Optimal Capacitor Placement
Costs Benefits Due to Loss Reductions

In general, capacitor banks are installed in power systems for voltage support, power factor correction, reactive power control, loss reduction, system capacity increase, and billing charge reduction. This process involves determining capacitor size, location, control method, and connection type (Wye or Delta). The main effort usually is to determine capacitor size and location for voltage support and power factor correction. Secondary considerations are harmonics and switching transients.

Methods

There are different methods for determining capacitor size and location.

1. The most common method (intuitive) is based on rules of thumb followed by running multiple load flow studies for fine-tuning the size and location. This method may not yield the optimal solution and can be very time consuming and impractical for large systems.
2. The second method is to use the ETAP Optimal Power Flow (OPF) program to optimize the capacitor sizes based on the candidate locations selected by the engineer. This method requires per-selected locations, since OPF can optimize the capacitor sizes but not the locations.
3. The most effective method is to use the Optimal Capacitor Placement (OCP) program to optimize capacitor sizes and locations with cost considerations. OCP employs a genetic algorithm, which is an optimization technique based on the theory of nature selection. OCP uses the "Present Worth Method" to do alternative comparisons. It considers initial installation and operating costs, which includes maintenance, depreciation, and interest rate.

To demonstrate the difference in benefits between the intuitive (rules of thumb + load flow) and OCP methods, a very simple distribution system is used.

Example System

The example considered is as shown in Figure 1. It is assumed that:

1) Design loading occurs 55% of the time
2) Maximum loading (110% of design loading) occurs 25% of the time
3) Minimum loading (90% of design loading) occurs 20% of the time
4) Average energy cost is $0.07/kWh
5) Planning period is 10 years

6) 4.16 kV capacitors: 200 kvar banks
Purchase cost is $20/kvar
Installation cost is $1,200
Operating cost is $200/year

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7) 13.8 kV capacitors: 300 kvar banks
Purchase cost $25/kvar
Installation cost is $1,600
Operating cost is $300/year

The objective of this exercise is to make all system bus voltages greater than 98% and less than 102%, while minimizing total cost, by adding capacitors to any bus with a nominal voltage of either 4.16kV or 13.8kV. The initial load flow study (Figure 1) shows that the voltages at buses 3, 4, 5, 6, 8, 9 and 10 are less than 98% at maximum loading conditions. The total loss of the system during maximum loading conditions is 616.3 kW.

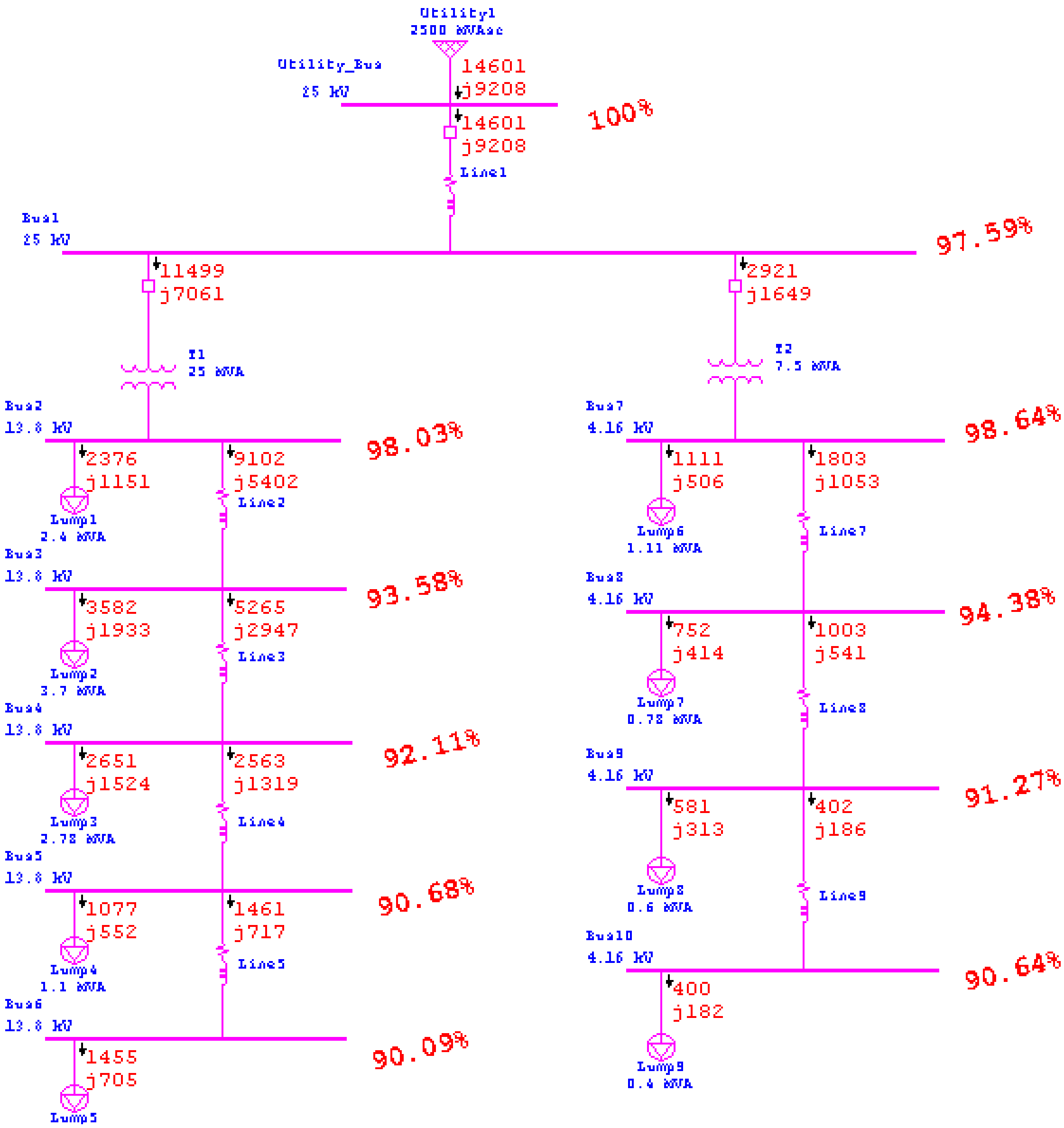

Figure 1: A Simple Distribution Power System with Power Flows Shown in kW + jkvar

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Comparison

Figure 2 shows OCP result in Crystal Report format. The results for both methods are summarized in Table 1 below.

Optimal Capacitor Placement Results

Candidate Buses					Capacitor Information					
		Operating Voltage						Cost ($)		
ID	Nominal kV	% Mag.	Angle	% PF	Rated kvar/Bank	Rated kV	# of Banks	Installation	Purchase	Oper. /Year
Bus2	13.800	101.000	-3.14	90.0						
Bus3	13.800	100.000	-5.55	-96.0	300.000	13.800	10	1600.00	75000.00	3000.00
Bus4	13.800	99.000	-6.33	-100.0	300.000	13.800	6	1600.00	45000.00	1800.00
Bus5	13.800	99.000	-7.12	89.0						
Bus6	13.800	99.000	-7.52	-89.0	300.000	13.800	5	1600.00	37500.00	1500.00
Bus7	4.160	101.000	-2.65	100.0	200.000	4.160	2	1200.00	8000.00	400.00
Bus8	4.160	100.000	-4.97	-97.0	200.000	4.160	3	1200.00	12000.00	600.00
Bus9	4.160	99.000	-6.67	98.0	200.000	4.160	1	1200.00	4000.00	200.00
Bus10	4.160	99.000	-7.12	-89.0	200.000	4.160	2	1200.00	8000.00	400.00

Figure 2: OCP Result in Crystal Report Format

Table 1: Capacitor Placement Results

		Number of Capacitor Banks Installed		
Bus ID	**Nominal kV**	**Original System**	**Intuitive Method**	**OCP Method**
Bus2	13.8	-	-	-
Bus3	13.8	-	1	3
Bus4	13.8	-	4	10
Bus5	13.8	-	6	1
Bus6	13.8	-	4	4
Bus7	4.16	-	-	-
Bus8	4.16	-	1	4
Bus9	4.16	-	1	3
Bus10	4.16	-	3	-
Total System Losses @ Max. Loading (kW)		616.3	449.1	431.7
Approx. Analysis Time (min.)			120	5

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The OCP method installed 3 more capacitor banks at 13.8 kV buses, and 2 more capacitor banks at 4.16 kV buses. Due to the additional capacitors, OCP results show $30,500 more one-time purchase cost, and $1,300 more operating cost each year; however, 17.4 kW of additional system loss reduction is achieved. Also, the total installation cost will be $1,200 less in the OCP method since no capacitors were installed on Bus10. Each year, savings due to the reduction in losses is $10,670 and the corresponding profit is $9,370. With respect to the intuitive approach, the total additional savings over the 10 year planning period is $64,400 and the cost break-even point is at 3.1 years.

Using the OCP generated Maximum, Minimum, and Average Loading reports, we can verify that the system voltage requirements have been achieved. The data from the three reports has been summarized in Table 2 below. It is shown in Table 2 that all bus voltages are above 98% and below 102%.

Table 2: Bus Voltage Summary

Bus ID	%V Min. Loading	%V Average Loading	%V Max. Loading
Bus1	99.32	99.07	98.81
Bus2	101.82	101.35	100.87
Bus3	100.88	99.97	99.02
Bus4	100.92	99.85	98.75
Bus5	100.64	99.43	98.19
Bus6	100.66	99.39	98.09
Bus7	101.88	101.48	101.06
Bus8	101.76	100.93	100.07
Bus9	101.20	100.06	98.89
Bus10	100.74	99.54	98.30

Conclusion

Even for a small system, the Optimal Capacitor Placement method yields considerable savings in both time to perform the analysis and system operating costs. Considering real power systems are much more complex, it becomes unrealistic for engineers to find a maximum cost solution by using the intuitive method. The ETAP OCP program is a powerful tool for finding the best capacitor locations and sizes, while meeting operating requirements and achieving minimum cost.

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