions that have nothing to do with the capacitor itself like U/V, O/V, O/L.
2. One lock out relay (86) from the functions that have some real capacitor fault to initiate it.

Figure (54) reflects the specification details mentioned above.

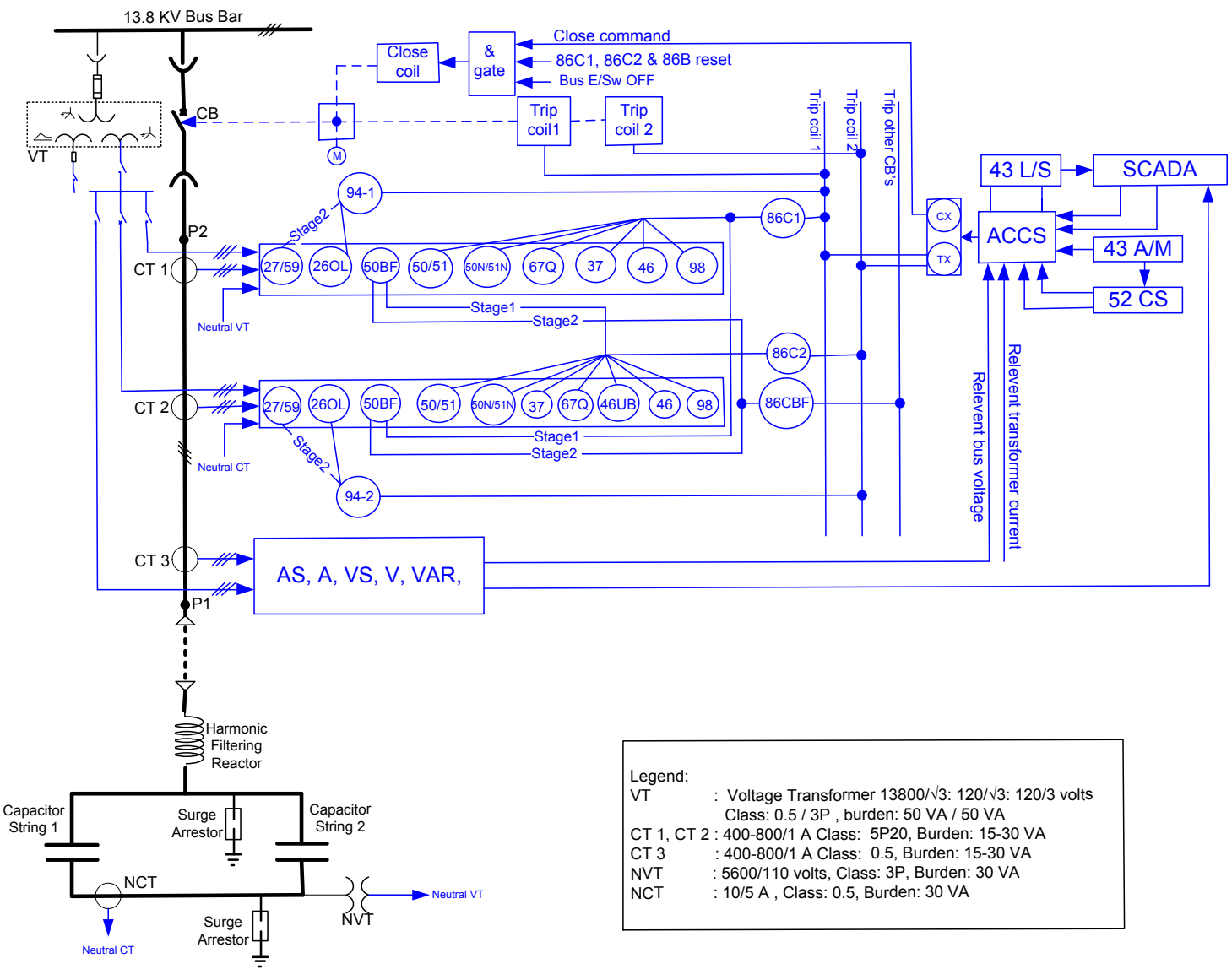


Figure 54: SFC specification for 13.8 KV power factor correction capacitors

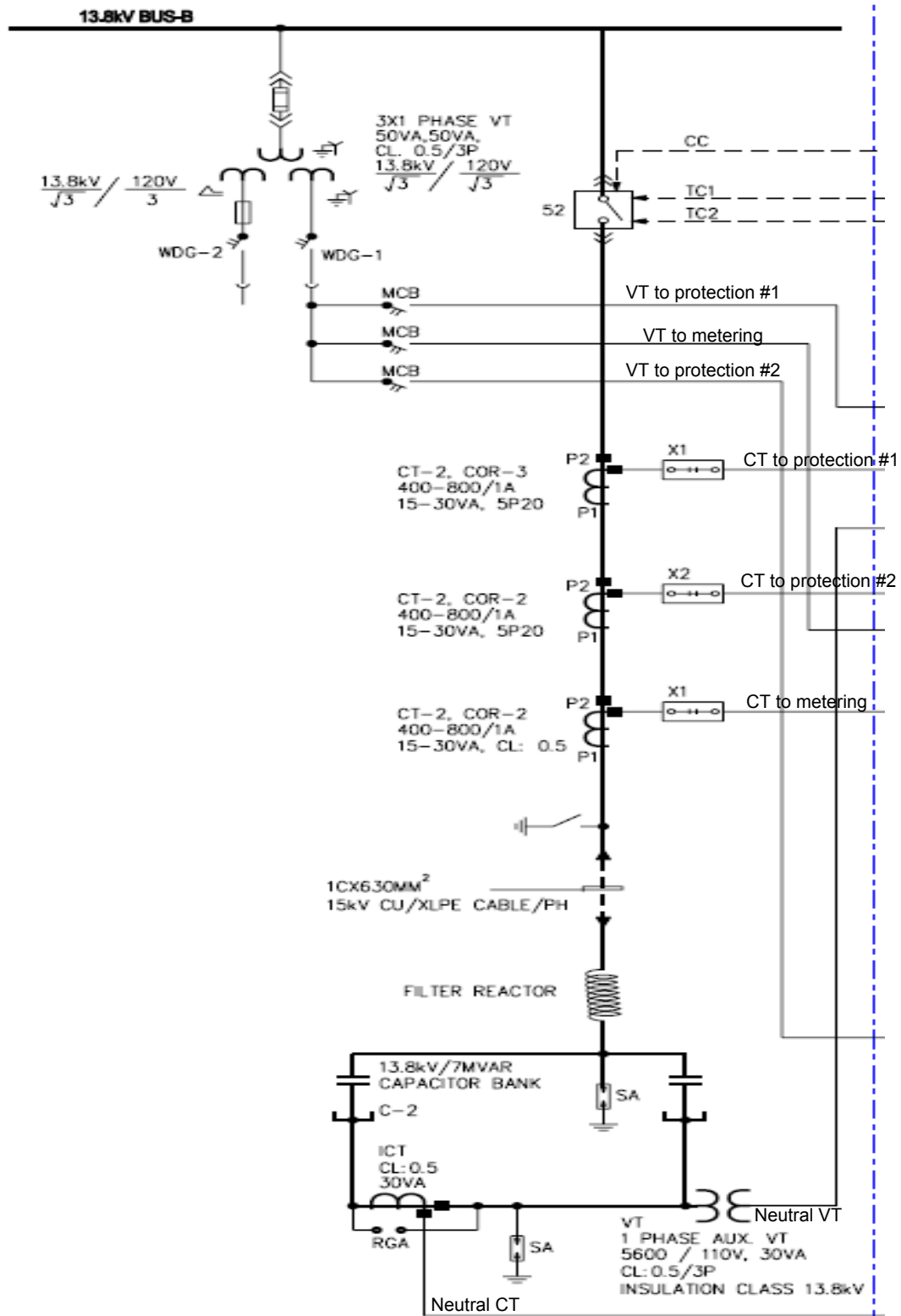


Figure 55: Capacitor, filtering reactor and the CT& VT for its protection & measuring purposes

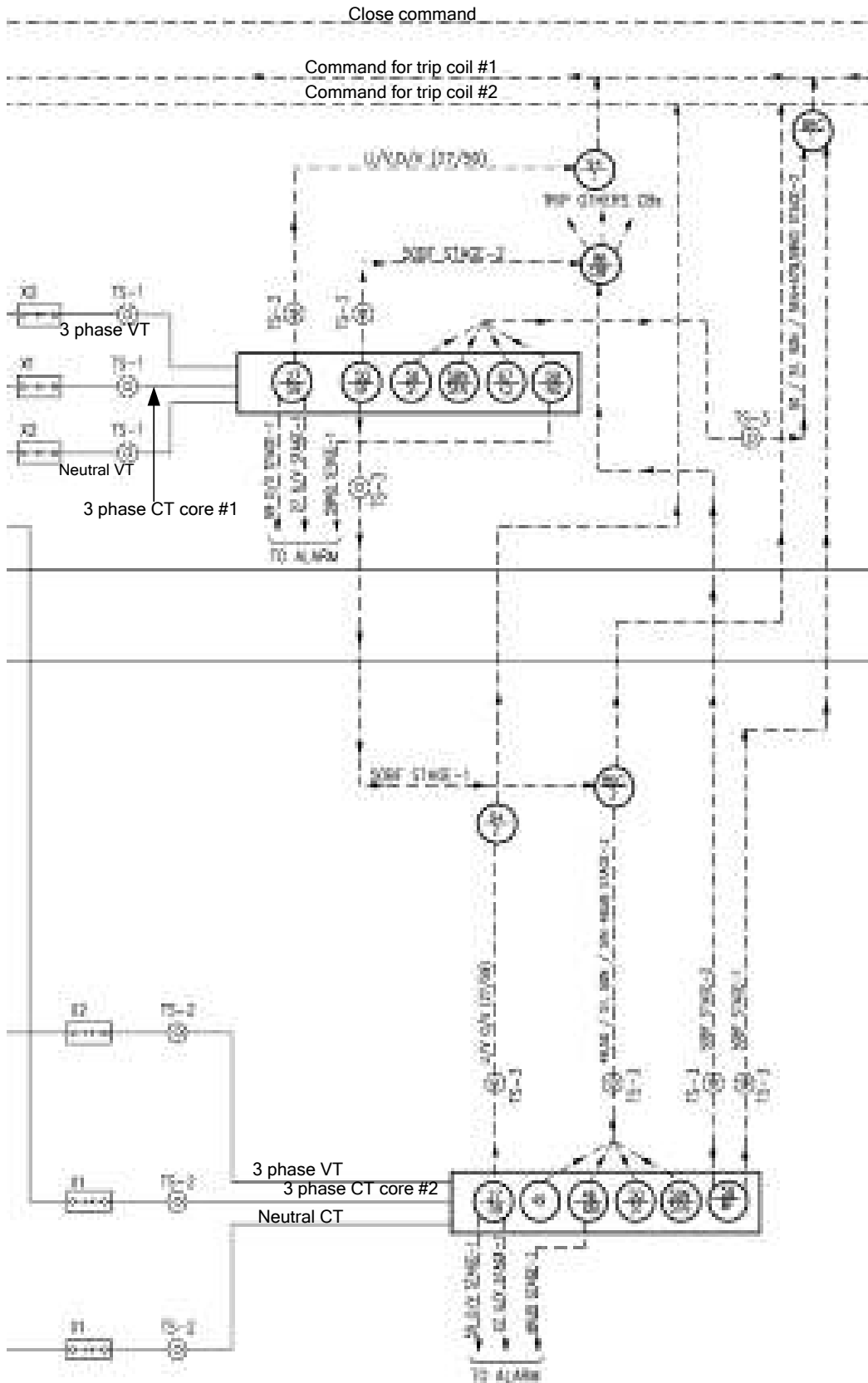


Figure 56: Protection set 1 & set 2 connections along with the tripping & lockout relays

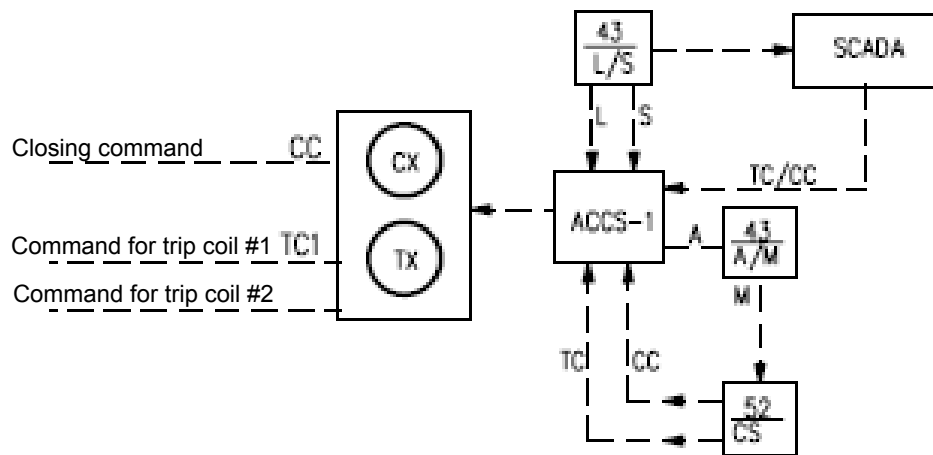


Figure 57: Local & remote commands for the capacitor circuit breaker

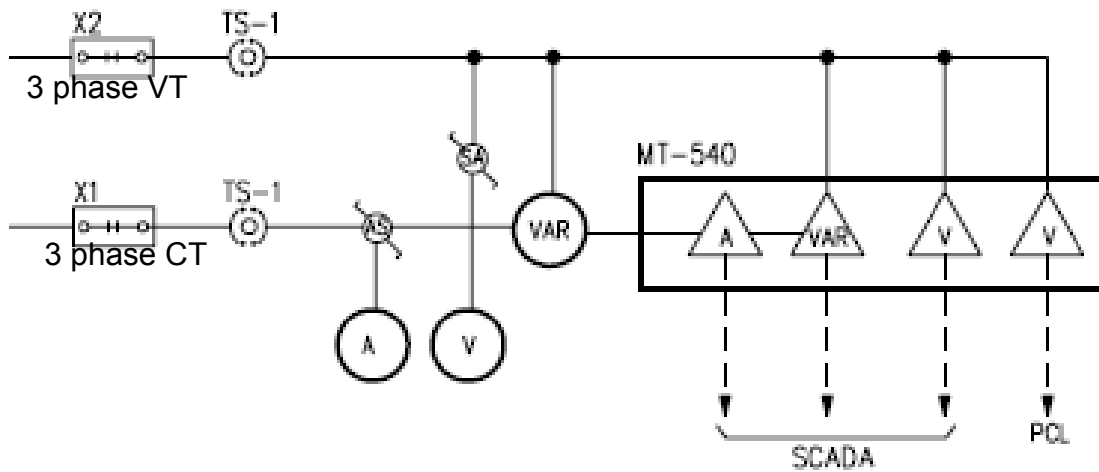


Figure 58: Local & remote measurements of the capacitor

## Capacitor Fusing

The consequences of capacitor failures due to dielectric faults are limited with the help of different fusing technologies. There are three methods of capacitor fusing. All technologies are good and safe. The application, the voltage and the power rating will decide the optimal one.

### 1. Internal fusing:

- Have one fuse on every element inside the capacitor unit.
- It is current limiting fuse and will effectively disconnect the element in the event of the failure. Thus, only a small part of the total capacity is lost and the rest of the capacitor remains in service which increases the capacitor availability.

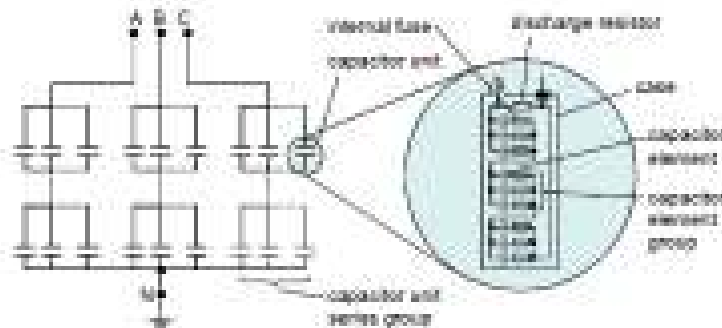


Figure 59: Internal fusing for the capacitors

## 2. External fusing:

- Have one fuse for the complete capacitor unit.
- It is applicable for high voltage and low power rating cases.
- The fuse will also operate during external flashover.

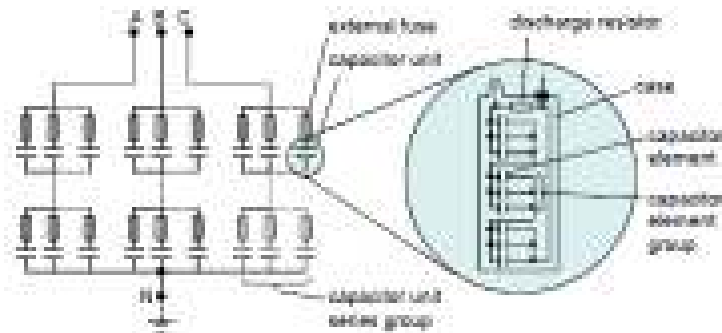


Figure 60: External fusing for the capacitor

## 3. Fuseless:

- Have no fuse at all for the complete capacitor unit.
- The capacitor bank is connected in strings of series units.
- In the event of a puncture, the group is still connected and the resulting over voltage is divided among the remaining healthy elements in the string.

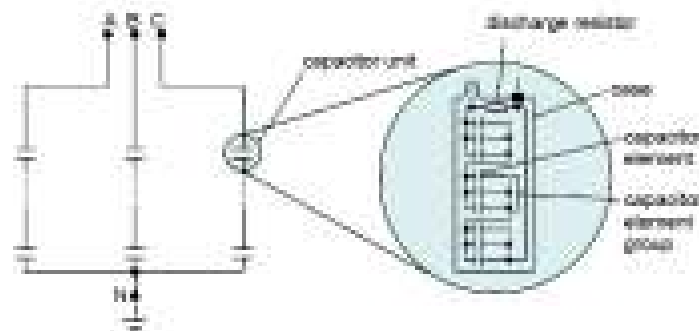


Figure 61: Fuseless capacitors

## Capacitor Unbalance Protection Schemes

The purpose of an unbalance protection is to trip a capacitor bank in the event of its fuse operation. This will prevent damaging over voltages across the remaining capacitor units in the group where the operation occurs, thereby protecting against the situation that can be immediately harmful to the capacitor units or associated equipment. In case of fuse failure, the voltages across the upper/ lower branches become two thirds/one third of the full voltage respectively. It is very clear that the voltage was one half of the full voltage before fuse blowing. Such a voltage increase is unacceptable, it should be detected and the unit must be isolated before significant damage occurs.

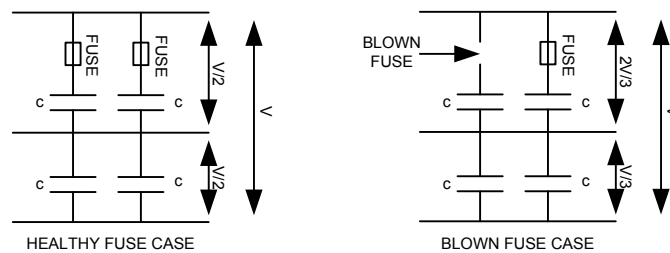


Figure 62: Voltage distribution along the capacitor units for both healthy and blown fuse cases

### Scheme 1: Neutral Current Sensing Using a Current Transformer

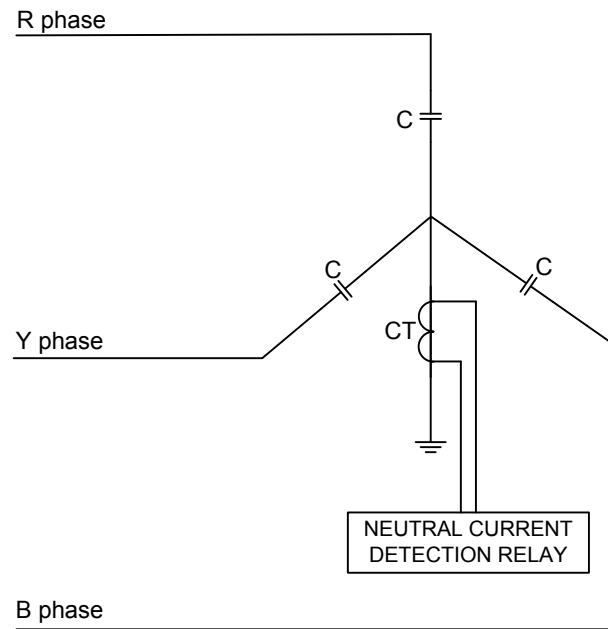


Figure 63: Scheme 1

The advantages of scheme 1 are:

1. The bank contains twice parallel units per series group compared to the double wye bank for a given KVAR which reduces the over voltage seen by the remaining units in a group in the event of a fuse operation.
2. Less substation area compared to the double wye banks.
3. Relatively inexpensive.

The disadvantages of scheme 1 are:

1. Sensitive to system unbalance.
2. Sensitive to triple harmonics and it needs filter circuit.
3. It will not operate if there is similar failure in all the phases.
4. It is not possible to identify the failed-capacitor phase.

## Scheme 2: Summation of Intermediate Tap-Point Voltage in a grounded Y capacitor bank

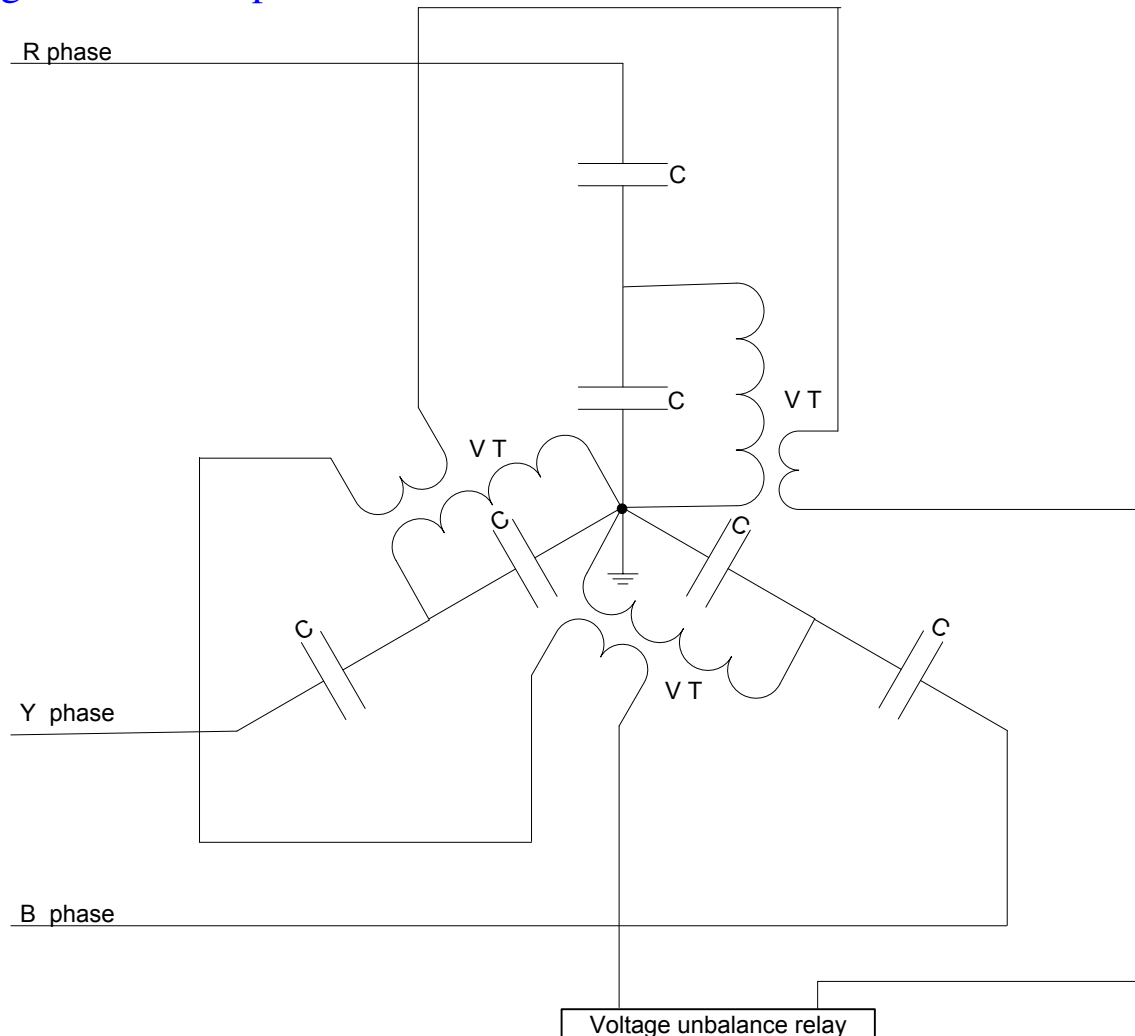


Figure 64: Scheme 2

The operation of this scheme depends on the fact that: any unbalance in the capacitor units will cause unbalance in the voltages at the tap points. The resultant voltage in the open delta provides an indication of the unbalance. It is sensitive to system unbalance.

### Scheme 3: unbalance detection in a grounded split-Y capacitor bank using two current transformers.

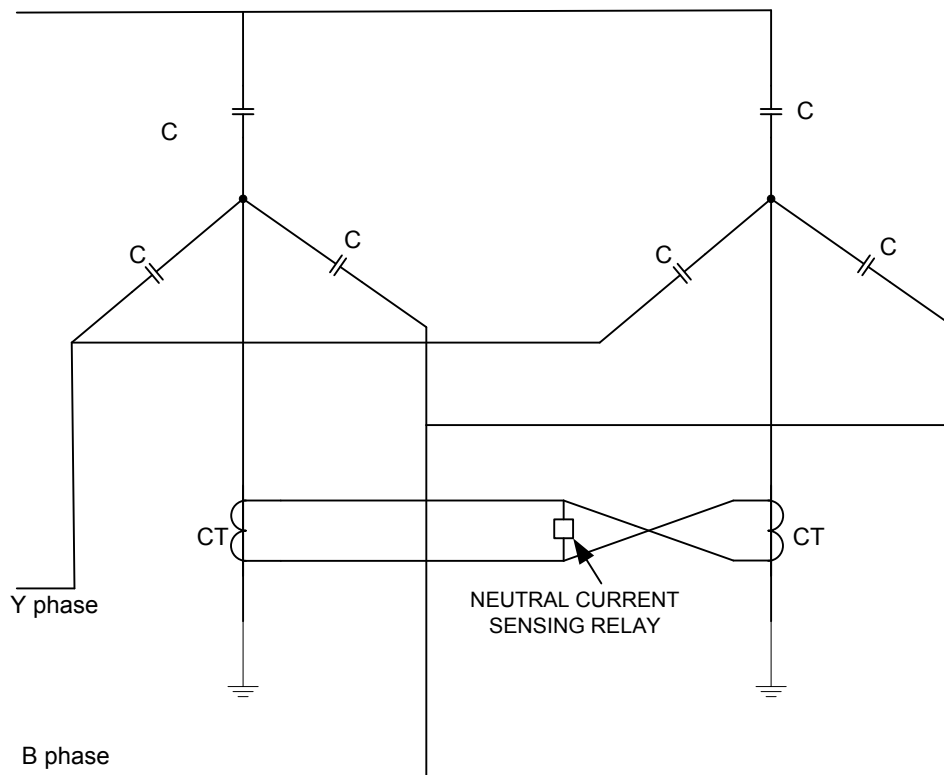


Figure 65: Scheme 3

The advantages of scheme 3 are:

1. It is insensitive to any system unbalance.
2. Harmonic currents do not affect this scheme.
3. For very large banks with more than one series group the amount of energy will decrease. This will lower the fuse interruption duty and may reduce the fuses cost.

The disadvantages of scheme 3 are:

1. Splitting the Y into two sections leads to less parallel units per series group, thereby increasing the over voltage on the remaining units in the series group in case of fuse failure.
2. It needs more substation area and connections.
3. It will not operate if there is similar failure in all the phases.

### Scheme 4: Voltage Difference for a Grounded Y Capacitor Bank

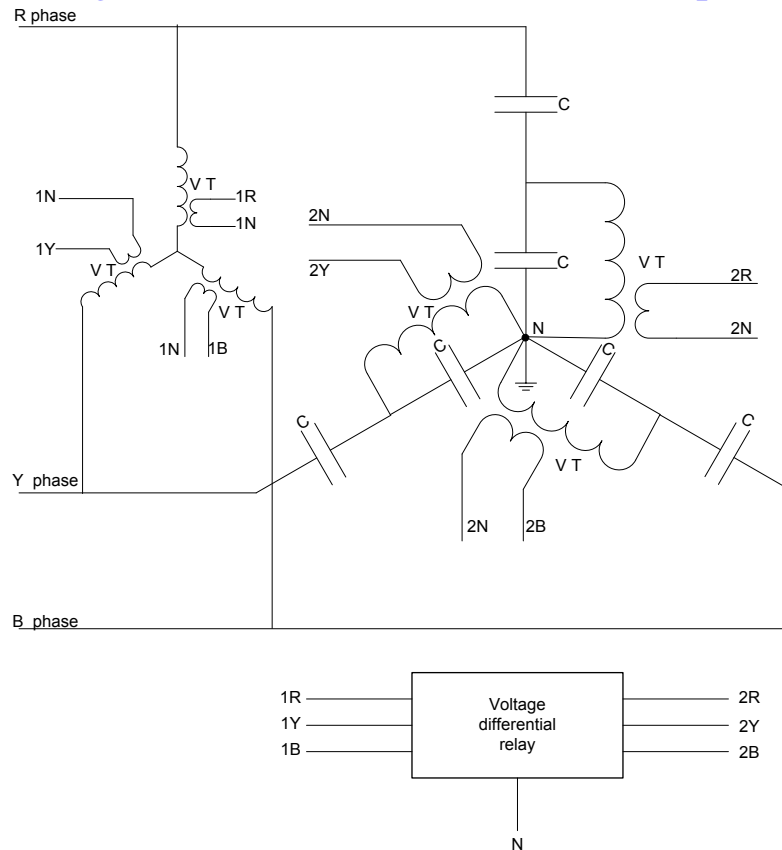


Figure 66: Scheme 4

Two three-phase VT outputs are compared in a differential relay  
Advantages of scheme 4:

1. The bank contains twice parallel units per series group compared to the double wye bank for a given KVAR which reduces the over voltage seen by the remaining units in a group in the event of a fuse operation.
2. Less substation area is needed.
3. Less sensitive to system unbalance.
4. It is sensitive to failure detection in the series capacitors.

Disadvantages of scheme 4:

1. The number of needed VT's are six (big number compared to other schemes).
2. Extensive connections are also required.

## Scheme 5: Neutral Voltage Unbalance Protection for Ungrounded Y-Connected Capacitor Bank Using a PT

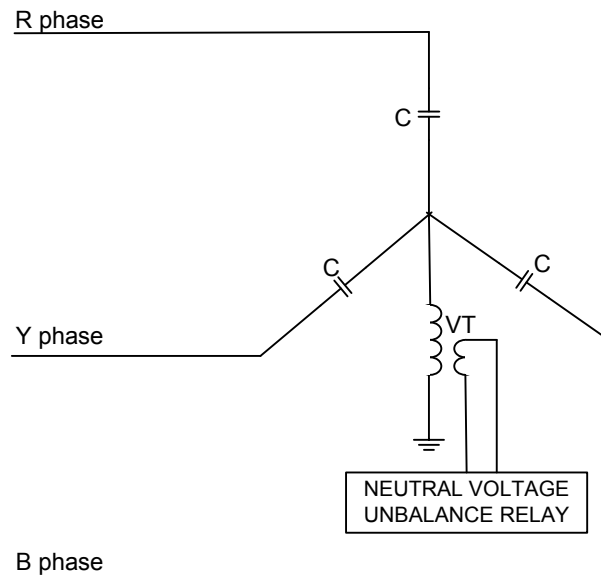


Figure 67: Scheme 5

The used relay is a time-delayed voltage relay with third harmonic filter connected across the secondary of the VT.

Advantages of scheme 5:

1. The bank contains twice parallel units per series group compared to the double wye bank for a given KVAR which reduces the over voltage seen by the remaining units in a group in the event of a fuse operation.
2. Less substation area is needed.
3. Less sensitive to system unbalance.

### Scheme 6: Neutral Voltage Unbalance Protection for Ungrounded Y-Connected Capacitor Bank Using a capacitor voltage divider

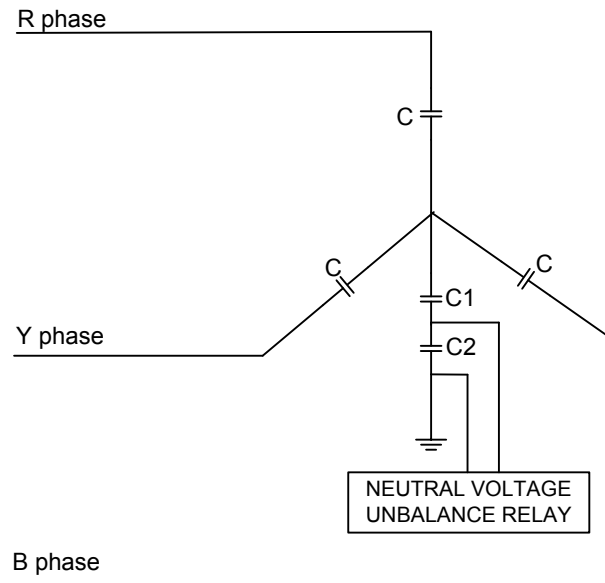


Figure 68: Scheme 6

The used relay is a conventional inverse time voltage relay connected across the grounding Y-capacitor. The grounding capacitor is a low voltage unit (2400 volts or less) sized to provide the desired unbalance voltage to the relay. This scheme has the same advantages of scheme 5.

### Scheme 7: Neutral Voltage Unbalance Protection for Ungrounded Y-Connected Capacitor Bank Using three PT's

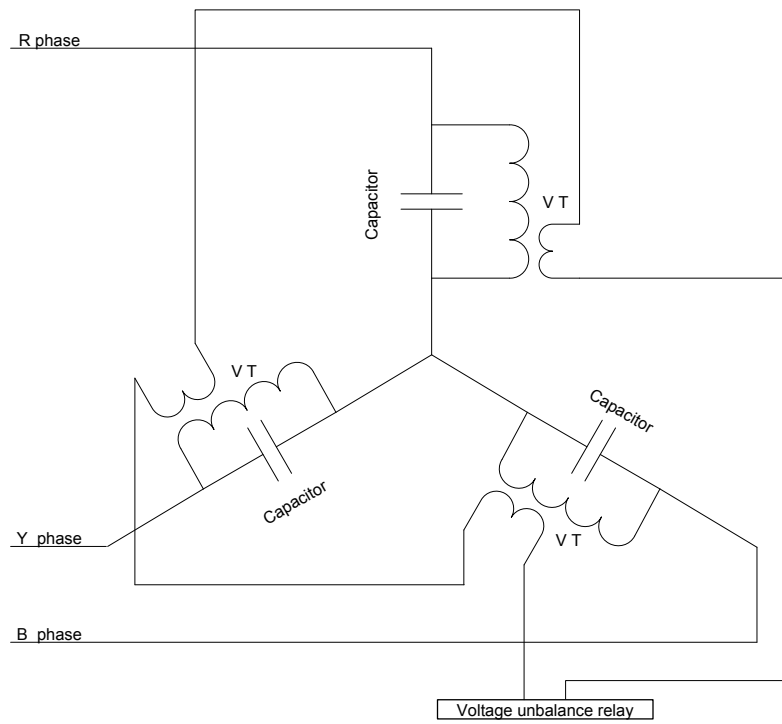


Figure 69: Scheme 7

This scheme has the same advantages of scheme 5.

The disadvantages of this scheme are:

- It is sensitive to third harmonic.
- It is expensive.

### Scheme 8: Neutral Voltage Unbalance Protection for Ungrounded split Y-Connected Capacitor Bank Using neutral CT

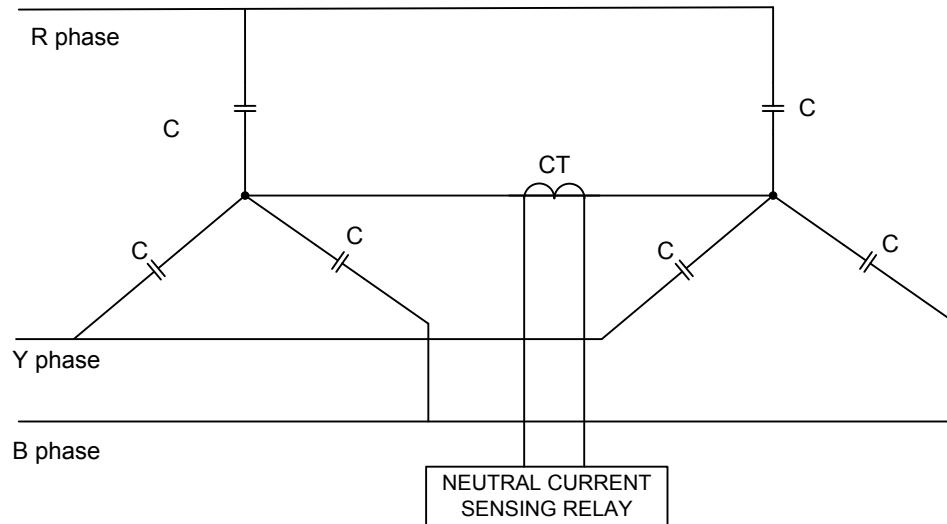


Figure 70: Scheme 8

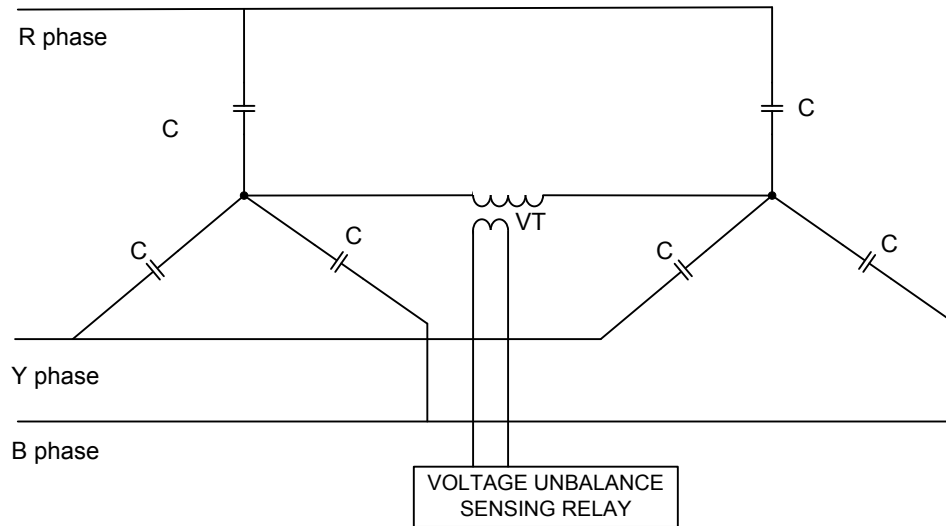
The advantages of scheme 8 are:

1. It is not sensitive to system unbalances.
2. It is sensitive to capacitor units failures.
3. It is not affected by harmonics.

The disadvantages of scheme 8 are:

1. The increase in the overvoltage per unit is high because there is fewer parallel units per series group.
2. It needs more substation area compared to the Y-connected capacitor banks.

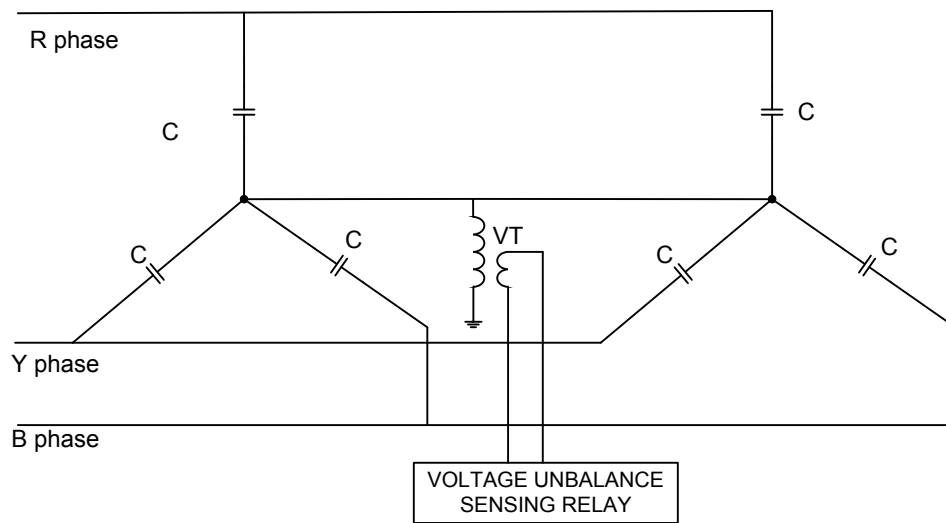
**Scheme 9: Neutral Voltage Unbalance Protection for Ungrounded split Y-Connected Capacitor Bank Using a PT**



**Figure 71: Scheme 9**

It is similar to scheme 8.

**Scheme 10: Neutral Voltage Unbalance Protection for Ungrounded split Y-Connected Capacitor Bank Using neutral PT**



**Figure 72: Scheme 10**

It is similar to schemes 8 & 9.

## Case study: capacitor wrong tripping analysis

### 451-2 – CAPACITOR BANK PROTECTION APPLICATION TRIP ANALYSIS (POST FAULT)

Prepared by: Rajkumar, SEL, Bahrain, dated 25/05/2009

Date of trip incident: 23/05/2009

Substation: 8119, Riyadh, Saudi Arabia

#### **Background:**

The 451-2 has been employed as Group-1 protection with 51, 51G, 67Q (definite time, directional), 37, 27, 59, and 51-OL (Overload) protection functions for 13.8Kv capacitor bank along with REC670 as duplicated Group-2 (with additional 46N- neutral current unbalance) protection.

#### **The system data:**

Capacitor bank: 7000KVAR, 13.8KV, YY ungrounded

451-2 CT input: Feeder CT 800/5A A, B, C

451-2 VT input: Bus/ Incomer VT: 13.8KV/1.732:120/1.732 V

In S/S 8119 13.8KV bus has three sections (A, B & C) and each section has one incomer from 132KV/13.8KV transformer (YNyn0d11, buried delta, 13.8KV neutral grounded through  $N_{ER}=10\text{ohms}$ ). Each section has number of outgoing radial cable feeders and one of the outgoing feeders is feeding 7000KVAR, YY capacitor bank. During tripping incidence, the three incomers were on and two bus sections (AB, BC) were off.

#### **Trip Incidence:**

Both Group -1 and Group-2 relays tripped with 67Q (definite time delayed directional negative sequence over current) in capacitor that connected on Section C (H46 panel), when another outgoing feeder (H38 panel), connected on same Section "c" bus had fault. The faulted feeder's fault current information not available as it is a static relay and indication has been reset by operator with recording them.

#### **Analysis:**

The schematic connection diagram and on load test are showing the CT /VT polarity connections the 451-2 relays are okay. The Event report has been downloaded from relay and analyzed as below.

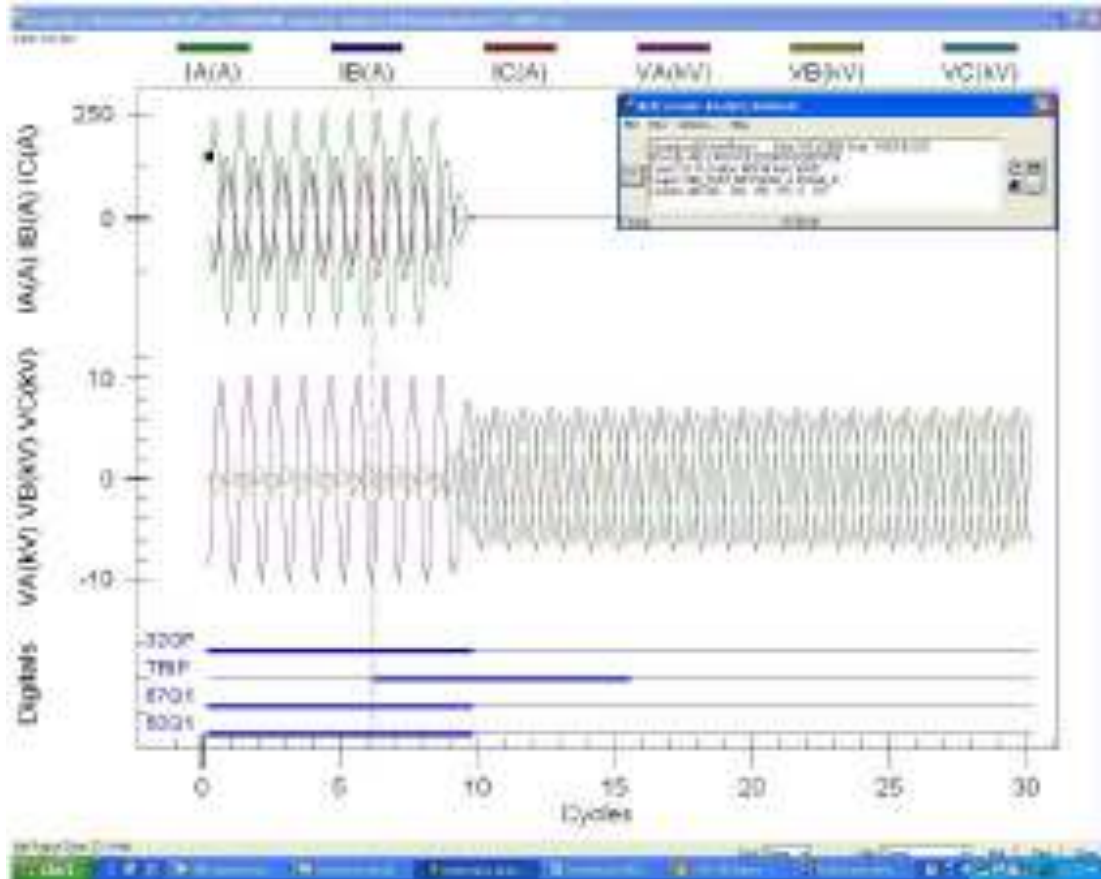


Figure 1

**Setting related to 67Q (directional 50Q):**

50Q1P = 0.57A (3I2 threshold, 10% of full load bank current)

67Q1D = 25cyc (415ms)

Directional Element:

E32=Y

Z1Ang = 70deg, Z0ANG= 70deg

Z2F=-0.1 ohm, Z2R= +0.1ohm, 50FP= 0.25A, 50RP=0.25A, a2 =0.1, K2 =0.2, ORDER=Q

**Note:** In fig.2, fist phasor diagram shows phase components, second phasor diagram shows sequence components and the table shows all the quantities magnitude in primary (A, KV) and angle referred to positive sequence voltage. Note that in fig.2 sequence components are referred to phase 'A'.

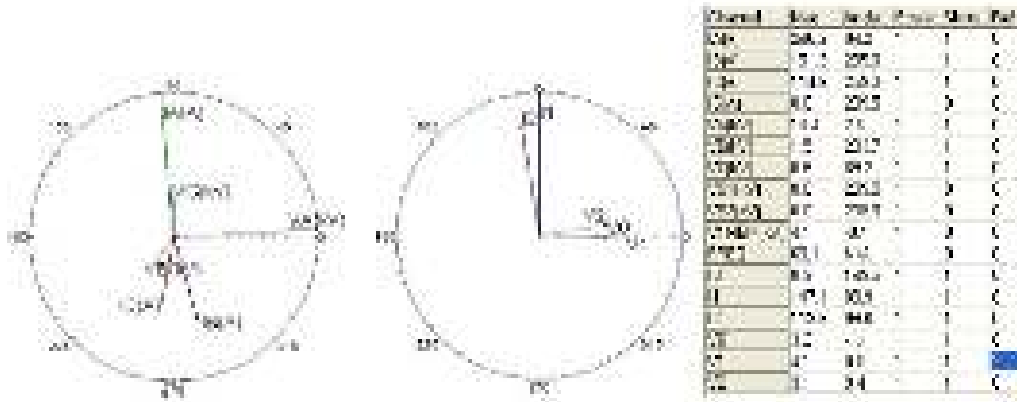


Fig 2



Fig 3

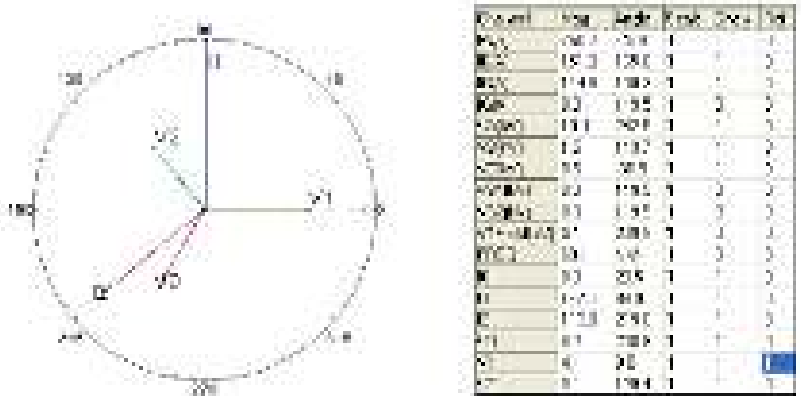


Fig 4

Note that in fig.3 sequence components are referred to phase 'B'.  
 Note that in fig.4 sequence components are referred to phase 'C'.

**Observation:**

From the above Event report the following shall be noted.

1. Bus voltages VB, VC voltages (1.5KV, 0.5KV) are collapsed. There is zero sequence voltage measured at bus, at the same time there is no zero sequence current in the capacitor feeder (YY ungrounded bank). So the zero sequence voltage is due to zero sequence current in the faulted feeder. From the observation the feeder could had a fault B-C-G.
2. Phase B, C capacitor bank current is not contribution to fault current, they are the return current of the capacitor load current on unfaulted phase 'A'.
3. The measured z2 by the relay is following from fig.2.

$$V2 = 3.1 \angle 9.4 \text{ KV (primary)} = 26.95 \angle 9.4 \text{ V (secondary)}$$

$$I2 = 113.8 \angle 99.6 \text{ A (primary)} = 0.71 \angle 99.6 \text{ A (secondary)}$$

$$Z1\text{ANG setting} = 70\text{deg}$$

$$\text{Relay measured } z2 = (V2/I2) * \cos(\angle V1 - \angle I2 - \angle Z1\text{ANG}) \text{ ----- eq (A)}$$

$$= (26.95/0.71) * \cos(9.4 - 99.6 - 70)$$

$$= \sim -35.66 \text{ ohms}$$

The forward threshold calculated by the relay at given V2, I2,

$$z2\text{FTH} = 0.75 * z2\text{F} - 0.25 * (V2/I2)$$

$$= 0.75 * (-0.1) - 0.25 * (26.95/0.71)$$

$$= -0.956 \text{ ohms}$$

When z2 is less than Z2FTH = -0.956ohm, the relay declares **forward** fault.



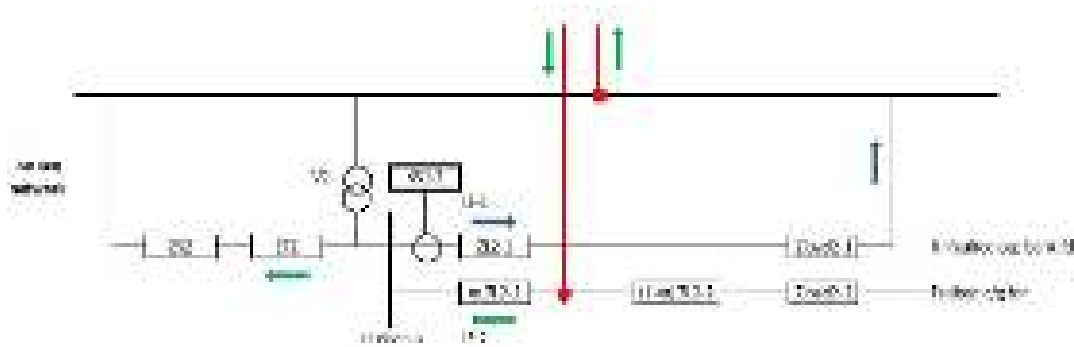


Fig.6  
Phase to phase Reverse fault

In general, the negative sequence quantities are injected to negative sequence network from the fault point. This quantity is available only during unbalance faults (P-P, P-G, and P-P-G).

**1. PHASE FAULT (REVERSE):**

In fig.6, we consider a phase to phase fault on adjacent feeder to capacitor bank feeder. There is negative sequence current I2-1 flows on capacitor feeder (actually injected by faulted feeder, it is part of I2-2), which is measured by 451-

2. At the same time the relay measured negative sequence voltage V2 related I2-1 is the voltage drop across ZL2-1 and Zload2-1.

So,  $V2 = I2-1 \times (ZL2-1 + Zload2-1)$

ZL2-1 is much smaller than Zload2-1. And Zload2-1 is capacitor reactance, which is  $-jXc$  ( note that the  $-ve$  sign because of capacitive reactance).

$z2$  measured by relay =  $V2/I2-1 = + Zload2-1 + (-jXc) = -jXc$  ----- eq1

**As conclusion, when there is a reverse phase fault 451- 2 directional element would see negative sequence impedance of capacitor bank in front of it, which is equal to  $-jXc$ .**

**2. PHASE FAULT (FORWARD):**

In fig.7, we consider a phase to phase fault on capacitor bank feeder. There is negative sequence current I2-1 flows on capacitor feeder towards bus, which is measured by 451-2. Here the negative sequence current injected from capacitor bank feeder, out of this current I2-1, small part is flowing through adjacent unfaulted feeder (s), which is negligible compare to current flowing through source impedance. At this time the relay measured negative sequence voltage V2 related I2-1 is the voltage drop across ZS2 and ZT2.

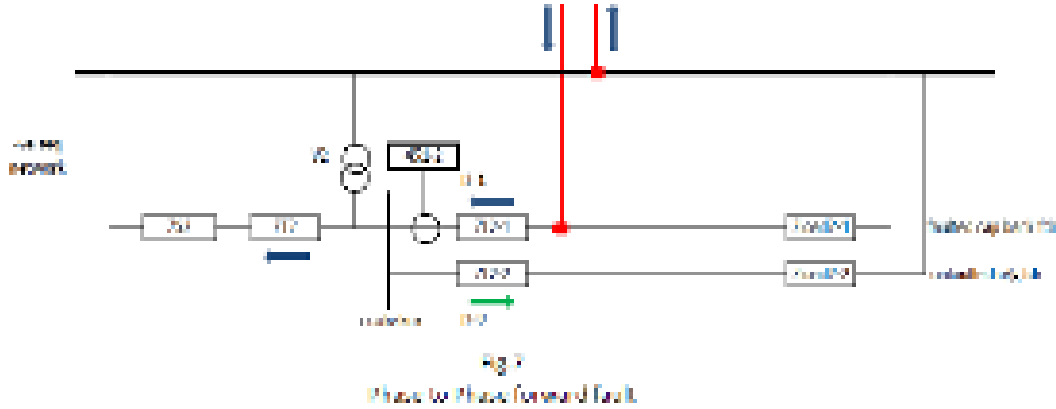
So,  $V2 = - (I2-1) \times (ZS2 + ZT2)$  · note:  $-ve$  sign because of reverse current flow.

ZS2 and ZT2, all together, it is negative sequence source impedance behind the 13.8KV bus, would be called as Z2source. This is an inductive reactance.

$z2$  measured by relay =  $V2/-(I2-1) = - Z2source = - (jXLs) = -jXLs$ ----- eq2

**As conclusion, when there is a forward phase fault 451-2 directional element would see negative value of negative sequence impedance of source behind the bus, which is equal to  $-jXLs$ .**

Note: The Phase-phase-ground also provide same quantities in addition to zero sequence. So, there is no need of discussion on that.



**3. GROUND FAULT (REVERSE):**

In fig.8, we consider a phase to ground fault on adjacent feeder to capacitor bank feeder. There is negative sequence current  $I2-1$  flows on capacitor feeder (actually injected by faulted feeder, it is part of  $I2-2$ ), which is measured by 451-

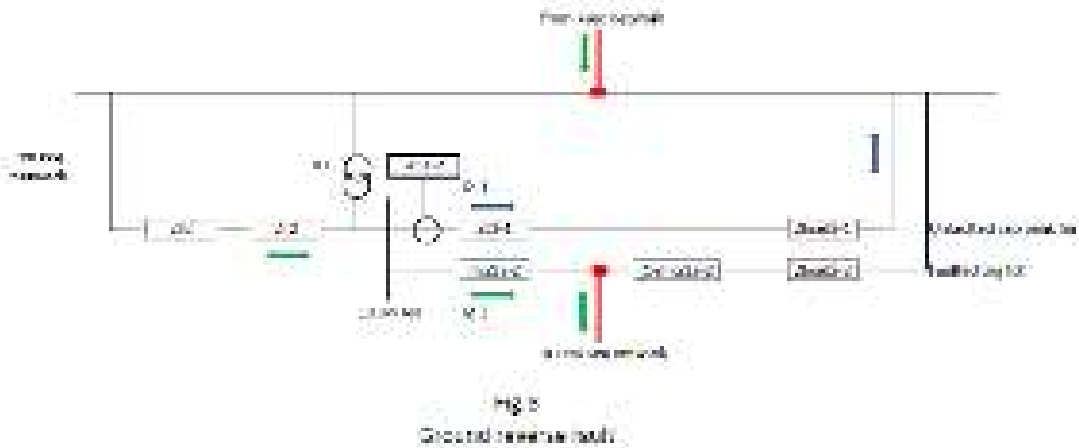
2. At the same time the relay measured negative sequence voltage  $V2$  related  $I2-1$  is the voltage drop across  $ZL2-1$  and  $Zload2-1$ .

So,  $V2 = I2-1 \times (ZL2-1 + Zload2-1)$

$ZL2-1$  is much smaller than  $Zload2-1$ . And  $Zload2-1$  is capacitor reactance, which is  $-jXc$  ( note that the  $-ve$  sign because of capacitive reactance).

$z2$  measured by relay =  $V2/I2-1 = + Zload2-1 = + (-jXc) = -jXc$  ----- eq3

**As conclusion, when there is a reverse ground fault 451- 2 directional element would see negative sequence impedance of capacitor bank in front of it, which is equal to  $-jXc$ . This is similar to case1.**



**4. GROUND FAULT (FORWARD):**

In fig.9, we consider a phase to ground fault on capacitor bank feeder. There is negative sequence current I2-1 flows on capacitor feeder outwards from bus, which is measured by 451-2. Here the negative sequence current injected from capacitor bank feeder, out of the current flowing through source impedance, small part is flowing through adjacent unfaulted feeder (s), which is negligible compare to current flowing through capacitor bank feeder I2-1. At this time the relay measured negative sequence voltage **-V2** related **I2-1** is the voltage drop across ZS2 and ZT2.

So, **-V2 = I2-1 x (ZS2 + ZT2)** > note: -ve sign of voltage is due to that the current flows from zero bus through source impedance, but the voltage drop V2 is being measured across source impedance by keeping zero bus is lower polarity.

ZS2 and ZT2, all together, it is negative sequence source impedance behind the 13.8KV bus, would be called as Z2source. This is an inductive reactance.

z2 measured by relay = (-V2)/I2-1 = - Z2source = - (jXLs) = -jXLs----- eq4

**As conclusion, when there is a forward phase fault 451- 2 directional element would see negative value of negative sequence impedance of source behind the bus, which is equal to -jXLs. This is similar to case2.**

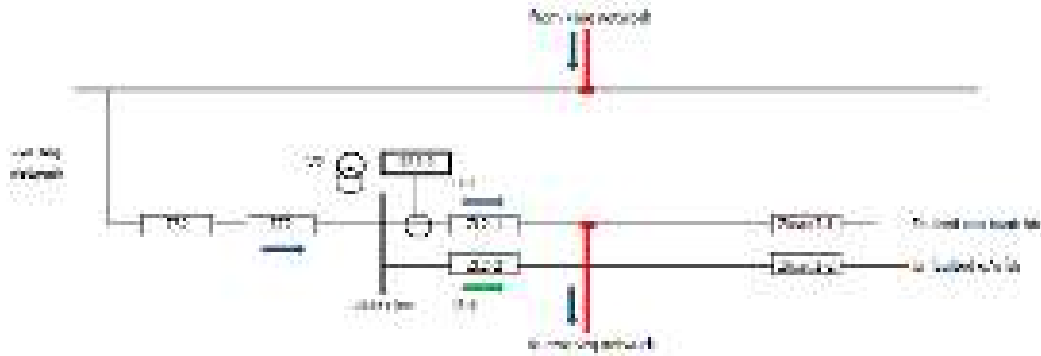


Fig.9  
Ground Forward fault

Now we put all above explanations into our system available data.

**System details:**

By considering 21KA maximum, 10KA minimum fault current at 13.8KV bus.  
 Minimum source impedance Z2source= 8000/21000 = 0.38 ohms @ 13.8KV  
 Maximum source impedance Z2source = 8000/10000 = 0.8 ohms @ 13.8KV

**Capacitor details:**

Rating: 7000KVAR, 13.8KV, 292A  
 CTR: 800/5A =160, VTR =13800/120V = 115  
 CTR/VTR = 160/115 =1.39

Impedance calculation:

Source impedance in secondary value =  $0.8 \times 1.39 = 1.1$  ohms

Capacitor bank impedance  $X_c = V/I_c = 13800/1.732 \times 292 = 27.28$  ohms

Capacitor bank impedance in secondary value =  $27.28 \times 1.39 = 37.92$  ohms

Impedance in complex form:

Source impedance =  $j1.1$  ohms

Capacitor bank impedance =  $-j37.92$  ohms

By considering Z1ANG setting in the relay is equal to 90 deg, Apply the same sequence quantities available at the actual fault incidence in our case with Eq (A).

$V_2 = 3.1 < 9.4$  KV (primary) =  $26.95 < 9.4$  V (secondary)

$I_2 = 113.8 < 99.6$  A (primary) =  $0.71 < 99.6$  A (secondary)

Z1ANG setting = 70deg

Relay measured  $z_2 = (V_2/I_2) * \cos (<V_1 - <I_2 - <Z1ANG)$  ----- eq (A)

=  $(26.95/0.71) * \cos (9.4 - 99.6 - 90)$

=  $\sim -37.96$  ohms (which is not thing but capacitor bank impedance)

**Conclusion:**

Since the directional element is applied on Capacitor bank feeder, there is a real challenge for the directional element to determine the fault direction. We should understand that the angle between negative sequence voltage  $V_2$  and current  $I_2$  seen by the relay would be same ( $<V_2 - <I_2 =$  around  $-90$  deg) during reverse or forward fault. But the type of fault could only be identified by negative sequence impedance seen by the relay.

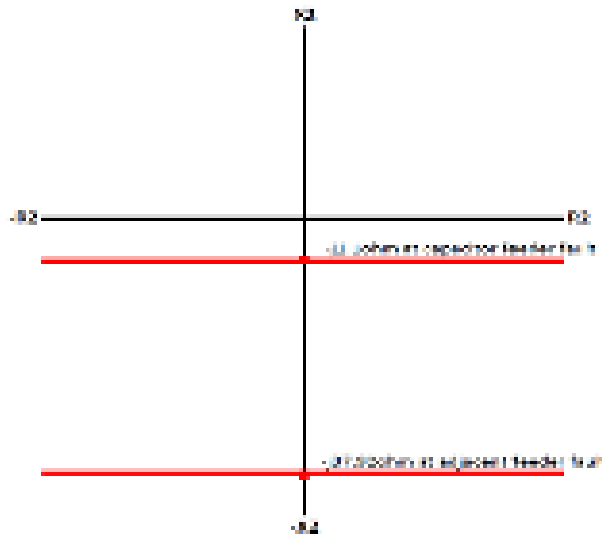


Fig.10 R2-I2 PLANE

With the present setting, and with available sequence quantities at relay during reverse fault, the relay would see capacitor bank impedance projected to Z1ANG = 70deg, as negative value, which lesser than  $z_{2F} = -0.1$ ohm and declares forward fault (which actually negative sequence current of capacitor load). So, The directional setting shall be recommended to change as below.

**SEL SOLUTION:****451-2 DIRECTIONAL ELEMENT REVISED SETTING:**

Z1ANG=90deg

Negative sequence directional Reverse reach  $z2R = -10.0\text{ohms}$ Negative sequence directional Forward reach  $z2F = -10.5\text{ohms}$ 

The relay directional characteristic shown as below in fig.11

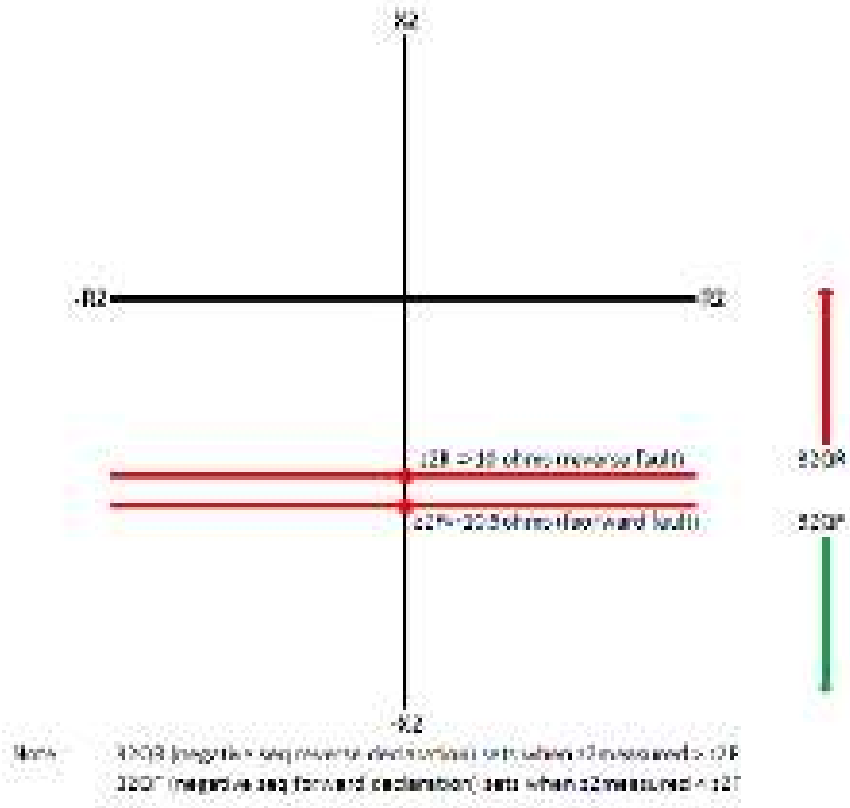


Fig.11

As per the negative sequence directional element characteristics, relay declares **FORWARD** (Relay word bit **32QF**) When measured  $z2$  lesser than  $z2F$  setting (-10.5ohms). And the relay declares **REVERSE** (Relay word bit **32QR**) when measured  $z2$  greater than  $z2R$  setting (-10ohms).

This is an important note that with this setting, relay declares **FORWARD** (Relay word bit **32QF**) during all the unbalanced faults on the system (adjacent feeders) and relay declares **REVERSE** (Relay word bit **32QR**) during all the unbalanced faults on the capacitor feeder. So, we need employ a reverse looking negative sequence over current to protect capacitor bank. We need to use 50Q3 instead of 50Q1 and 67Q3 instead of 67Q1.

In 451-2, when directional element is enabled, the directional output of Negative sequence over current set as below.

67Q1 (associated non directional 50Q1) → Forward fixed (enabled by 32QF)

67Q2 (associated non directional 50Q2) → Forward fixed (enabled by 32QF)

67Q3 (associated non directional 50Q3) → Forward/ reverse by setting (enabled by 32QF/32QR)

67Q4 (associated non directional 50Q4) → Forward/ reverse by setting (enabled by 32QF/32QR)

The relay's directional neg seq o/c setting snapshots are below

### Line Configuration

**Line Configuration Settings**

CTRW Current Transformer Ratio - Input W  
 Range = 1 to 50000

CTRS Current Transformer Ratio - Input S  
 Range = 1 to 50000

PTRY Potential Transformer Ratio - Input Y  
 Range = 1 to 10000

WYOPV FT Nominal Voltage (L-L) - Input Y (VDC, sec)  
 Range = 60 to 300

PTRE Potential Transformer Ratio - Input E  
 Range = 1 to 10000

WYOPV FT Nominal Voltage (L-L) - Input E (VDC, sec)  
 Range = 60 to 300

Z1PWS Pos./Seq. Line Impedance Magnitude (ohms, sec)  
 Range = 0.00 to 200.00

Z1AWE Pos./Seq. Line Impedance Angle (Degrees)  
 Range = 5.00 to 90.00

### Directional

[Basic Filtered Direct Use](#)

OPD Level 2 Directional Control  
 [Select L, N, R](#)

OPD Level 3 Directional Control  
 [Select L, N, R](#)

---

EOL Directional Control  
 [Select L, N, R, D](#)

[Directional Control / Derivat Settings](#)

OPDR Ground Dr. Derivat. Factor (Landing O.P.1)  
 [Select L, O, Y](#)

OPR Forward Dr. Derivat. Factor (asp, sec)  
 Range = 0.05 to 1.08

OPR Reverse Dr. Derivat. Factor (asp, sec)  
 Range = 0.05 to 1.08

OPF Forward Dr. Derivat. Factor (asp, sec)  
 Range = 0.08 to 0.80

OPR Reverse Dr. Derivat. Factor (asp, sec)  
 Range = 0.08 to 0.80

OPF Pos. Seq. Restrain Factor, 0.10  
 Range = 0.02 to 1.08

OPF Neg. Seq. Restrain Factor, 0.10  
 Range = 0.02 to 1.08

OPR Forward Dr. Derivat. Factor (asp, sec)  
 Range = 0.08 to 0.80

OPR Reverse Dr. Derivat. Factor (asp, sec)  
 Range = 0.08 to 0.80

OPF Pos. Seq. Restrain Factor, 0.10  
 Range = 0.02 to 1.08

OPD Auto-Rec. Voltage and Current Enable (DR Logit)

### Negative-Sequence Instantaneous Overcurrent

ESQ Neg.-Seq. Inst., Definite-Time O/C Elements

3  Select: N, 1-4

---

**Negative-Sequence Instantaneous Overcurrent 1**

58Q1P Level 1 Pickup (amps, sec)  
 Range = 0.25 to 100.00, OFF

67Q1D Level 1 Time Delay (cycles in steps of 0.125)  
 Range = 0.000 to 16800.800

67Q1TC Level 1 Torque Control (SELogic)

---

**Negative-Sequence Instantaneous Overcurrent 2**

58Q2P Level 2 Pickup (amps, sec)  
 Range = 0.25 to 100.00, OFF

67Q2D Level 2 Time Delay (cycles in steps of 0.125)  
 Range = 0.000 to 16800.800

67Q2TC Level 2 Torque Control (SELogic)

---

**Negative-Sequence Instantaneous Overcurrent 3**

58Q3P Level 3 Pickup (amps, sec)  
 Range = 0.25 to 100.00, OFF

67Q3D Level 3 Time Delay (cycles in steps of 0.125)  
 Range = 0.000 to 16800.800

67Q3TC Level 3 Torque Control (SELogic)

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**Negative-Sequence Instantaneous Overcurrent 4**

58Q4P Level 4 Pickup (amps, sec)  
 Range = 0.25 to 100.00, OFF

67Q4D Level 4 Time Delay (cycles in steps of 0.125)  
 Range = 0.000 to 16800.800

67Q4TC Level 4 Torque Control (SELogic)

### Trip Logic

**Trip Logic**

TR\_TRIP (SELogic)

All the relevant output contacts shall be programmed for 67Q3T, instead of 67Q1T.

**Case by Case directional element setting:**

Capacitor bank	Cap bank current	Cap bank Imp	CTR	VTR	Cap Imp on Sec	Sys Imp Sec [3ohm pri]	Directional setting		
							ELANG	ADR	ADR
13.8KV, 700KVAR	292A	27.28 ohms	350 (500/5 A)	115 (13.8/ 0.138KV)	37.32 ohms	1.35 ohms	90deg	-10.5 ohms	10 ohms
8.8KV, 100KVAR	175A	505.7 ohms	50 (400/5 A)	400 (44/ 0.11KV)	28.48 ohms	0.266 ohms	90deg	-10.5 ohms	-10 ohms
13.8KV, 400KVAR	347A	27.28 ohms	500 (500/5 A)	115 (13.8/ 0.138KV)	189 ohms	0.59 ohms	90deg	50.5 ohms	-50 ohms
8.8KV, 100KVAR	175A	505.7 ohms	400 (400/5 A)	300 (33/ 0.11KV)	144.9 ohms	1.35 ohms	90deg	50.5 ohms	-50 ohms

Note: if there are any other cases, the setting shall be adjusted accordingly.

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