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Energy loss reduction through automatic capacitor bank: 110/15 kV, 50 MVA Breshna Kot Substation in Afghanistan

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Abstract
Due to the higher energy cost, increased world demand and growing concerns about climate protection, the easiest and most effective measure is to improve energy efficiency and reduction energy losses. Reactive power flow as a component of apparent power has a significant effect on power factor and energy efficiency. To achieve these objectives, the most effective approach which recently used to the electrical distribution networks is power factor correction (PFC). This paper presents the positive impact of power factor correction (PFC) and different solutions where (PFC) system can be installed on electrical networks will be discussed. And capacitor banks designed for power factor correction at (110/15 kV, 50 MVA Breshna Kot Substation in Afghanistan). By improving the power factor correction of the site from 0.836 to 0.95 the kVA capacity on the distribution transformer (supplying the factory) increases by 12% in Breshna Kot Substation. Analyses of the results prove that (PFC) significantly Raises the energy capacity and efficiency in Breshna Kot Substation, and reduces the electricity cost, energy losses, and causes the voltage to be more regulate and stable.

Keywords: automatic capacitor bank, energy efficiency, loss reduction, power factor improvement, case study of Afghanistan

1. Introduction
The required power supply is called the apparent power which depends on the active power (real electrical resistance power consumption in the circuit) and reactive power (imaginary inductive and capacitive power consumption in the circuit). The apparent power S (VA), which must be available and transmitted on the systems, is the vector addition of the active power P (W) and the reactive power Q (VAr) [1]. The ratio of these quantities P/S (W/VA) is called the power factor (PF) and is dependent on the type of machine in use. The more reactive power (VAr) required for magnetization of the internal inductive load, caused the greater the unusable power and increase in apparent power (VA) requirements within the electrical system [2]. Supplying reactive power requirement of the network components only by generation unit or substation transformer causes large system current and hence increases the power loss and voltage drop, such studies have been facilitated by the fact that, power factor correction through installation of capacitor banks upgrades the energy efficiency in the distribution system, and prevents power loss and decrease voltage drop [3]. Various investigations using different techniques, methods, and solutions are conducted to compensate for reactive power and reduce energy losses in a distribution system. In [4], a review of the most interesting solutions for single-phase and low power applications is carried out. A study is carried out in [5] to enhance power quality, minimize power loss and improve the voltage profile in the distribution system. Author of [6] proposed automatic switching of capacitors to changes circuit conditions such as voltage, the current flowing and power factor improvement. In [7], the author deal with shunt capacitor bank designing for power factor improvement considering overvoltage for substation installation. Likewise, several techniques and strategies for power factor correction have been applied, using several case studies under different conditions [8-15]. This paper presents the positive impact of power factor correction (PFC) and different solutions where (PFC) system can be installed on electrical networks will be discussed. And capacitor banks designed for power factor correction at (110/15 kV, 50 MVA Breshna Kot Substation in Kabul-Afghanistan) as a case study.

2. Principle and advantages of power factor improvement
Apparent power is the product of the average current and voltage. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power may be greater than the real power [16]. In electrical engineering, the power factor of an alternating current (AC) electrical power system is defined as the ratio of the active power absorbed by the load (W) to the apparent power flowing in the circuit (VA).

$$\text{Power Factor} = (\cos\theta) = \frac{\text{Active Power (W)}}{\text{Apparent Power (VA)}} \tag{1}$$

The cosine of the phase angle between the active power and apparent power represents the power factor (PF) of the load [7]. This is shown in Figure 1. A power factor of less than one indicates the voltage and current are not in phase, in an electric power system, a load with a low power factor draws more current than a load with a high-power factor for the same amount of useful power transferred. For the same active power according to higher reactive power, a higher apparent power must be applied and it causes the higher currents to increase the energy loss in the distribution system, and require larger wires and other equipment. Because of the costs of larger equipment and wasted energy, electrical utilities will usually charge a higher cost to industrial or commercial customers where there is a low power factor.

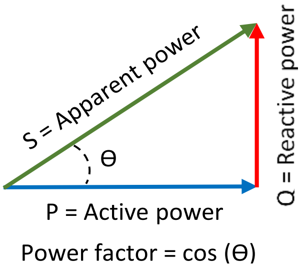

Fig 1: Power triangle and PF.

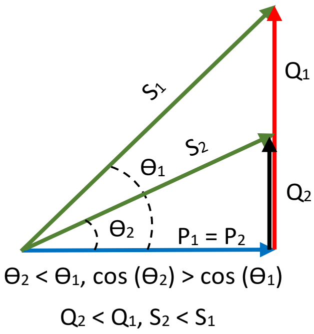

Fig. 2: PFC.

For these reasons, reactive energy must be produced as closely as possible to the loads, to prevent the unnecessary circulation of current in the network. This is what is known as "Power factor correction" is shown in Figure 2. The universal solution to produce reactive energy is to use capacitor banks, which is a mature and reliable technology with safe protection and service life. Figure 3 shows the power factor correction through the installation of the capacitor bank, all the reactive power (noted as Q_1) of the facility is supplied by the utility, so the apparent power (noted as S_1) is high because both the active and the reactive power have to be supplied by the utility. The added capacitor bank supplied reactive power (noted as Q_C) to the load, so the facility doesn't have to draw this reactive power from the utility, but rather only the difference ($Q_2=Q_1–Q_C$). Low demand for reactive power (noted as Q_2) translated into a low consumption of apparent power (noted as S_2) to the utility, thus releasing the capacity in the system.

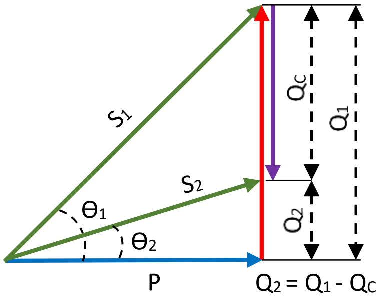

Fig 3: Power factor correction through Capacitor Bank.

2.1 Advantages of power factor correction

The advantages that can be achieved by applying the correct power factor correction are

- Reduction of power consumption due to improved energy efficiency. Reduced power consumption means less greenhouse gas emissions and fossil fuel depletion by power stations.
- Reduction of electricity bills.
- Extra kVA availability from the existing supply.
- Reduction of (I^2R) losses in transformers and distribution equipment.
- Reduction of voltage drops in long cables.
- Reduced electrical burden on cable and electrical components.

3. Methods of capacitor banks installation

We need to choose the optimum type, size, and the number of capacitors for the substation. There are four methods of capacitor installations [7]:

3.1 Method 1: Capacitor at Load

Installed a single capacitor at each sizeable motor and energize it whenever the motor is in operation. This method usually offers the greatest advantage of all in capacitors.

3.2 Method 2: Fixed Capacitor Bank

Installed a fixed quality of VAr electrically connected at one or more locations in the plant's electrical distribution systems, and energized at all times. This method is often used when the facility has few motors of any sizeable horsepower to which capacitors can economically be added.

3.3 Method 3: Automatic capacitor bank

It is installed at the motor control center at the service entrance. This bank will closely maintain a preselected value of the power factor. This is accomplished by taming a controller switch steps of VAr on, as off, as needed. Automatic switching ensures the exact amount of power factor correction, eliminates over capacitance and resulting in overvoltage.

3.4 Method 4: Combination of methods

Since no two electrical distribution systems are identical, each must be carefully analyzed to arrive at the most cost-effective solution, using are or more of the method.

4. PFC system locations

The actual location of capacitor banks depends on the size and location of the various loads. The distribution of the capacitors depends on load locations and operating conditions on each feeder to obtain the maximum benefits [1]. The basic types of power factor correction stated below should be distinguished:

- Individual correction (LV or MV)
- Group correction (LV or MV)
- Central correction (LV or MV)
- On high voltage network (HV)

5. Automatic capacitor bank installation

It is installed at the control center at the service entrance. This bank will closely maintain a pre-selected value of the power factor. This is accomplished by having a controller switch steps of VAr on, or off, as needed. This type of bank eliminates the concern of having too much VAr energized at light load periods [7]. Automatic switching also ensures the exact amount of power factor correction.

6. Load data and field data

6.1 Analysis of load data with power factor changes

Breshna Kot Substation is located in Kabul Afghanistan, which is connected 110 kV to the 15 kV, distribution network which applied two 25 MVA transformers from 110 kV step down to 15 kV, with radial lines system. Single Line Diagram is shown in Feg.7 in Appendices. Table 1. is to illustrate some variables obtained from power factor changes at 15 kV bus bar, Feeder 512 (Supplying the Jangalak Factory with low power factor) Capacitor rating added to improve power factor can be determined.

Table 1: 15 kV (Feeder 512) Log Sheet Data

Time	kV	A	MW	MVA	PF
1:00	14.7	106	2.7	3.2	0.8438
2:00	14.6	104.8	2.65	3.1	0.8548
3:00	14.8	101.4	2.6	3.11	0.836
4:00	14.8	99.48	2.55	2.9	0.8793
5:00	14.9	96.87	2.5	3	0.8333
6:00	14.9	98.81	2.55	3.02	0.8444
7:00	14.8	101.4	2.6	3.09	0.8414
8:00	14.8	106.5	2.73	3.2	0.8531
9:00	14.8	109.2	2.8	3.32	0.8434
10:00	14.7	113.9	2.9	3.46	0.8382
11:00	14.6	118.6	3	3.5	0.8571
12:00	14.6	122.6	3.1	3.71	0.8356
13:00	14.7	113.9	2.9	3.46	0.8382
14:00	14.6	118.6	3	3.56	0.8427
15:00	14.7	113.9	2.9	3.4	0.8529
16:00	14.7	102.1	2.6	3.1	0.8387
17:00	14.6	103.2	2.61	3.08	0.8474
18:00	14.6	126.5	3.2	3.8	0.8421
19:00	14.5	139.4	3.5	4.18	0.8373
20:00	14.5	144.1	3.62	4.33	0.836
21:00	14.5	139.4	3.5	4.2	0.8333
22:00	14.6	130.9	3.31	3.92	0.8444
23:00	14.7	114.3	2.91	3.4	0.8559
0:00	14.7	106	2.7	3.2	0.8438

6.2 Field Data of Breshna Kot Substation

The following data are obtained from Breshna Kot Substation to design the capacitor bank for power factor correction. It has shown in Table 2.

Table 2: The 15 kV Main 25 MVA Parameters

Parameters	Value	Units
Transformer rating	25	MVA
Transformer reactance	8	%
Voltage	15	kV
Present maximum load MW	3.62	MW
Present maximum MVA	4.33	MVA
Power factor (maximum load)	83.6	%
Desired power factor	95	%
Present minimum load MW	2.5	MW
Present minimum MVA	3	MVA
Power factor (minimum load)	83.33	%

7. Design calculation of capacitor banks size

Present load (maximum) = 3.62 MW

Present power factor (maximum load) = 83.6%

$$\text{Present MVA Demand} = \frac{\text{Present load}}{\text{Present power factor}} = \frac{3.62}{0.836} = 4.33\ \text{MVA} \quad (2)$$

If the power factor is raised to 95%

$$\text{Desired MVA Demand} = \frac{\text{Present load}}{\text{Desired power factor}} = \frac{3.62}{0.95} = 3.81\ \text{MVA} \quad (3)$$

The size of the capacitor required to accomplish this is determined from the MVAr at the two values of power factor as follows [2]:

$$\mathrm{Q} = \sqrt{\mathrm{S}^2 - \mathrm{P}^2} \quad \text{or} \quad \mathrm{MVAr} = \sqrt{\mathrm{MVA}^2 - \mathrm{MW}^2} \quad (4)$$

At 83.6% PF: $\mathrm{Q}_1(\mathrm{MVAr}) = \sqrt{4.33^2 - 3.62^2} = 2.376\ \mathrm{MVAr}$

At 95% PF: $\mathrm{Q}_2(\mathrm{MVAr}) = \sqrt{3.81^2 - 3.62^2} = 1.19\ \mathrm{MVAr}$

$$\text{Capacitor Rating} = Q_1 - Q_2$$

$$= 2.376 - 1.19 = 1.186\ \mathrm{MVAr} \quad (5)$$

Figure 4, the power triangle shows apparent power demand on a system before and after adding capacitors. By installing power capacitors and increasing power factor to 95%, apparent power is reduced from 4.33 MVA to 3.81 MVA (reduction of 12%). Theoretically, capacitors could provide 100% of needed reactive power. In practical usage, however, power factor correction to approximately 95% provides maximum benefit.

From Table 3 (Calculation table for capacitor selection) in Appendices [17].

Multiplying factor = 0.343

If the multiplying factor is in percentage, we use Eq. (6) as below:

$$\text{Multiplying factor} = \frac{\text{Value from the table (\%)}}{100} \quad (6)$$

$$\text{Capacitor Rating} = \text{Multiplying Factor} \times \text{MW Demand} \quad (7)$$

$$= 0.343 \times 3.62 = 1.2416 \approx 1.25\ \mathrm{MVAr}$$

Capacitor Rating = 1.25 MVAr

PF 95% is a good economic power factor for industrial purposes. In this paper, this power factor is corrected from 83.6%. Therefore, the installation of 1.25 MVAr capacitor bank is determined for achieving a power factor of 95% while providing the same productive power of 3.62 MW.

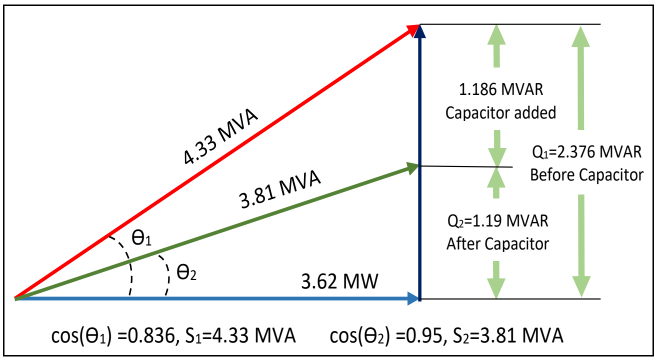

Fig 4: Required apparent power before and after adding capacitors.

8. Check calculation for after installation of capacitor banks

8.1 Power Factor Calculation

For Minimum Load Condition

$$\mathrm{Q}_1 = \mathrm{MVAr}_1 = \sqrt{\mathrm{MVA}^2 - \mathrm{MW}^2} = \sqrt{3^2 - 2.5^2} = 1.66\ \mathrm{MVAr}$$

$$\mathrm{Q}_2 = \mathrm{MVAr}_2 = \mathrm{MVAr}_1 - \text{Capcitor Rating} = 1.66 - 1.25 = 0.41\ \mathrm{MVAr}$$

$$\mathrm{P}_2 = \mathrm{MVA}_2 = \sqrt{\mathrm{MW}^2 + \mathrm{MVAr}_2^2} = \sqrt{2.5^2 + (0.41)^2} = 2.53\ \mathrm{MVA}$$

$$\mathrm{PF} = \frac{\mathrm{MW}}{\mathrm{MVA}} = \frac{2.5}{2.53} = 0.988$$

For Maximum Load Condition:

$$\mathrm{Q_1} = \mathrm{MVAr_1} = \sqrt{\mathrm{MVA^2} - \mathrm{MW^2}} = \sqrt{4.33^2 - 3.62^2} = 2.376\ \mathrm{MVAr}$$

$$\mathrm{Q_2} = \mathrm{MVAr_2} = \mathrm{MVAr_1} - \text{Capcitor Rating} = 2.376 - 1.25 = 1.126\ \mathrm{MVAr}$$

$$\mathrm{P_2} = \mathrm{MVA_2} = \sqrt{\mathrm{MW^2} + \mathrm{MVAr_2^2}} = \sqrt{3.62^2 + 1.126^2} = 3.791\ \mathrm{MVA}$$

$$\mathrm{PF} = \frac{\mathrm{MW}}{\mathrm{MVA}} = \frac{3.62}{3.791} = 0.955$$

8.2 Voltage Rise

The approximate voltage changes due to capacitors at a transformer secondary bus are determined by using the Eq. (8) [7]:

$$\%\ \text{Voltage Rise} = \frac{\text{Capacitor MVA}\times\%\ \text{Transformer Reactance}}{\text{Transformer MVA}} \qquad (8)$$

$$\%\ \text{Voltage Rise} = \frac{1.25\times 8}{25} = 0.4\%$$

Capacitor Rating = 1.25 MVAr
Transformer Reactance = 8%
Transformer MVA = 25 MVA

The voltage regulation of a system from no-load to full load is practically unaffected by the number of capacitors unless the capacitors are switched. However, the addition of capacitors can raise the voltage level. The voltage rises due to capacitors in most industrial plants with a modern power distribution system and a single transformation is rarely more than a few percents.

8.3 Line Current and Lower Losses

Line current Reduction: The percent line current reduction may be approximated from Eq. (9).

$$\%\ \text{Line Current Reduction} = 100 \times \left[1 - \frac{\text{Present PF}}{\text{Improved PF}}\right] \qquad (9)$$

$$= 100 \times \left[1 - \frac{0.836}{0.955}\right] = 12.461\ \%$$

Lower Losses: An estimate of the reduction of power losses can be made using the following Eq. (10).

$$\%\ \text{Loss Reduction} = 100 \times \left[1 - \left(\frac{\text{Present Power Factor}}{\text{Improved Power Factor}}\right)^2\right] \qquad (10)$$

$$= 100 \times \left[1 - \left(\frac{0.836}{0.955}\right)^2\right] = 23.37\%$$

There is a 23.37% reduction in power losses.

9. Result and Discussion

After installing 1.25 MVAr capacitor bank for the entire substation power factor improvement, the following results are obtained in Table 4. These results are the benefits of this installation. And Figure 5 shows the voltage profile before and after the installation 1.25 MVAr capacitor bank.

Table 4: Result Data after Power Factor Improvement

Load Data	15 kV Bus bar	Units
MV Demand	3.62	MV
Power Factor	95	%
Voltage Rise	0.4	%
Line Current Reduction	12.461	%
Power Losses Reduction	23.37	%

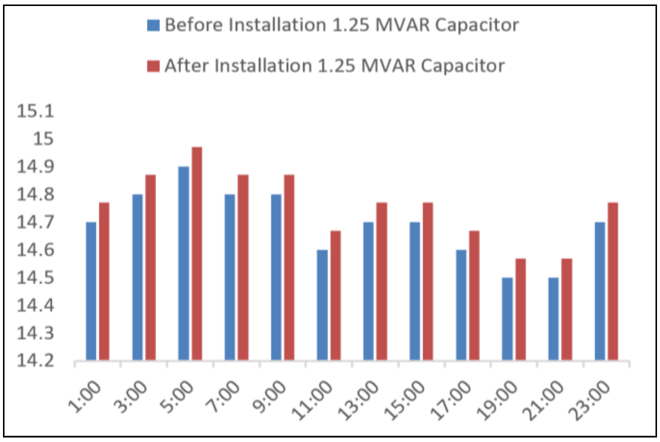

Fig 5: Voltage chart before and after installation 1.25 MVAr capacitor bank.

After the installation 1.25 MVAr capacitor bank at 15 kV bus bar, the lowest power factor 0.833 becomes 0.988 and the highest power factor 0.836 becomes 0.955. It has shown in Figure 6.

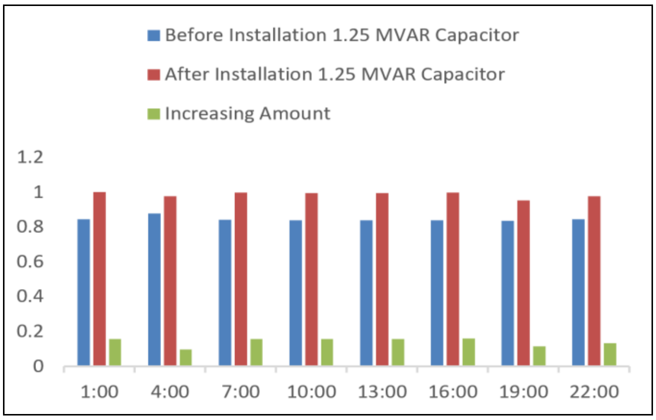

Fig 6: Power factor chart before and after installation 1.25 MVAr capacitor bank.

10. Conclusion

The study of reactive power flow, power loss and voltage quality problems of a real distribution system were made in this paper. Voltage regulation and voltage unbalance factors in the case study area are within the recommended limits. Percentage power losses at maximum power transfer for some branch circuits in the case study area are above the recommended value. Moreover, the power factor as a major parameter of energy quality is not in a statutory and acceptable condition. After installing the accurate value of the capacitor bank for the entire substation, the power factor improved to 0.955 from 0.833. And reactive power compensation at these branch circuits saves energy loss of 23.37 %.

Table 3: (Calculation table for capacitor selection)

INITIAL PF	**REQUIRED POWER FACTOR**										
	0.90	**0.91**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**	**0.97**	**0.98**	**0.99**	**UNITY**
0.65	0.685	0.713	0.740	0.774	0.806	0.840	0.877	0.918	0.967	1.026	1.169
0.66	0.654	0.682	0.709	0.743	0.775	0.809	0.846	0.887	0.935	0.995	1.108
0.67	0.624	0.652	0.679	0.713	0.745	0.779	0.816	0.857	0.905	0.965	1.108
0.68	0.595	0.623	0.650	0.684	0.716	0.750	0.786	0.827	0.875	0.935	1.078
0.69	0.565	0.593	0.620	0.654	0.686	0.720	0.757	0.798	0.845	0.906	1.049
0.70	0.536	0.564	0.591	0.625	0.657	0.691	0.728	0.769	0.817	0.877	1.020
0.71	0.508	0.536	0.563	0.597	0.629	0.663	0.700	0.741	0.789	0.840	0.992
0.72	0.480	0.507	0.534	0.568	0.600	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.452	0.480	0.507	0.541	0.573	0.607	0.644	0.685	0.733	0.793	0.936
0.74	0.425	0.453	0.480	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.398	0.426	0.453	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.370	0.399	0.426	0.460	0.492	0.526	0.563	0.604	0.652	0.712	0.855
0.77	0.345	0.373	0.400	0.434	0.466	0.500	0.537	0.578	0.626	0.686	0.829
0.78	0.318	0.347	0.374	0.408	0.440	0.473	0.510	0.551	0.599	0.659	0.802
0.79	0.292	0.320	0.347	0.381	0.413	0.447	0.484	0.525	0.573	0.633	0.776
0.80	0.226	0.294	0.321	0.355	0.387	0.421	0.458	0.499	0.547	0.607	0.750
0.81	0.240	0.268	0.295	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82	0.214	0.242	0.269	0.303	0.335	0.369	0.406	0.447	0.405	0.555	0.698
0.83	0.188	0.216	0.243	0.277	0.309	0.343	0.380	0.421	0.460	0.529	0.672
0.84	0.162	0.190	0.217	0.251	0.283	0.317	0.354	0.396	0.443	0.503	0.646
0.85	0.136	0.164	0.191	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86	0.109	0.140	0.167	0.198	0.230	0.264	0.301	0.342	0.390	0.450	0.593
0.87	0.083	0.114	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88	0.056	0.085	0.112	0.143	0.175	0.211	0.248	0.289	0.337	0.397	0.540
0.89	0.028	0.059	0.086	0.117	0.149	0.183	0.220	0.261	0.309	0.369	0.512
0.90	-	0.031	0.056	0.089	0.121	0.155	0.192	0.233	0.281	0.341	0.484
0.91	-	-	0.027	0.058	0.090	0.127	0.164	,0.205	0.253	0.313	0.456
0.92	-	-	-	0.031	0.063	0.097	0.134	0.175	0.223	0.283	0.428
0.93	-	-	-	-	0.032	0.066	0.108	0.144	0.192	0.252	0.395
0.94	-	-	-	-	-	0.034	0.071	0.112	0.160	0.220	0.363
0.95	-	-	-	-	-	-	0.037	0.078	0.126	0.186	0.329
0.96	-	-	-	-	-	-	-	0.041	0.089	0.149	0.292
0.97	-	-	-	-	-	-	-	-	0.048	0.108	0.251
0.98	-	-	-	-	-	-	-	-	-	0.060	0.203
0.99	-	-	-	-	-	-	-	-	-	-	0.143

Multiplying Factor for calculating the rating For Power Factor Improvement.

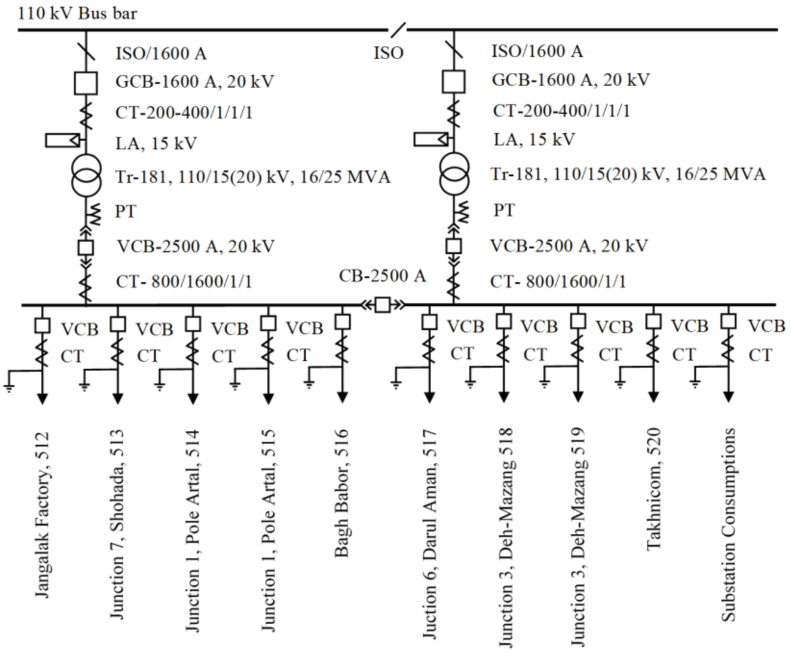

Fig 7: Single Line Diagram of 110 kV Breshna Kot Substation.

11. Acknowledgments

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