Journal of Power Technologies 101 (3) (2021) 144–153

Optimal Placement of Power Factor Correction Capacitors Considering Transient Switching Events and Load Uncertainty

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Abstract

Power factor correction projects are required to supply reactive power locally to power system loads. The main advantage for the consumer is reducing the electricity bill, which factors in reactive demand. Other advantages can also result from these projects, including voltage regulation at local buses, energy loss minimization in the transmission lines and increased system capacity to add additional load. These advantages will be maximized by optimally allocating the power factor correction devices to reduce the bill. With these great advantages, consideration needs to be given to several technical issues, including resonance and switching transient associated with capacitor installations. The latter is investigated in this paper in the context of a planning horizon of 20 years. The objective function is to implement the lowest cost option that meets both the energy loss minimization and voltage regulation requirements. A new factor is considered during placement: the effect of transient switching events when energizing and de-energizing capacitor banks.

Keywords: Power factor correction (PFC), shunt capacitors, energy loss minimization, transient switching

1 Introduction

The current tariff system in Saudi Arabia accounts for reactive power consumption of industrial loads only. Industrial customers are penalized for power factors of less than 0.85. This regulation is expected to change in the next few years. Industrial customers will be penalized for even higher power factors while residential customers are also expected to pay for their high reactive power consumption [1]. To address this issue, industrial consumers can install power factor correction capacitors at selected buses to improve the facility's overall power factor. In addition, utilities would rectify the power factor to increase the system MVA capacity of their residential systems. Such a system change should be planned carefully, considering all technical factors that would emerge over the planning horizon. The introduction of capacitors to the electrical system might result in parallel or series resonance points or might produce excessive damaging currents or voltages during switching events.

This problem has been extensively discussed in extant literature, with researchers considering different factors and optimization techniques [2]; [3]; [4]; [5]; [6]; [7]; [8]; [9]; [10]; [11]; [12]; [13]; [14]; [15]; [16]; [17]; [18]; [19]. A good starting point for the present investigation is the work reported in [2], where the authors conduct a thorough review of the techniques that are available for solving the capacitor placement problem. These techniques include analytical, numerical programming, heuristics, artificial intelligence and multidimensional methods. Six methods are simulated and compared in terms of voltage regulation, energy loss minimization and system capacity increase. Another group of authors [3] use the genetic algorithm (GA) optimization technique [4] to determine the optimal size and location of the capacitor banks in distribution networks. The cost function includes the installation, energy loss and capacity increase costs. The energy loss cost includes the losses resulting from the harmonic distortion in the systems. The genetic algorithm is used because of its capability to determine the global minimum of the cost function. In addition, the authors compared different methods in terms of computation time, reporting that the time required by the GA is four times that of the other methods, thus justifying the use of GA in planning solving techniques. [?? a longer computation time is better??]

In [5], the authors utilized a hybrid optimization algorithm they developed to solve this problem, considering the load growth and load duration curve (LDC). The cost function includes only the investment and energy loss costs. They further consider the possibility of having either fixed or switched capacitors according to the load variation at the bus. One more factor considered in [6] is the lifetime of the switched capacitors, which is calculated from the number of operations of capacitors resulting from load uncertainty. The lifetime of the capacitors affects the investment cost during the planning period. The optimal solution is developed using a genetic algorithm in search of the global minimum of the cost function. The cost function includes only the energy loss cost and the investment cost. Other works on this topic include practical examples and actual case studies of capacitor placement problems. For example, in [7], the researchers studied the effect on energy consumption in the system of replacing old conductors in the overhead lines and installing new PFC capacitors. Moreover, the authors of the work reported in [8] developed a systematic procedure for replacing capacitors on medium-voltage networks for three different distribution systems. The effect of capacitor replacement on harmonic distortion in the system is also considered.

The authors of [9] proposed a cuckoo search algorithm (CSA) method to identify the optimal capacitor location and size, demonstrating the method's effectiveness for three test systems. It uses a very simple approach that consists of first ranking the candidate buses according to their power loss indices and then running a CSA to find the optimal buses. The cost function contains the power factor penalty, installation cost and energy loss minimization cost [9]. Later work in this field considered uncertainty in demand and the impact of distribution generator units [10]. Another paper discussed the same problem using a new optimization method, named crow search algorithm [11]. The method yielded similar results to well-known methods including particle swarm optimization. A comprehensive work on optimal capacitor placement is presented in [12] where distorted networks are considered. Resonance constraints are introduced to meet the IEEE safe operation requirement. The cost function considered the same variable considered in [9].

The application of shunt capacitors provides many advantages for both distribution and transmission systems. These advantages include: correcting the system power factor by providing reactive power locally, reducing utility penalty charges due to low power factors, supporting system voltage during normal and contingency operation, reducing energy losses in transmission lines and underground cables, and finally increasing system capacity and thus allowing new loads to be installed along with physical expansion of the system.

However, although these benefits may seem tempting, engineers should be careful regarding the misapplication of capacitors, as their presence in the system can lead to less reliable operation. Capacitors can change the system's harmonic profile and thus lead to resonance events and meaningless trips, especially in the presence of a significant number of harmonic sources in the distribution system, such as uninterruptable power supplies (UPS) and adjustable frequency drives (AFD). Capacitor installation at certain buses can lead to other types of trips due to transient events during their energizing and de-energizing. Many authors discussed the problem of trips resulting from the introduced capacitors, ranging from small blown fuses to catastrophic failures. Such events can cause voltage dips that might lead to the dropping of some or all of the adjacent load [15]; [16]; [8].

The most common problems accompanying shunt capacitors in power systems are harmonics and transient switching. The first problem has been discussed thoroughly in planning studies, listing issues such as excessive harmonics, parallel resonances, series resonance, de-tuning filters and active filters. However, the same attention has not been given to transient switching events in the context of power system planning, because it is primarily discussed in conjunction with power system operation and power system failures. The switching overvoltage, switching inrush current and switching frequency are entirely dependent on the new capacitor size and the system impedance, as seen from the bus where the capacitor is to be located where the system impedance varies from one bus to another. Moreover, when a new capacitor is installed at a location where a capacitor already exists, the size of the existing capacitor must be considered so as to avoid switching events. The solution of the switching transient problems is also discussed in [16], which utilizes a series damping reactor along with the capacitor to limit transient switching failures.

Based on the above, the authors will consider the PFC capacitor switching transient issues in planning problems in order to fill this gap in the literature. The objective of this paper is to identify the optimal size and location of capacitors for a given power system network while accounting for the transient events' constraints over a planning period. The transient constraints considered are the inrush current and switching frequency. The cost function represents the investment cost, the energy reduction cost and the power factor penalty avoidance cost. The investment cost includes the installation of the capacitor and the series damping reactor if the transient switching limits are violated. The paper is organized as follows: Section 2 will discuss the required modeling to execute the problem. Section 3 will discuss methodology and formulation of the problem and Section 4 will present the results.

2 Capacitor Switching Transient and Load Modeling

2.1 Switching Transient Modelling

The fact that a capacitor's voltage does not change instantly might lead to many issues during capacitor switching on and off events. Such issues are certain to occur for a three-pole breaker without a control, and the resultant switching frequency can exceed the breaker limit, thereby leading to an outage at the load points or other types of trips. The resultant switching frequency primarily depends on the system impedance and capacitor size. The system impedance is determined by the load impedance as well as the impedances of the generator, transmission lines, and cables.

The transient switching frequency and inrush current have been previously modeled [16] for two cases. The first considers only one capacitor bank in a bus, and the second case pertains to back-to-back switching, in which one capacitor already exists on the same bus where the switching action occurs for another capacitor bank. Figure 1, inspired by [16], presents the power system model with a new capacitor installed. An example of a transient switching event is shown in Figure 2, where the voltage reaches almost 2 p.u. at the bus for which both the voltage and the current waveforms are affected by high switching frequency [17].

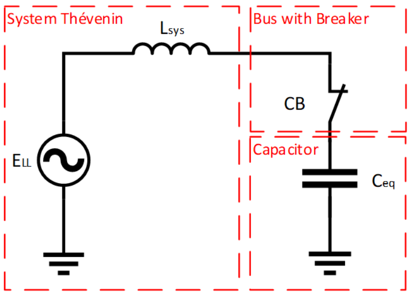

Figure 1: Capacitor Switching Model

When the switched capacitor bank is installed in a bus where no other capacitor exists, the transient frequency and inrush current are given by the expressions below:

$$i_{peak} = \frac{\sqrt{2}E_{LL}}{\sqrt{3}}\sqrt{\frac{C_{eq}}{L_{sys}}} \tag{1}$$

$$f = \frac{1}{2\pi\sqrt{\boldsymbol{C_{eq}L_{sys}}}} \tag{2}$$

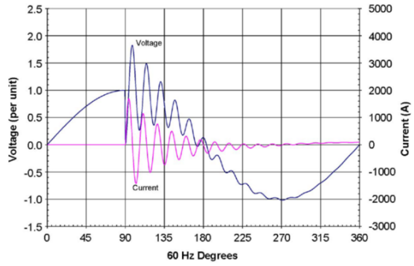

Figure 2: Capacitor Switching Effect in a Power System [17]

where L_{sys} is the system inductance seen from that bus and C_{eq} is the equivalent capacitance of the energized bank. The circuit breaker should be specified to withstand the inrush current and the transient frequency.

For back-to-back switching, the power system model and the voltage across the switched and the initial capacitor are depicted in Figures 3 and 4, respectively.

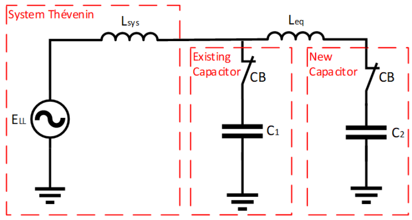

Figure 3: Back-to-Back Switching Model

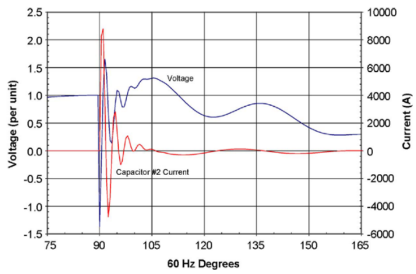

Figure 4: Voltage due to capacitors for back-to-back switching [17]

The transient frequency of the voltage and inrush current are given as:

$$i_{peak} = \frac{\sqrt{2}E_{LL}}{\sqrt{3}}\sqrt{\frac{C_1C_2}{L_{sys}\left(C_1+C_2\right)}} \tag{3}$$

$$f = \frac{1}{2\pi\sqrt{\frac{C_1C_2L_{eq}}{C_1+C_2}}} \tag{4}$$

Table 1: Load growth forecast using 2-step moving average

Year No.	Load Growth	Year No.	Load Growth
1	6.1100%	11	6.3231%
2	6.4300%	12	6.3234%
3	6.2700%	13	6.3233%
4	6.3500%	14	6.3234%
5	6.3100%	15	6.3233%
6	6.3300%	16	6.3233%
7	6.3200%	17	6.3233%
8	6.3250%	18	6.3233%
9	6.3225%	19	6.3233%
10	6.3238%	20	6.3233%

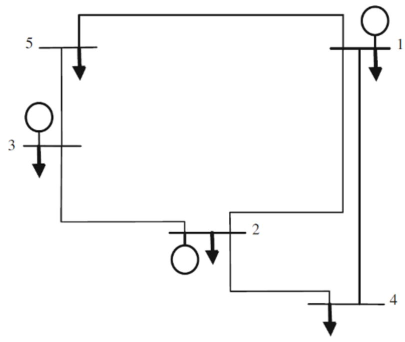

Figure 5: Garver's Test System [18]

In the case of back-to-back switching, L_{eq} can be approximated as the inductance between the two capacitor banks of interest. This inductance is usually very small in comparison with the system inductance, and the two inductances are in parallel. Thus, the equivalent inductance is approximately equal to the cable inductance. In [16], a measured inductance of 16 µH between two banks was used in the analysis. The same value is adopted in this work.

Figures 2 and 4 show that the voltage over the bus is slightly lower in the back-to-back switching case. However, it is also evident that the switching frequency and inrush current are much greater, which will be proven by the planning problem results.

2.2 Load Growth Modeling

The load growth over the planning horizon, which was chosen to be 20 years, was modeled by using the 2-step moving average. In Saudi Arabia, the growth factors for the past two years were 6.11% and 6.43% [1]. The load growth factor for the next 20 years is shown in Table 1.

3 Methodology and Case Studies

In this study, Garver's test system is used to explain the solution of this problem. The one-line diagram of the system is shown in Figure 5.

The data for the lines and the buses can be found in [18]. The above system can be approximated as a sub-transmission system feeding five distribution load points at each bus. A sub-transmission voltage of 69 kV was chosen for this problem. The load values presented in the appendix are affected by the load growth factor considering the average constraints. The uncertain load model is another factor affecting the demand when finding the probabilistic constraints.

Initially, the load flow was analyzed to determine the power factor and the energy losses at each load point. Next, the violated load points with no available generation at the bus were identified. In this test system, as bus 4 and bus 5 have no generation, they were included in the placement problem. The generators at the slack and PV buses can provide the reactive power locally, due to which the power factor can be corrected without the need for capacitors.

Then, the placement problem can be solved to find the optimal size and location of capacitors considering the transient frequency and inrush current constraints of the circuit breaker. Table 2 provides ANSI C37.0732 limits for the circuit breakers for different voltage levels.

In addition to the other constraints, the choice of the optimal solution is affected by the system impedance and capacitor impedance. The cost function is selected to be:

$$Minimize \quad C_{tot} = C_{ins} - C_{PFC} - C_{ELM} \qquad (5)$$

Such that:

$$\begin{aligned} &PF_N \geq 0.95 && \forall PQBusN \\ &0.95 \leq V_N \leq 1.05 && \forall \text{ bus } N \\ &f_x = 3360 \text{ Hz} && \forall \text{ bus } N \\ &\boldsymbol{i}_N = 16\boldsymbol{kA} && \forall \text{ bus } N \end{aligned} \qquad (6)$$

Where:

C_{in} is the installation cost,

C_{PFC} is the avoidance cost of low PF penalty, and

C_{ELM} is the energy loss minimization cost.

Table 2: Maximum operation limits of circuit breaker

Operating Voltage (kV)	Max. Current (kA)	Max. Frequency (Hz)
Vmax <15	15	2000
15 <Vmax <72	16	3360
120 <Vmax <145	16	4250
169 <Vmax <362	20	4250

Table 3: Economic data used in solving the problem

Variable	Value
Discount rate	5.0%
Capacitor (equipment + installation)	$87.5M/MVar
Inductor (equinment + installation)	$300/1 mH
Capacitor power cable	$3.2M/capacitor
Capacitor ar inductor kuidding	S675M/capacitor
Energy cost [23]	$0.0479/kWh
Reactive power cost [23]	$0.0133/kVarh

The C_{PFC} at each corrected bus can be calculated using the expression:

$$C_{PFC} = C_{kVARh} \times P \left(\tan\left(\cos^{-1} 0.95\right) - \tan\left(\cos^{-1} PF\right)\right) \times 8760 \tag{7}$$

To find the system inductance seen at any bus, the per unit impedance matrix is determined using the system Y-bus, the inductance being calculated as follows:

$$L = \frac{x_{pu} V_{base}^2}{2\pi f S_{base}} \tag{8}$$

Then, the capacitance of the added Mvar at each bus is obtained using

$$C = \frac{VAR}{2\pi f V^2} \tag{9}$$

The economic data utilized in solving this problem are real industry values, presented in Table 3.

Finally, the probability of having a switching event is calculated for comparison purposes—or even for inclusion in the total cost value—as a risk value. However, because the switching transient effect is not definite, this problem's total cost did not include this probability in the final cost; thus, it can be used for comparison or risk assessment studies. This probability value was determined by conducting a Monte Carlo simulation in hourly intervals for a 1-year period. The aim sensitivity analysis is not needed to rank the potential solutions because only two buses are available. A sensitivity analysis would be required when there are many starting points (initial population) available.

The analysis was conducted for year 1 and then repeated again for the following 20 years with different growth factors. The total cost pertaining to each year was identified by discounting the obtained amount by the predefined rate in order to obtain the net present value. The flow chart presented in Figure 6 shows that the analysis was modified to be conducted at 5-year intervals, instead of annually, to avoid having to make investments every year that would yield only a few additional kVARs.

4 Results & Analysis

As stated in the flow chart, an initial load flow analysis was conducted to find the buses violating the power factor limits. The load flow modeling was conducted in the MATLAB environment using the Newton-Raphson method [19]. As future load expansion/growth was considered, the results pertaining to the original system were modified to handle this load increment. The original system results are presented in Table 5 while the modified system results are shown in Table 7. The system was modified slightly to accommodate the increase in load in the following twenty years by dividing the impedance of each transmission line by 10.

According to the initial load flow results, bus 4 and bus 5 are in violation of the voltage constraints. In addition, all loads are in violation of the power factor limits, which was set at 0.95. The power factor for all buses is the same in this case study. Moreover, the line flow shows that the total line losses are 20.3979 MVA. However, the modified system has total line losses of 3.2678 MVA due to the lower impedance.

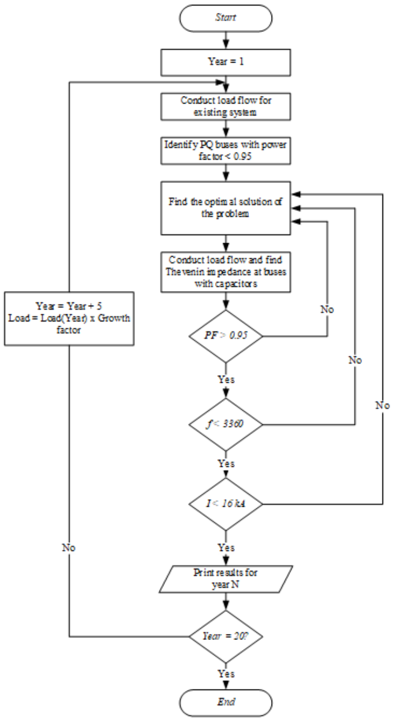

Figure 6: Summarized flow chart of the problem

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Thus, a power factor correction is required for the PQ buses. This paper will consider the use of PFC capacitors in load buses. Therefore, bus 4 and bus 5 are the points of interest for this investigation. In order to validate the proposed approach, three study cases will be examined: (i) without considering the switching transient constraints, (ii) only considering the inrush current constraints, and (iii) both inrush current and transient frequency limits are considered. Each case will be thoroughly explained with proven results.

4.1 Capacitor Placement with No Transient Constraints

In this case, the capacitor placement problem was solved using MATLAB by considering power factor and voltage constraints in Eq. (5) and excluding the switching transients limits. As stated before, the planning horizon is 20 years. However, to avoid making an investment each year due to yearly load growth, the planner would instead forecast the load every five years. Doing this would save on the investment amount that would otherwise be required for additional building and breakers every year. Hence, the results of the planning are given for 5-year intervals. Using the load growth table presented in the modeling section, the forecast load compared to that of the base year will be as illustrated in Table 9.

Table 5: Load flow results (original system)

Bus	1	2	3	4	5
V(pu)	1	1	1	0.899	0.941
Angle	0	-5.057	-2.111	-9.512	-4.912
Load (MW)	24	72	12	48	72
Load (Mvar)	11.6	34.8	5.8	23.2	34.8
Gen (MW)	117.9	50	65	0	0
Gen (Mvar)	39.01	67.94	23.03	0	0
Cap (Mvar)	0	0	0	0	0
pf	0.9	0.9	0.9	0.9	0.9
pf	Lagging	Lagging	Lagging	Lagging	Lagging

$2,965,000, but the energy loss minimization cost is $316,094 and the low power factor penalty avoidance is $9,829,003. These last two values pertain to the entire 5-year period including the discount rate.

The same analysis was repeated for the following years, and the final technical and economic results are presented in Table 13, which shows the locations and sizes of the added capacitors and the total project cost. The cumulative cost was $7,714,573, which is slightly higher than the total cost of the project for the first five years, because the more the planner invests in the power factor to achieve the desired value in the beginning, the less investment will come later. As the power factor was very low initially, the initial investment will be high. In subsequent years, the power factor was already good, although slightly below the target value, so the effects were less as well.

Because of this investment, four capacitor banks are installed at buses 4 and 5. This was due to cutting the investment cost to 5-year cycles. This case did not consider transient behavior or the system impedance, which will be considered in the next section.

4.2 Capacitor Placement with Inrush Current Transient Constraints

In this case, in each of the four investment years, the planner will check for current transient violations and adjust the problem accordingly.

For the first five years, the results were the same as for Case A with a capacitor bank at bus 4 equal to 6 Mvar and another capacitor bank at bus 5 equal to 8 Mvar. In addition, the inrush current resulting from the new capacitor banks was limited to 1030.5

Table 7: Load flow results (modified system with new Z = Z/10 for line capacity increase)

Bus	1	2	3	4	5
V(pu)	1	1	1	0.988	0.993
Angle	0	-0.639	-0.24	-1.182	-0.617
Load (MW)	32.64	97.92	16.32	65.28	97.92
Load (Mvar)	15.776	47.328	7.888	31.552	47.328
Gen (MW)	154.47	68	88.4	0	0
Gen (Mvar)	42.04	84.54	26.462	0	0
Cap (Mvar)	0	0	0	0	0
pf	0.9003	0.9003	0.9003	0.9003	0.9003
pf	Lagging	Lagging	Lagging	Lagging	Lagging

Table 9: Load growth multiplier at the end of year N

Year	Growth Factor
Year 5	1.36
Year 10	1.84
Year 15	2.51
Year 20	3.40

A and 1290.6 A, respectively. This low current value was mostly due to the high voltage application. No back-to-back event was considered here, because no capacitors are installed at these buses at this time.

For the following five years, the results were same as the previous case, but the inrush current limit due to back-to-back switching at bus 5 was nearly reached. The two inrush currents were approximately 9.73 kA at bus 4 and 15.5 kA at bus 5, which is very close to the limit of 16 kA.

However, for the next five years, a violation of the circuit breaker's current limit occurred, and the optimal solution could not be found, owing to the conflicting requirements of a higher power factor (higher capacitance) and a lower inrush current (lower capacitance). Consequently, the designer has the option to either upgrade the circuit breaker for a higher inrush current capability or pay the reactive power penalty because of system power factor violation regarding the desired limit. In this project, the authors decided to relax the requirement on the power factor to 0.94 and pay the penalty. The following tables illustrate this case.

It can be seen from Table 14 that the power factor

Table 11: Load Flow Results (Year 5)

Bus	1	2	3	4	5
V(pu)	1	1	1	0.99	0.994
Angle	0	-0.638	-0.239	-1.201	-0.628
Load (MW)	32.64	97.92	16.32	65.28	97.92
Load (Mvar)	15.776	47.328	7.888	31.552	47.328
Gen (MW)	154.47	68	88.4	0	0
Gen (Mvar)	42.04	84.54	26.462	0	0
Cap (Mvar)	0	0	0	6	8
pf	0.9003	0.9003	0.9003	0.9575	0.9522
pf	Lagging	Lagging	Lagging	Lagging	Lagging

requirement was violated to avoid having an inrush current higher than 16 kA experienced by the breaker every time the capacitor is energized, as 1.5 Mvar was installed at bus 4 and 2.1 Mvar was installed at bus 5.

For the next five years, a similar issue occurs, causing the planners to relax the power factor requirement again to 0.94 to find an optimal solution. In the calculations for the previous two 5-year cycles, the cost function was modified to include the power factor penalty. However, the positive effect of the cost avoidance of the power factor penalty still partially exists. Table 15 presents the final technical decision for this case along with the economic results.

The PFC cost becomes negative for the first time, owing to the high load at load points 4 and 5 (growth factor = 3.4) and the high penalty for the factor. As the cost avoidance is not high, owing to the small improvement in the power factor, it does not result in a positive return on the investment. In such a case, it might be better to consider upgrading the circuit breaker.

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Capacitor Placement with Inrush Current and Switching Frequency Transient Constraints

In this case, the same analysis was done as for the previous two cases. The switching frequency constraint given by Eq. (5) was considered here. The first five years of the planning period resulted in the same outcome as reached previously. The switching frequency is not an obstacle, because the maximum switching frequency at the two buses was calculated at 870.8 Hz and 818 Hz, both of which are well below the breaker's maximum capability.

However, for the subsequent planning years, when additional capacitor banks were added, back-to-back

Table 13: Case study A (no transient constraints)

Year	1		6		11		16	
Location	4	5	4	5	4	5	4	[HTML]F2F2F25
Size	6	8	1	3	2.6	3.2	3.4	5.1
Installation Cost ($)	-2,965,000		-1,422,884		-1,241,836		-1,122,237	
ELM Cost ($)	316,094		83,035		148,859		235,134	
PFC Cost ($)	9,829,003		1,032,763		1,591,388		1,230,253	
Total Cost ($)	7,180,097		307,085		498,411		343,150	
Cummul. Cost ($)	7,180,097		6,873,012		7,371,423		7,714,573	

Table 14: Load flow with violated PF requirement

Bus	1	2	3	4	5
V(pu)	1	1	1	0.98	0.988
Angle	0	-1.187	-0.451	-2.229	-1.166
Load (MW)	60.24	180.72	30.12	120.48	180.72
Load (Mvar)	29.11	87.35	14.56	58.23	87.35
Gen (MW)	286.25	125.5	163.15	0	0
Gen (Mvar)	69.833	152.4	43.263	0	0
Cap (Mvar)	0	0	0	8.5	13.1
pf	0.9003	0.9003	0.9003	0.9453	0.9467
pf	Lagging	Lagging	Lagging	Lagging	Lagging

Table 15: Case study B (transient inrush current constraint)

Year	1		6		11		16	
Location	4	5	4	5	4	5	4	5
Size	6	8	1	3	1.5	2.1	1.6	2.1
Installation Cost ($)	-2,965,000		-1,422,884		-851,420		-856,946	
ELM Cost ($)	316,094		83,035		71,825		107,022	
PFC Cost ($)	9,829,003		1,032,763		1,246,894		-1,933,977	
Total Cost ($)	7,180,097		307,085		467,299		-2,683,902	
Cummul. Cost ($)	7,180,097		6,873,012		7,340,312		4,656,410	

with sizes of 4.7 mH at bus 4 and 1.8 mH at bus 5 will limit the switching frequency. However, the investment cost will increase due to installing damping reactors. The same analysis was conducted for the following years and the results are summarized in Table 17.

It can be seen from the results that the net present value is lower when the transient frequency is considered.

Table 17: Case study C (transient inrush current and frequency constraint)

Year	1		6		11		16	
Location	4	5	4	5	4	5	4	5
Size Mvar	6	8	1	3	1.5	2.1	1.6	2.1
mH			4.7		3.2		3.2	
Installation Cost ($)	-2,965,000		-1,575,671		-954,557		-937,757	
ELM Cost ($)	316,094		83,035		71,825		107,022	
PFC Cost ($)	9,829,003		1,032,763		1,246,894		-1,933,977	
Total Cost ($)	7,180,097		459,872		364,162		-2,764,713	
Accum. Cost ($)	7,180,097		6,720,025		7,084,386		4,319,674	

5 Conclusion

This work discussed the effect of transient switching on the optimal capacitor placement planning decision. The results show that transient switching can have an effect in terms of both the inrush current and the transient frequency. The circuit breaker should handle these events when energizing a single capacitor on the bus or during back-to-back switching. The latter scenario has a greater effect on the planning problem, thus resulting in a higher inrush current and a higher transient frequency. In the first case, the authors opted to relax the power factor constraints to achieve a converged optimal plan. The cost of not meeting the power factor requirement was added to the planning cost. Another option would be to upgrade the breaker, which was not discussed in this case. In the second case, an additional investment was required to install the new capacitor bank in damping series reactors in order to reduce the transient switching frequency to an acceptable limit. The investment cost was added to the total cost, thus greatly reducing the income generated by this project.

5.1

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