White Paper
WP917001EN
Effective November 2020

COOPER POWER
SERIES

Optimal allocation of a capacitor bank in the power distribution system

Heliton Vilibor,
Engineer,
CPFL

Joao Paulo Alves Moura,
Marketing,
Eaton

Rafael Mariano,
Application Engineering,
Eaton

Overview

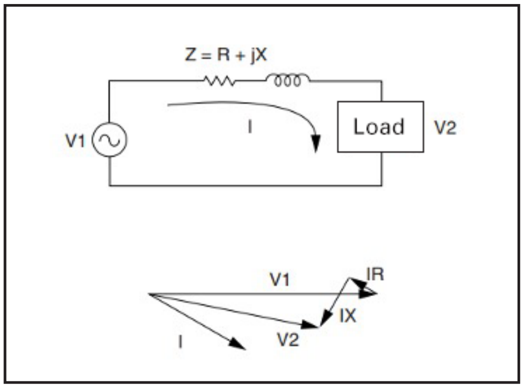
In this work, the optimal use of a capacitor bank in the energy distribution system was addressed with the aid of CYMDIST software. A comparison was made between the use of an automatic capacitor bank in the substation and in distribution using the feeder IEEE 34 Node Test Feeder. For the simulations, four different load levels were considered. It was observed that the use of automatic capacitor banks in distribution enhanced the electric power quality, which improved power factor and voltage profile, as well as reducing power losses and providing system capacity

I. Introduction

In the electrical power distribution system, there are essential components, such as transformers and motors, that consume a portion of reactive power which does not produce useful work. The incidence of the circulation of reactive power in the network is primarily due to industrial installations. Due to the inherent characteristics of their loads, the inductance of these loads causes a delay in current in relation to voltage [3]. Fig. 1 represents a simple circuit where a power source overcomes the reactive power consumed by the load.

Generally, the utility fulfills the role of this energy source. In this case, a portion of the current should flow in the feeder to feed reactive power. This portion of current is responsible for increasing the power losses that are due to the Joule effect since the current interacts with the resistance of the feeder. Power related to power losses is proportional to the square of the current, as can be seen by Eq. 1.

Figure 1: Voltage drop due to current flowing in the feeder



Source: Adapted from [3}

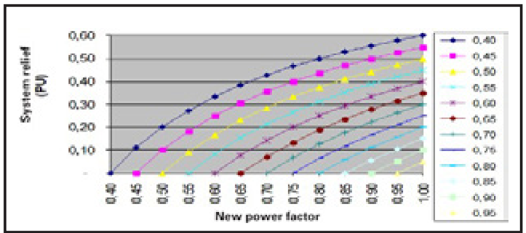
Equation 1

$$P = I^{2} \cdot R$$

The compensation of reactive power provides technical benefits from the electric power quality perspective, and can also bring economic benefits. There are ways to compensate reactive power, such as a super excited synchronous motor, active filter, single-phase reactive generator, or, in a more economic and often-used option, through the installation of a fixed and/or automatic bypass capacitor bank. In this document, the installation of a capacitor bank was considered for reactive power compensation.

From the power utility perspective, for example, the best option is to compensate reactive power locally, i.e., next to the load, since the magnitude of the current being dispatched by the substation is smaller, reducing the power losses, increasing the system utilization factor, postponing investments to increase the capacity of the feeder, system load relief depending on the power factor (PF) correction can be seen in Fig. 2.

Figure 2 – System relief depending on PF



Source: Eaton's Cooper Power Systems Division

Powering Business Worldwide

When compensating reactive power locally in a radial circuit, as shown in Fig. 1, the percentage reduction in current can be approximated by Eq. 2, shown in [3]. This equation applies to upstream current from the installation of the capacitor bank.

Equation 2

$$\%\Delta I = 100\left[1 - \left(\frac{PF\ old}{PF\ new}\right)\right]$$

$\%\Delta I$: Percentage reduction in current

PF_{old}: Power factor without correction;

PF_{new}: Corrected power factor.

When compensating reactive power locally, the percentage reduction in power losses is estimated by Eq. [3], as can be seen in [3].

Equation 3

$$\%\Delta P_{L\,losses} = 100 \cdot \left[1 - \left(\frac{PF_{old}}{PF_{new}}\right)^2\right]$$

$\%\Delta P_{L\,losses}$: Percentage reduction in power losses;

In [5], Eq. 4 is proposed, which represents the economic PF_e taking into account the increased system capacity. Fig. 3 represents the Eq. 4 chart.

Equation 4

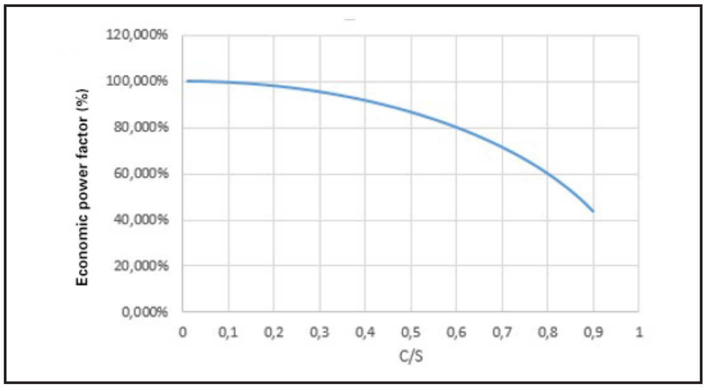
$$PF_e = \sqrt{1 - \left(\frac{C}{S}\right)^2}$$

PF_e: Economic power factor

C: Cost of capacitor bank per kVAR

S: System cost per kVA

Figure 3: Economic power factor



Source: Author

Capacitor banks can also be employed to assist in voltage regulation. Most voltage regulation problems in circuits are related to very high impedance in the system, i.e. long or poorly designed lines, or as mentioned by [3], the circuit may be weak for the installed load. In this scenario, the source voltage is adjusted to overcome the impedance of the circuit; however, loads may be removed from the system for some reason, which may cause sustained voltage surge events.

In [3], a few solutions are proposed to improve the voltage profile:

I. Add capacitor banks to reduce current I and thus decreasing voltage drop due to current interaction and line impedance
II. Add voltage regulators to adjust voltage
III. Increase conductor cross section to reduce impedance Z
IV. Replace transformers to reduce impedance Z
V. Add some dynamic generator of reactive power
VI. Add capacitors in series to cancel the inductive portion of Z impedance

In most cases, solutions I and II are the most employed. In this study, the influence of capacitor banks in the voltage profile is also verified. As can be seen in Fig. 5, the installation of a capacitor bank improves the upstream voltage profile from the installation.

Equation 5

$$\%\Delta V \ = 100\,\frac{kvar_{cap} \cdot Z_{tx}\,(\%)}{kVA_{tx}}$$

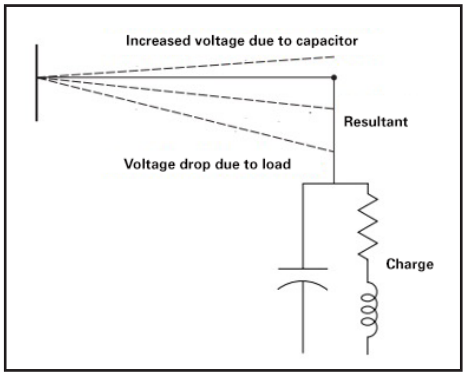
$\%\Delta V$: Percentage increase in voltage

$kvar_{cap}$: Rated power of the capacitor bank

$Z_{tx}\,(\%)$: Transformer impedance, %

kVA_{tx}: Rated power of the transformer

Figure 4: Influence of a capacitor bank in a radial circuit



Source: Adapted from [3]

Eq. 5 assumes that the transformer impedance predominantly represents the system impedance to the point of application of the capacitors. Second [3], when a capacitor bank is energized, a 2% to 3% increase in voltage is common.

Increased voltage when employing capacitor banks in distribution can be beneficial or detrimental from the power quality perspective. This occurs because they can contribute to increased voltage if loads are removed from the system causing a sustained voltage surge. The use of automatic capacitor banks can minimize this type of problem.

In brief, the advantages of using a capacitor bank in distribution, not in the substation, are as follows:

- Reduction of power losses
- Improvement of voltage level
- System relief
- Relief of transformers
- Suitable for Volt/VAR systems

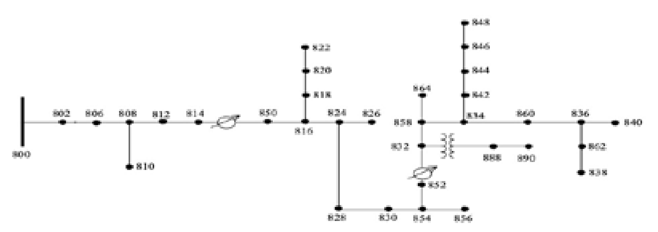
The analyses above were based on a circuit with radial topology and no branches, i.e., the information is more of a qualitative than quantitative nature.

As circuit complexity increases, tools are required to assist planners to assess the benefits of a capacitor bank installation in the distribution system, both in technical terms and from the perspective of economic viability.

From the power utility point of view, the optimum point for the capacitor bank installation is in distribution, and, in some cases, to determine the optimum point of action can be complicated, as feeders can have high complexity.

For the preparation of this work, the CYMDIST software was used to perform the power flow, and to find the optimal allocation of the capacitor banks, in accordance with some system restrictions. For the preparation of this document, simulations were implemented in the IEEE 34 Node Test Feeder, represented in Fig. 6.

Figure 6: Feeder IEEE 34 node test feeder



Source: Adapted from [2]

2 Parameters and results

Below, the parameters of the feeder used are presented, followed by the results of the simulations.

2.1 Feeder *IEEE 34 node test feeder*

The IEEE 34 Node Test Feeder has a radial topology, with a long feeder and load imbalance. The feeder parameters, available in [2], are presented below.

Table 1: Regulators

Regulator:	1		
Location:	814		
Connection:	3F - Yn		
Bandwidth:	2.0 V		
PT ratio:	120		
CT ratio:	100		
Compensator configuration:	F-A	F-B	F-C
R (%):	2.7	2.7	2.7
X (%):	1.6	1.6	1.6
Voltage level (V)	122	122	122
Regulator:	2		
Location:	852		
Connection:	3F - Yn		
Bandwidth:	2.0 V		
PT ratio:	120		
CT ratio:	100		
Compensator configuration:	F-A	F-B	F-C
R (%):	2.5	2.5	2.5
X (%):	1.5	1.5	1.5
Voltage level (V)	124	124	124

Source: Adapted fro [2]

Table 2: Load

Node A	**Node B**	F-1 kW	F-1 kVAR	F-2 kW	F-2 kVAR	F-3 kW	F-3 kVAR
802	**806**	0	0	30	15	25	14
808	**810**	0	0	16	8	0	0
818	**820**	34	17	0	0	0	0
820	**822**	135	70	0	0	0	0
816	**824**	0	0	5	2	0	0
824	**826**	0	0	40	20	0	0
824	**828**	0	0	0	0	4	2
828	**830**	7	3	0	0	0	0
854	**856**	0	0	4	2	0	0
832	**858**	7	3	2	1	6	3
858	**864**	2	1	0	0	0	0
858	**834**	4	2	15	8	13	7
834	**860**	16	8	20	10	110	55
860	**836**	30	15	10	6	42	22
836	**840**	18	9	22	11	0	0
862	**838**	0	0	28	14	0	0
842	**844**	9	5	0	0	0	0
844	**846**	0	0	25	12	20	11
846	**848**	0	0	23	11	0	0
Local loads							
860		20	16	20	16	20	16
840		9	7	9	7	9	7
844		135	105	135	105	135	105
848		20	16	20	16	20	16
890		150	75	150	75	150	75
830		10	5	10	5	25	10

Table 3: Transformer parameters

	kVA	**High kV**	**Low kV**	**R%**	**X%**
Substation	2500	69 D	24.9 Yn	1	8
XFM-1	500	24.9 Yn	4.16 Yn	1.9	4.08

Source: Adapted from [2]

Table 4: Line parameters

Node A	Node B	Length (ft)	Configuration
800	**802**	2580	300
802	**806**	1730	300
806	**808**	32230	300
808	**810**	5804	303
808	**812**	37500	300
812	**814**	29730	300
814	**850**	10	301
816	**818**	1710	302
816	**824**	10210	301
818	**820**	48150	302
820	**822**	13740	302
824	**826**	3030	303
824	**828**	840	301
828	**830**	20440	301
830	**854**	520	301
832	**858**	4900	301
832	**888**	0	XFM-1
834	**860**	2020	301
834	**842**	280	301
836	**840**	860	301
836	**862**	280	301
842	**844**	1350	301
844	**846**	3640	301
846	**848**	530	301
850	**816**	310	301
852	**832**	10	301
854	**856**	23330	303
854	**852**	36830	301
858	**864**	1620	303
858	**834**	5830	301
860	**836**	2680	301
862	**838**	4860	304
888	**890**	10560	300

Source: Adapted from [2]

Config 300

Z[ABC] Ω / 1000 ft

0,2532 + j0,2527	0,0979 + j0,1094	0,04034 + j0,09497
0,03979 + j0,1094	0,2507 + j0,257	0,03912 + j0,08695
0.04034 + j0,09497	0,03912 + j0,08595	0,2518 + j0,2551

Y[ABC] μ / 1000 ft

0 + j1,012	0 – j0,2895	0 – j0,1877
0 – j0,2895	0 + j0,0671	0 – j0,1169
0 – j0,1877	0 – j0,1169	0 – j0,9274

Config 301

Z[ABC] Ω / 1000 ft

0,3655 + j0,2673	0,04406 + j0,122	0,04467 + j0,1078
0,04406 + j0,122	0,3628 + j0,2705	0,04333 + j0,0992
0,04467 + j0,1078	0,04333 + j0,0992	0,364 + j0,2691

Y[ABC] μ / 1000 ft

0 + j0,9711	0 – j0,2715	0 – j0,1774
0 – j02715	0 + j0,9306	0 – j0,1119
0 – j0,1774	0 – j0,1119	0 - j0,8947

Config 302

Z[ABC] Ω / 1000 ft

0,5302 + j0,2813	0	0
0	0	0
0	0	0

Y[ABC] μ / 1000 ft

0 + j0,8002	0	0
0	0	0
0	0	0

Config 303

Z[ABC] Ω / 1000 ft

0	0	0
0	0,5302	0
0	0	0

Y[ABC] μ / 1000 ft

0	0	0
0	0 + j0,8002	0
0	0	0

Config 304

Z[ABC] Ω / 1000 ft

0	0	0
0	0	0
0	0	0,5302 + j0,2813

Y[ABC] μ / 1000 ft

0	0	0
0	0	0
0	0	0 + j0,8002

Source: Adapted from [2]

2.2 Simulations

For the purpose of this study, three simulations were performed using the *CYMDIST* software.

I. Without a capacitor bank;

II. Using a capacitor bank in the substation;

III. Using a capacitor bank using the CYMDIST *software Capacitor Placement* module.

Originally, the feeder *IEEE 34 Node Test Feeder* features two capacitor banks at nodes 844 and 848, totaling 750 kVAR. They were removed for the simulations performed in this document. The voltage at the source is adjusted at 1.05 pu to prevent voltages from being breached, as the feeder is quite long.

For the analysis of power losses, power flows were performed considering the load levels represented in Table 5. In addition, in Table 5 the load time in the year corresponding to each load level was considered.

Table 5: Transformer parameters

Levels	Feeder load [%]	Loading time [% in year]
1	P = 100% Q = 100%	20%
2	P = 80% Q = 80%	30%
3	P = 60% Q=60%	30%
4	P = 40% Q = 40%	20%

Source: Author

Table 6 represents the rated load installed. Analysis of results were performed in four sections, considering the power flow, magnitude of the current being dispatched by the substation, power losses and the voltage profile.

Table 6: Rated load installed

	kW	kVAR	kVA	PF (%)
Rated load installed	1769.00	1044.00	2054.09	86.12

Source: Author

Table 7: Power flow without a capacitor bank in the substation

	kW	kVAR	kVA	PF (%)
Level 1 – P = 100% and Q = 100%				
Substation	2103.72	1129.69	2387.85	88.1
Load	1750.69	1041.16	2036.89	85.95
Capacitor bank	0	0	0	0
Line capacitance	0	-153.98	153.98	0
Losses in line	344.06	223.25	410.15	–
Losses in the transformer	8.97	19.25	21.24	–
Total losses	**353.03**	**242.51**	**428.3**	**–**
Level 2 – P = 80% and Q = 80%				
Substation	1648.49	842.75	1851.42	89.04
Load	1427.37	846.56	1659.53	86.01
Capacitor bank	0	0	0	0
Line capacitance	0	-156.57	156.57	0
Losses in line	214.69	138.98	255.75	–
Losses in the transformer	6.42	13.79	15.21	–
Total losses	**221.12**	**152.77**	**268.76**	**–**
Level 3 – P = 60% and Q = 60%				
Substation	1189.66	557.22	1313.69	90.56
Load	1073.93	636.11	1248.19	86.04
Capacitor bank	0	0	0	0
Line capacitance	0	-158.99	158.99	0
Losses in line	112.12	72.34	133.43	–
Losses in the transformer	3.61	7.76	8.56	–
Total losses	**115.73**	**80.1**	**140.75**	**–**
Level 4 – P = 40% and Q = 40%				
Substation	767.6	296.8	822.98	93.27
Load	720.21	426.09	836.82	86.07
Capacitor bank	0	0	0	0
Line capacitance	0	-162.23	162.23	0
Losses in line	45.78	29.49	54.45	–
Losses in the transformer	1.6	3.45	3.8	–
Total losses	**47.39**	**32.93**	**57.7**	**–**

Source: Author

2.2.1 Power flow

I. Simulation without capacitor bank

Initially, the feeder power flow was performed, without a capacitor bank, for the load levels listed in Table 5. The data obtained is represented in Table 7.

Table 7 represents the summary of the power balance of the elements that make up the feeder. Where the power dispatched by the substation, PF and power losses for each load level are displayed.

The installation of the capacitor bank improved the PF of the substation, but there was no impact on power losses and voltage profile, as seen in the next sections.

For the voltage class greater than or equal to 69 kV, through REN 756/2016, the Agência Nacional de Energia Elétrica (Brazilian Electricity Regulatory Agency, ANEEL) establishes that PF at the point of connection with the transmitters must be above 0.95 inductive. In all the load levels, PF is below the threshold defined by the ANEEL regulation. Therefore, it is necessary to compensate reactive power.

II. Simulation – Using a capacitor bank in the substation

Therefore, the feeder power flow was performed with an automatic capacitor bank in the substation, with rated power of 900 kVAR and 14.4 kV, with two stages. The first stage was 300 kVAR and the second stage was 600 kVAR. The application of the 300 kVAR capacitor bank in substations is challenging due to low power, which will preclude the capacitor bank two-star connection, requiring single-star type connection, meaning more sophisticated and non-traditional protection, in addition to the disadvantage of cost and reliability.

From Table 8, it is noted that the active power dispatched by the substation is nearly the same as in the previous simulation. However, the reactive power is lower, since the capacitor bank installed starts to supply reactive power to the system, improving the PF of the substation. It is noted that the capacitor supplies reactive power above its nominal rating. This happens because the voltage at the installation point is 1.05 pu.

The capacitor bank operates in the first stage for levels 3 and 4, when the load is lower, and in the second stage when the feeder is in the load levels 1 and 2.

Table 8: Power flow capacitor bank in the substation

	kW	kVAR	kVA	PF (%)
Level 1 – P = 100% and Q = 100%				
Substation	2104.4	141.6	2109.15	99.77
Load	1752.17	1042.05	2038.62	85.95
Capacitor bank	0	-988.21	988.21	0
Line capacitance	0	-154.17	154.17	0
Losses in line	343.24	222.65	409.13	–
Losses in the transformer	8.98	19.28	21.27	–
Total losses	**352.22**	**241.93**	**427.3**	–
Level 2 – P = 80% and Q = 80%				
Substation	1648.88	-146.3	1655.36	-99.61
Load	1427.99	846.94	1660.27	86.01
Capacitor bank	0	-989.27	989.27	0
Line capacitance	0	-156.5	156.5	0
Losses in line	214.47	138.74	255.43	–
Losses in the transformer	6.42	13.79	15.21	–
Total losses	**220.89**	**152.53**	**268.43**	–
Level 3 – P = 60% and Q = 60%				
Substation	1189.71	227.31	1211.23	98.22
Load	1074.18	636.27	1248.48	86.04
Capacitor bank	0	-329.85	329.85	0
Line capacitance	0	-159.06	159.06	0
Losses in line	111.92	72.2	133.18	–
Losses in the transformer	3.61	7.76	8.56	–
Total losses	**115.53**	**79.95**	**140.49**	–
Level 4 – P = 40% and Q = 40%				
Substation	767.69	-33.39	768.42	-99.91
Load	720.37	426.19	837.01	86.07
Capacitor bank	0	-330.17	330.17	0
Line capacitance	0	-162.29	162.29	0
Losses in line	45.71	29.44	54.37	–
Losses in the transformer	1.6	3.45	3.8	–
Total losses	**47.32**	**32.88**	**57.62**	–

Source: Author

III. Using a capacitor bank in energy distribution

To assist with optimal location of capacitor banks, the CYME software Capacitor Placement module was used. In its execution, the strategy of reducing power losses has been adopted and established as a unit PF. Table 9 summarizes the philosophy adopted.

Table 9: Capacitor Placement module report

Capacitor Placement module report	
Objective	**Loss reduction**
Power factor	100%
Restrictions	
Minimum installation	100.0 kVAR/stage
Capacitor bank increment	100.0 kVAR/stage

Source: Author

When executing the capacitor placement module, the installation of three automatic capacitor banks was suggested by CYMDIST, as represented in Table 10, where CYMDIST suggests the location, power, contribution in voltage gain and electrical loss reduction of each Capacitor Bank when energized. A control strategy per VAR was adopted, monitoring the reactive power dispatched by the substation.

Table 10: CYMDIST – Suggested capacitor banks

	Capacitors (total kVAR)			
Section	**Fixed**	**Automatic**	**Reduction (kW total)**	**Voltage Gain (%)**
858-834	0.0	300.0	51.43	1.41
854-852	0.0	300.0	28.67	1.33
842-844	0.0	300.0	15.56	1.42
Total	0.0	900.0	95.66	

After the optimum allocation of the capacitor banks, power flows were performed for the load levels shown in Table 5. The data obtained is represented in Table 11.

From Table 11, it is noted that the active power that the substation dispatches is almost the same as in previous cases I and II. As in case II, capacitor banks are providing reactive power to the system, improving the substation PF.

Using capacitor banks in distribution, the current portion to supply reactive power no longer interacts with the impedance of the line, since it does not circulate throughout the feeder line, and the power losses are lower.

Table 11: Currents dispatched by the substation

Level	IA (A)	IB (A)	IC (A)
Currents without a capacitor bank			
1	61.3	51	46
2	46.8	40	36
3	32.8	28.6	25.8
4	20.2	18.2	16.2
Currents with a capacitor bank in the substation			
1	61.3	51	46.1
2	46.8	40	36
3	32.8	28.6	25.8
4	20.2	18.2	16.2
Currents with a capacitor bank in distribution			
1	51.4	44.1	40.7
2	40.3	35.3	32.1
3	29.9	26.2	23.7
4	18.4	17.1	15.4

Source: Author

2.2.2 Magnitude of the substation currents

Table 12 represents the magnitude of the substation currents of each load level for the simulations performed.

Table 12: Currents dispatched by the substation

	kW	kVAR	kVA	PF (%)
Level 1 – P = 100% and Q = 100%				
Substation	2041.96	182.14	2050.06	99.6
Load	1769.6	1050.25	2057.79	86
Capacitor bank	0	-904.68	904.68	0
Line capacitance	0	-156.93	156.93	0
Losses in line	262.32	171.95	313.66	–
Losses in the transformer	10.04	21.55	23.77	–
Total losses	**272.36**	**193.5**	**334.1**	–
Level 2 – P = 80% and Q = 80%				
Substation	1608.19	213.54	1622.31	99.13
Load	1435.41	851.58	1669	86
Capacitor bank	0	-601.59	601.59	0
Line capacitance	0	-159.05	159.05	0
Losses in line	166.36	108.81	198.79	–
Losses in the transformer	6.42	13.79	15.21	–
Total losses	**172.78**	**122.6**	**211.86**	–
Level 3 – P = 60% and Q = 60%				
Substation	1173.93	260.62	1202.51	97.62
Load	1076.15	637.45	1250.78	86.04
Capacitor bank	0	-285.63	285.63	0
Line capacitance	0	-160.18	160.18	0
Losses in line	94.17	61.23	112.33	–
Losses in the transformer	3.61	7.76	8.56	–
Total losses	**97.78**	**68.99**	**119.67**	–
Level 4 – P = 40% and Q = 40%				
Substation	768.04	-2.85	768.04	-100
Load	727.76	430.87	845.75	86.05
Capacitor bank	0	-298.66	298.66	0
Line capacitance	0	-163.68	163.68	0
Losses in line	38.67	25.17	46.14	–
Losses in the transformer	1.6	3.45	3.8	–
Total losses	**40.27**	**28.61**	**49.4**	–

Source: Author

It is noted that the currents of simulations I and II are almost the same. On the other hand, when using the capacitor banks in distribution, the current dispatched by the substation is lower, relieving the load in the system. Table 13 shows the percentage reduction in current in phase A. Operating at the rated load, the system relief (phase A) reaches 16.2%.

Table 13: Percentage reduction in IA

Level	With a capacitor bank in the substation [A]	With a capacitor bank in distribution [A]	Percentage reduction in IA [%]
1	61.3	51.4	16.2%
2	46.8	40.3	13.9%
3	32.8	29.9	8.8%
4	20.2	18.4	8.9%

Source: Author

2.2.3 Power losses

Analyzing power losses over one year, it is noted that the use of a capacitor bank in the substation does not contribute toward reducing power losses, as it can be seen in Table. 14. This is due to the fact that the current flowing in the feeder line is nearly the same as seen in the previous section, i.e., it still interacts with line impedance, causing the same power losses.

However, using the capacitor bank in distribution, the decrease in power losses is noted.

Table 14: Annual power losses

	kW	Loading in year [%]	MW-h/year
Without a capacitor bank			
Level 1	353.03	20%	618.51
Level 2	221.12	30%	581.10
Level 3	115.73	30%	304.14
Level 4	47.39	20%	83.03
		Total	**1586.78**
With a capacitor bank in the substation			
Level 1	352.22	20%	617.09
Level 2	220.89	30%	580.50
Level 3	115.53	30%	303.61
Level 4	47.32	20%	82.90
		Total	**1584.11**
With a capacitor bank in distribution			
Level 1	272.36	20%	477.17
Level 2	172.78	30%	454.07
Level 3	97.78	30%	256.97
Level 4	40.27	20%	70.55
		Total	**1258.76**
Comparison			
With a capacitor bank in the substation			1584.11
With a capacitor bank in distribution			1258.76
MW-h/year reduction			**325.35**
Percentage reduction			**20.54%**

Source: Author

Table 14 represents annual power losses considering the load levels established in Table 5. Comparing power losses in one year, due to the installation of capacitor banks, it was estimated that using them in distribution resulted in an annual loss reduction of 325.35 MW-h, representing a percentage reduction of 20.54%.

2.2.4 Voltage

Finally, the influence of installing capacitor banks in the voltage profile is reviewed. For the analysis of results, some strategic nodes were adopted. The simulations were performed considering that the feeder operates at rated load.

According to [4], voltage should be between 95% and 105% of rated voltage. In the tables below, voltages above 105% of rated voltage are highlighted in green, while voltages below 95% are highlighted in red.

Table 15: Voltage profile without a capacitor bank

Node	VA (p.u.)	VB (p.u.)	VC (p.u.)
Voltage without a capacitor bank			
800	1.05	1.05	1.05
808	1.004	1.022	1.021
812	0.957	0.995	0.991
814	0.919	0.973	0.967
824	0.999	0.998	0.998
828	0.998	0.997	0.997
830	0.975	0.976	0.976
854	0.975	0.975	0.975
852	0.936	0.937	0.937
888	1.027	1.017	1.018
890	0.948	0.946	0.941

Source: Author

Table 15 represents voltages in the nodes without the use of a capacitor bank. It is noted that voltage at nodes 814, 852 and 890 is below 95%. In this node, regulator 1 is used to compensate for the voltage in this segment.

Table 16 represents the voltage in the nodes with the use of a capacitor bank in the substation. The voltage profile is known to be similar to Table 15, i.e., the use of a capacitor bank in the substation does not contribute to improving the voltage profile.

Table 16: Voltage profile with a capacitor bank in the substation

Node	VA (p.u.)	VB (p.u.)	VC (p.u.)
Voltage using capacitor banks in the substation			
800	1.05	1.05	1.05
808	1.005	1.023	1.022
812	0.957	0.996	0.991
814	0.92	0.974	0.967
824	1	0.998	0.999
828	0.999	0.998	0.998
830	0.976	0.976	0.976
854	0.976	0.976	0.976
852	0.936	0.938	0.938
888	1.028	1.018	1.019
890	0.949	0.947	0.941

Source: Author

Table 17 represents voltage in the nodes with the use of a capacitor bank in distribution, with the aid of the CYMDIST software Capacitor Placement module. Using a capacitor bank in the optimum points, voltage was not breached, remaining between 95% and 105%.

Table 17: Voltage profile with a capacitor bank in distribution

Node	VA (p.u.)	VB (p.u.)	VC (p.u.)
Voltage using banks in distributionn			
800	1.05	1.05	1.05
808	1.038	1.043	1.043
812	1.025	1.036	1.035
814	1.015	1.03	1.029
824	1.017	1.013	1.019
828	1.017	1.013	1.019
830	1.01	1.007	1.012
854	1.01	1.006	1.012
852	0.998	0.995	1.001
888	1.043	1.046	1.046
890	1.01	1.016	1.013

Source: Author

Table 18 represents the percentage comparison of voltage gain by using capacitors at the optimum point. At node 814, the voltage gain reached 10.33%. Data obtained in Table 18 shows that the use of automatic capacitor banks in distribution contributes to improve the voltage profile.

Table 18: Percentage comparison of voltage gain

Node	Case II	Case III	% Voltage gain
Percentage comparison of voltage gain			
800	1.05	1.05	0.00%
808	1.005	1.038	3.28%
812	0.957	1.025	7.11%
814	0.92	1.015	10.33%
824	1	1.017	1.70%
828	0.999	1.017	1.80%
830	0.976	1.01	3.48%
854	0.976	1.01	3.48%
852	0.936	0.998	6.62%
888	1.028	1.043	1.46%
890	0.949	1.01	6.43%

Source: Author

Conclusion

Through the study performed, it was possible to understand that the use of an automatic capacitor bank in distribution is the optimal application of a capacitor bank in the energy distribution system, taking into consideration its positive impacts on the system power quality.

Through the data obtained, it was possible to verify that the installation of capacitor banks in distribution reduced the magnitude of the current at feeder phase A by 16.2%, i.e., providing relief to the system, allowing the utility to postpone investments to increase the system capacity.

In addition, it has been verified that the installation of capacitor banks in distribution can positively impact the voltage profile, which can be observed in the simulations performed, where there was no voltage violation when installing capacitor banks in distribution. As shown in Table 17, the voltage gain at node 814 was 10.33%.

Regarding power losses, considering the load profile of Table 5, for the feeder studied, it was verified that, within one year, the installation of capacitor banks in distribution provided a reduction of 20.54% in power losses.

Therefore, the use of automatic capacitor banks in distribution can provide technical and economic benefits for energy utilities.

If you have any questions or need additional information on the application of reclosers and circuit breakers, contact your local Eaton Cooper Power series product representative.

Sources

1. [1] RESOLUÇÃO NORMATIVA N° 756 (NORMATIVE RESOLUTION N° 756), DATED DECEMBER 16, 2016.Agência Nacional De Energia Elétrica (Brazilian Electricity Regulatory Agency, ANEEL) –ANEEL, 2016.
2. IEEE 34 NODE TEST FEEDER. Distribution System Analysis Subcommittee
3 DUGAN, Roger C.; MCGRANAGHAN, Mark F.; BEATY, H. Wayne. Electrical power systems quality. New York, NY: McGraw-Hill,| c1996, 1996
4 DE DISTRIBUIÇÃO, Procedimentos (Distribution Procedures). Módulo 8–qualidade da energia elétrica (Module 8 - electric power quality). Agência Nacional de Energia Elétrica–ANEEL, 2010.
5 IEEE 1036 – 2010 – "IEEE Guide for the Application of Shunt Power Capacitors", IEEE 1036, pp 1-97, 2010.

About Eaton

Eaton's mission is to improve the quality of life and the environment through the use of power management technologies and services. We provide sustainable solutions that help our customers effectively manage electrical, hydraulic, and mechanical power—more safely, more efficiently, and more reliably. Eaton's 2019 revenues were $21.4 billion, and we sell products to customers in more than 175 countries. We have approximately 92,000 employees. For more information, visit Eaton.com.

Eaton
1000 Eaton Boulevard
Cleveland, OH 44122
United States
Eaton.com

Eaton's Power Systems Division
Rodovia Marechal Rondon Km 125
Porto Feliz, SP CEP 18540-000
Brazil
Eaton.com/cooperpowerseries

Powering Business Worldwide

Publication No. WP9170001EN / GG
November 2020