OPTIMAL DESIGN OF CAPACITORS CONSIDERING TRANSIANT SWITCHING EVENTS AND RELIABILTIY CONSTRAINTS

BY

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Dedicated to

My Beloved Parents

It's impossible to thank you adequately for everything you've done, from loving me unconditionally to raising me in a stable household, where you instilled traditional values. I could not have asked for better parents or role-models.

My Beloved Brothers and Sister for covering my laziness and help my parents during my absence

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بسم الله الرحمن الرحيم

In the Name of Allah, the Most Beneficent, the Most Merciful.

> Praise belongs to Allah, the Lord of all the worlds (2) The All Merciful, the Very Merciful. (3) The Master of the Day of Requital. (4) You alone do we worship, and from you alone do us seek help. (5) Take us on the straight path (6) the path of those on whom you have bestowed Your Grace, Not of those who have incurred your wrath, nor of those who have gone astray. (7)

Al-Fatiha

In the name of Allah, the most Merciful, the most Gracious. All praise is due to Allah; we praise Him, seek His help, and ask for forgiveness. Peace be upon the Prophet Mohammad, his family, his companions, and all those who followed him until the Day of Judgment.

I then would like to show my deepest gratitude and respect to my family, especially my parents, the ones to whom I owe all the success in my life. No words can express my gratitude to them, but I pray God to bless them and reward them. Any success in my life so far is mostly charged to them and consequently any success in the future will have their signature as well.

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NOMENCLATURE

ABBREVIATIONS

ACSA	:	Ant Colony Search Algorithm
ANSI	:	American National Standard Institute
AFD	:	Adjustable Frequency Drive
BC	:	Battery Charger
BSFS	:	Backward Sweep Forward Sweep
BWO	:	Black Wolf Optimizer
CB	:	Circuit Breaker
CS	:	Charging Stations
CSA	:	Cuckoo Search Algorithm
CSO	:	Crow Search Optimizer
DG	:	Distributed Generator
DR	:	Damping Reactor
EA	:	Evolutionary Algorithm
ELM	:	Energy Loss Minimization
FL	:	Fuzzy Logic

FR	:	Failure Rate
FTA	:	Fault Tree Analysis
GA	:	Genetic Algorithm
GWO	:	Gray Wolf Optimizer
HCA	:	Heuristic Algorithm
IEEE	:	Institute of Electrical and Electronics Engineers
IET	:	Institute of Engineering and Technology
MCS	:	Monte Carlo Simulation
MGA	:	Microgenetic Algorithm
MILP	:	Mixed Integer Linear Programing
MOV	:	Metal Oxide Varistors
NEC	:	National Electric Code
NESC	:	National Electric Safety Code
OPF	:	Optimal Power Flow
PFC	:	Power Factor Correction
PSO	:	Particle Swarm Optimization
RBD	:	Reliability Block Diagram

SCA	:	Sine Cosine Algorithm
THD	:	Total Harmonic Distortion
UPS	:	Uninterruptable Power Supply
VFD	:	Variable Frequency Drive
VSD	:	Variable Speed Drive

SYMBOLS

C_{ELM}	:	Energy Loss Minimization Cost
C_{ins}	:	Capacitors including Accessories Installation Cost
C_{PFC}	:	Low Power Factor Penalty
C_{RC}	:	Reliability/Failure Cost
C_{tot}	:	Objective Function (Total Cost)
f/y	:	Failure per Year
mH	:	Damping Reactor Unit Size
MVA	:	Apparent Power
MVAR	:	Reactive Power
MW	:	Real Power
P	:	Real Power
PF	:	Power Factor
Q	:	Reactive Power
R	:	Resistance
S	:	Apparent Power
X_C	:	Capacitance

X_L	:	Inductance
Z	:	Impedance
$	:	Dollar Currency Used in This Thesis

ABSTRACT

Full Name : Abdulaziz Abdullah Al Muhanna

Thesis Title : Optimal Design of Capacitors Considering Transient Switching Events and Reliability Constraints

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Capacitors have long been used at certain locations in power systems to correct the power factor. Such an installation comes with many advantages that lead to an optimal power operation. This thesis proposes a new formulation of the optimal capacitor design problem in electrical power systems. The effect of the transient switching events when energizing and de-energizing the capacitor banks is considered in the proposed formulation. The formulation includes the reliability failure rate to calculate the failure cost and consider the objective function. The objective function is to identify the lowest cost option that meets both the energy loss minimization and voltage regulating requirements which leads to higher cost avoidance. The grey wolf optimization (GWO) has been developed to solve the formulated problem. The developed GWO is evaluated using a several efficient evolutionary optimization techniques. The proposed approach has been tested using two different networks. The results demonstrate the effectiveness of reducing the total cost with the proposed formulation. The robustness of the optimized capacitor location is confirmed against the load uncertainty and future expansion of load.

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ملخص الرسالة

الأسم الكامل	:	عبد العزيز عبد الله عبد العزيز المهنا
عنوان الرسالة	:	التصميم المثالي للمكثفات الكهربائية مع الأخذ بالإعتبار حالات التحويل اللحظية وحدود الكفاءة
الدرجة	:	الماجستير في العلوم
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كانت المكثفات ومازالت تستخدم في أماكن معينة في الأنظمة الكهربائية لأجل إصلاح عامل القوى. هذه الإصلاحات تأتي بمميزات كثيرة تؤدي إلى تشغيل مثالي للطاقة وتحسين الأداء. هذه الرسالة، تقترح طريقة محسنة جديدة لإستخدام المكثفات في الشبكة الكهربائية. مع الأخذ بالإعتبار خلال إستخدام الطريقة المقترحة، التأثر بسبب التحول اللحظي في قواطع الكهرباء بين التوليد وقطع التوليد عن بنك المكثفات الكهربائية. وكذلك سيتم الأخذ بالإعتبار الحسابات لمستوى كفاءة الشبكة الكهربائية ومدى تأثير هذه المكثفات على معدل الفشل والإنقطاع للشبكة. سيتم اضافة هذه الحسابات لدالة الهدف. وهذا لأجل عمل حسابات المبالغ المالية المترتبة بسبب هذة الخسائر وإضافتها للمبالغ الإجمالية التي ستصرف لأجل عمل هذا المشروع. المعادلة الرياضية لحساب المبالغ النهائية لدراسة جدوى المشروع سوف يتم حلها بواسطة طرق خوارزمية. ستعمل هذه الخوارزميات على إجاد أفضل مكان وعدد يمكن إستخدامه من هذه المكثفات لأجل الحصول على أفضل وأرخص تكلفة إجمالية للمشروع التي تؤدي إلى تفادي صرف بعض المبالغ. سيتم الأخذ بالإعتبار ان المكثفات الكهربائية تحسن من أداء الجهد الكهربائي الشبكة وتنقص من كمية الطاقة المهدرة. حيث ان هذه الطاقة المهدرة تودي الى خسائر مالية. أحد الطرق الخوارزمية المستخدمة تسمى بالذئب الرمادي الأقوى (GWO). حيث تم تحسينها كذلك ومقارنة النتائج مع خوارزميات أخرى نتائجها قوية. المعادلة الرياضية المقترحة التي تم حلها بواسطة هذه الطرق من الخوارزميات تم إختبار فعاليتها على شبكتين كهربائيتين مختلفتين في التصميم. والإجابة النهائية للمعادلة كانت مثالية في إختيار التكلفة الإجمالية الأفضل مع الأخذ بالإعتبار كل التكاليف المترتبة على ذلك. بالإضافة إلى ذلك تم إثبات متانة الشبكة والطريقة المقترحة لتركيب المكثفات ضد التغير العشوائي والزيادة المستقبلية للأحمال الكهربائية.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن في الظهران

أبريل 2019

CHAPTER 1

INTRODUCTION

1.1 Overview

Power factor is a parameter representing the difference between real and reactive power consumption. This leads to a phase shift difference between the voltage and current, leading to a few issues in the electrical system such as voltage drops, and energy loses. Lower power factor leads to higher phase angle difference. There are several solutions to solving the low power factor issue. However, the most used and effective solution is installing power factor correction (PFC) capacitors.

Capacitors have many advantages such as correcting the power factor, improving voltage profile, reducing energy flow and increasing system capacity. With all these advantages, designers and planning engineers might overlook the consideration of other issues during the capacitors design planning.

1.2 Motivation

Most of the countries account for real power load in the tariff. Utility companies are installing voltage regulators and compensation systems to solve power system issues.

These issues—high voltage drop and energy losses—are due to a low power factor. Recently, many countries have started penalizing the industrial consumers with low power factors to minimize the high reactive power consumption [1].

This issue became a major concern and it requires engineering solutions to address all the aspects that impact the installation cost, system reliability and system performance. The most effective solution is installing PFC capacitors. However, installing capacitors require a thorough engineering planning analysis to address all reliability and electrical system issues introduced through capacitor installations.

1.3 Thesis Objectives

The objective of this thesis is to identify the optimal size and location of the capacitors for a given power system network, while accounting for the transient event constraints. The transient constraints considered are the inrush current and the switching frequency. PFC capacitors have many advantages that can improve system reliability. However, the capacitor-switching transient will negatively impact the system reliability. Thus, such consideration in planning studies must be considered. The cost function represents the investment cost, the energy reduction cost, the power factor penalty avoidance cost and the reliability/failure cost. The investment cost of the series-damping reactor has been considered in the proposed formulation, in case of transient switching limits violation. Then, the robustness of the proposed approach against the load uncertainty factor is evaluated by testing the optimized installation plan under extreme load growth values.

The main objectives of this work can be summarized as follows:

1. Install capacitors banks to enhance the system power factor, while accounting for transient switching events and voltage constraints.
2. Optimize the installation by maximizing the total avoided cost including the avoided penalty.
3. Integrate stochastic reliability calculations with the objective function to be part of the final optimized solution.

1.4 Thesis Contribution

To achieve the objectives described in 1.3, the following contributions are made:

1. A new formulation in PFC capacitor planning, considering the hidden capacitor failures due to transient resonance events, is proposed.
2. A novel optimization technique called black wolf optimizer (BWO), as an enhancement of the gray wolf optimizer (GWO), is introduced, along with the comparison of results using a genetic algorithm (GA).
3. A novel methodology is developed that integrates a Monte Carlo simulation (MCS) platform with an optimal search platform, to quantify transient switching events in reliability calculations.

1.5 Thesis Organization

The thesis is organized in the following order:

- Chapter 2 provides a complete literature review of all the technical aspects provided in the thesis, including PFC capacitors, capacitor switching transients, GA and optimal capacitor design solutions and methodologies.
- Chapter 3 discusses the problem formulation and methodology for the objective function considering reliability, transience, and other constraints. This chapter also explains in detail all the proposed optimization techniques used in this research and introduces the enhanced technique.
- Chapter 4 provides a step-by-step procedure for the initialization, optimization techniques, and output solution.
- Chapter 5 introduces the case studies with future load expansion to evaluate the proposed formulation.
- Chapter 6 presents the results of this work for the following: Monte Carlo Simulation (MCS), results with/without considering transient limits and reliability impact.
- Chapter 7 discusses the main conclusions and potential future work to enhance the solution approach methodology.

CHAPTER 2

LITERATURE SURVEY

2.1 Capacitor Application Issues and Failure Analysis

There are several applications for capacitor installations in power system applications [2] [3] [4] [5] [6] [7] [8]. These applications to correct the power factor will contribute to a few enhancements such as energy loss minimization and improving the system voltage. However, such installations will have other issues like harmonics and transient overvoltage due to capacitor switching, which was found in the 1990's [9] [10] [11] [12]. These papers proved the transient switching effects in capacitor applications. Starting from the paper [10], which provided information on capacitor impacts in generating parallel and series resonance. These resonances caused the total harmonic distortion (THD) to increase. As the paper explained, the increase in harmonics can cause many issues, such as unwanted relay actions, which will cause random tripping. In addition, the harmonics damage the sensitive electronic devices and the transformers will require a special design, as the harmonics can cause an overload condition.

The paper [9] discussed the installation of PFC capacitors on a system basis by evaluating each system circuit individually and providing the analysis for each case. The system was divided into distribution, sub-transmission, transmission, and generation. Each one was evaluated for installing the PFC capacitors. The evaluating criteria were based on the investment, losses and the reactive power. Each case was thoroughly discussed, and the recommendation provided in detail which proves the requirement of detailed analysis for the whole system, starting from the generator to the distribution, prior to implementing such an application.

The harmonics, in general, are causing a lot of issues to the electrical system, such as overload and overheating of the electrical equipment. The paper [10] used harmonic filtering to solve this issue, which minimized the THD and helped in regulating the voltage. Regulating the voltage will help in limiting the capacitor switching to overvoltage. However, the main solution for the overvoltage condition is to increase the inductance in the electrical circuit [10]. The case study was provided for the adjustable frequency drive (AFD) in the paper, and the recommendations were to increase the internal circuit inductance or increase the AC reactance in order to save the AFD from random tripping [10].

The paper [11] went through overcurrent protection after discussing the capacitor advantages, which could be summarized as minimizing the energy losses, improving the power factor and system voltage. The overcurrent protection is deeply required to avoid the unexpected failure of the capacitors. Capacitors must be perfectly sized to make sure they do not contribute to the system harmonics by providing the series and parallel resonance [11]. The paper studied the overcurrent protection case in order to protect the installed capacitors from transient inrush current [11]. It also provided the means for selecting the fuse type and rating [11]. Detailed calculations provided in the paper, prove the requirement of current limiting fuses in such applications.

The paper [12] discussed in detail the capacitor switching transient events. Figure 2.1 shows the capacitor switching transient which could reach double the system voltage at the supplied bus [12]. This phenomenon has become a bigger concern, as the number of capacitors in the electrical system is increasing due to higher penalties implemented by the utility [12].

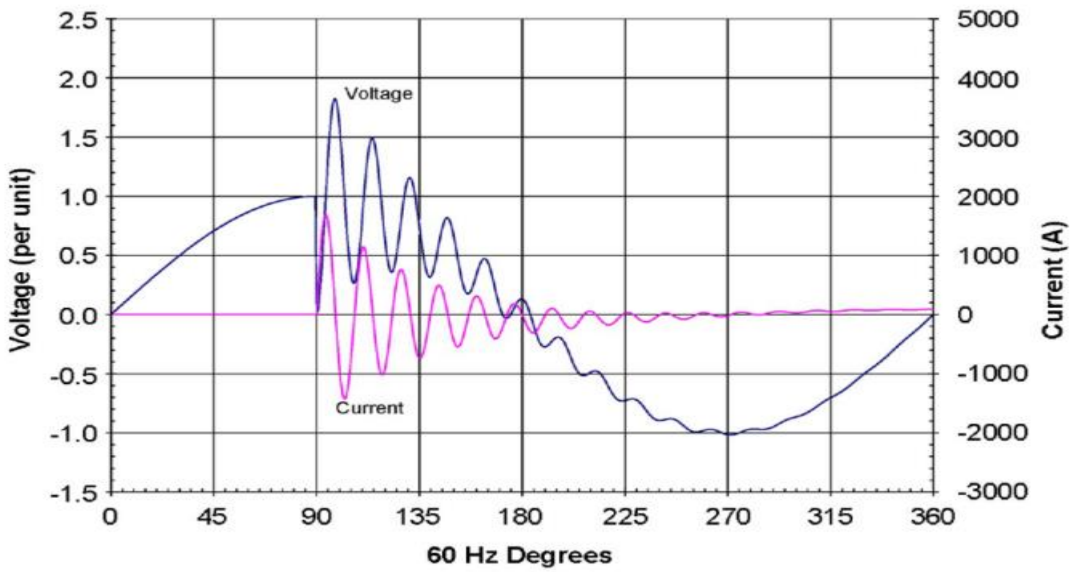


Figure 2.1 Capacitor Switching Effect on the System [13]

The paper [12] conducted some analysis related to transient impact for low and high voltage systems, which proves higher capacitor ratings at a higher voltage will cause higher magnification. The paper provided recommendations to exert some control on the transient events of the switched capacitors [12]:

1. It is important that the capacitor closing is at zero crossing, which means that when the voltage sinusoidal signal passes zero, the magnitude of the voltage became zero.

2. A resistor is installed at the capacitor switching device to minimize the voltage and reduce the switching transient.

Paper [12] recommended using the PFC capacitors as a series harmonics filters by applying the LC circuit, rather than sizing the capacitors to only correct the power factor. This will help in limiting the transient impact as well as minimizing the harmonics at the connected bus.

Following all the stated concerns and analysis of capacitor applications, recent papers were written concluding all previous and additional findings with more analysis [13] [14]. These two papers concluded the capacitor applications and the failure analysis. The paper [13] started with the parameters required to size the capacitors for PFCs in applications in which they are the desired power factor level—the current reactive and active powers consumption. Following which, the paper reviewed the capacitor applications issues in details. The applications issues were concluded as the following [13]:

1. Capacitor rating design following IEEE Std 18-2012 [15].
2. Capacitor protection requirement as per NEC [16].
3. Conductor and disconnecting switch rating design, following the NEC.
4. Capacitor selection criteria such as fixed or switched capacitors, IEEE Std 1036-2010 [17].
5. Capacitor design criteria, including the physical and electrical locations.
6. Harmonics calculations for series and parallel resonance, following IEEE Std 519-2014 [18].
7. Capacitor switching transient events.

Moving to paper [14] which reviewed the capacitor failures after having random failures reported due to automatic capacitor switching to maintain the power factor at the desired value. These failures were causing an increase in the electrical bill due to utility company penalties. The paper did a thorough analysis of the harmonics and transient effects of the capacitor for a specified case study. The result concluded that the failure was due to the capacitor switching transient. For more detailed calculations, refer to paper [14].

The following sections will provide more details on the harmonics analysis and transient events due to capacitor switching.

2.2 Capacitor Harmonics Analysis

The harmonics are generated from power electronic devices such as adjustable frequency drive (AFD), uninterruptable power supply (UPS), battery charger (BC), etc. In addition, the resonance circuit will cause a resonance frequency which will reduce the capacitor life. Thus, it is always recommended to install the capacitors on buses without power electronics devices connected directly to it [14]. The harmonics studies shall be done in accordance with the IEEE Std 519-2014.

There are two types of resonance—series and parallel resonance. These two will be explained in detail in the following sections. The details of these analyses can be found in [19] [13] [14].

The series resonance is having the capacitor installed in a series with the inductance as shown in Figure 2.2 and 2.3. The inductance doesn't require to be a physical reactor, it could be the accumulative system inductance after conducting the load flow, including cables and transformers. Figure 2.2 shows the system connection and Figure 2.3 shows the equivalent series resonance circuit.

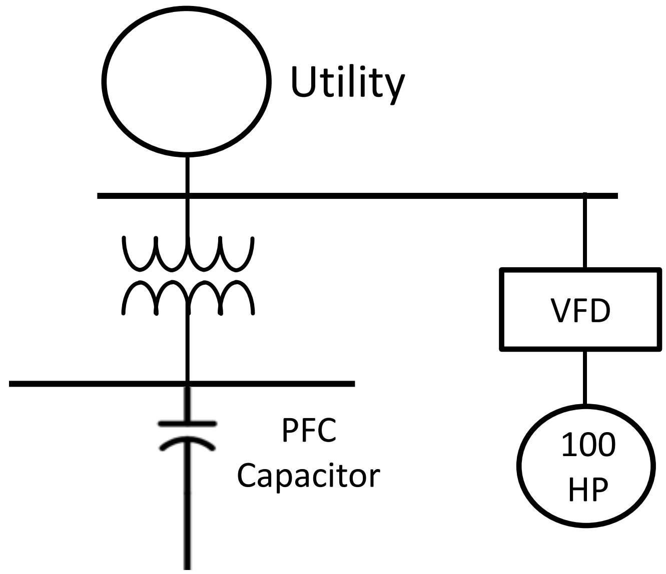


Figure 2.2 Series Resonance

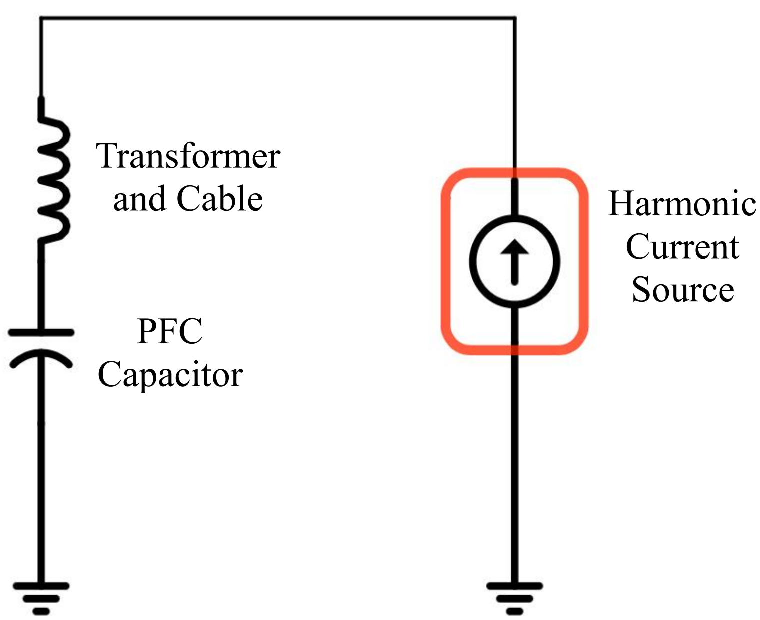


Figure 2.3 Series Resonance Equivalent Circuit

Most of the electrical applications are series resonances which can be easily resolved by harmonics filters. Even the PFC capacitors can be configured as a passive harmonics filter by increasing the series inductance [13] [14]. The series inductance can be increased in many ways, such as installing reactors in series with the capacitors. This will help in reducing the harmonics as well as solving the transient event's issues, which will be explained in the transient section.

The parallel resonance is to have the capacitor installed parallel to the inductance, as shown in Figure 2.4 and 2.5. As stated before, the inductance doesn't require to be a physical reactor, it could be the accumulative system inductance after conducting the load flow including cables and transformers. Figure 2.4 shows the system connection and Figure 2.5 shows the equivalent parallel resonance circuit.

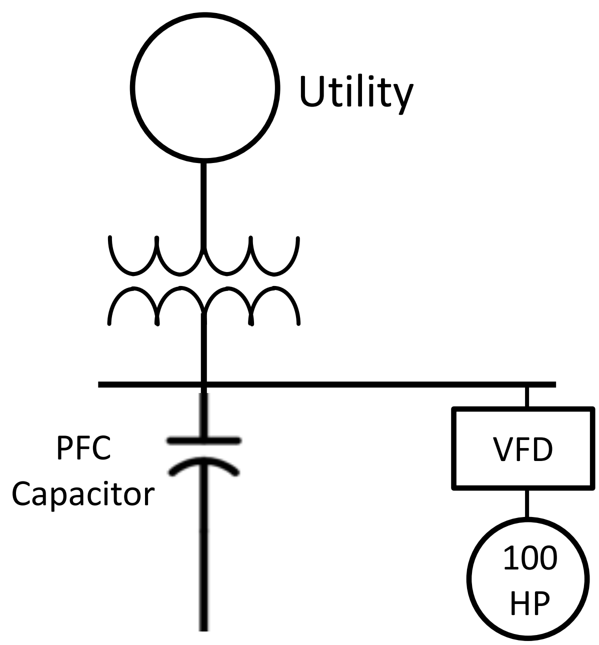


Figure 2.4 Parallel Resonance

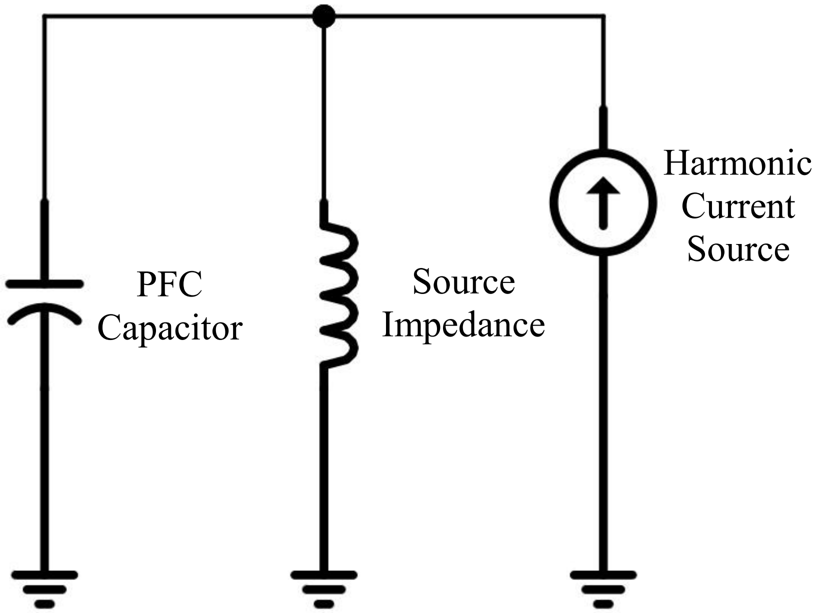


Figure 2.5 Parallel Resonance Equivalent Circuit

The parallel resonance occurs very rarely and can be avoided by installing the capacitor at a different bus than the ones involving harmonic sources and power electronics devices.

The resonance frequency at the secondary transformer can be calculated using the following equation:

$$h = \sqrt{\frac{KVA_{transformer}}{(\%Z_{transformer}/100) \times kvar}} \quad (2.1)$$

Where, $KVA_{transformer}$ is the transformer power rating, $\%Z_{transformer}$ is the transformer impedance percentage and $kvar$ is the PFC capacitor rating. While h is the tuned harmonic. This means that any high harmonics at the same value will be amplified by the parallel resonance condition [13] [14].

2.3 Capacitor Switching Transient

Capacitor switching transient is a phenomenon occurring due to capacitor energization while it has some stored energy [13] [14]. The worst case is when the capacitor voltage is energized, and it is on the negative peak, while the system voltage at the positive peak. There are several solutions for this issue:

1. The capacitor is an energy storing device, which must be fully discharged prior connecting it to the system.
2. Closing the capacitor at zero crossing for the system voltage requires a fast-acting device such as the static switch.
3. A capacitor discharger can be installed for fast capacitor discharging, and to keep it ready for system connection.

There are two methods for capacitor switching, reviewed in the next two sections.

The single capacitor switching is when there are no capacitors connected to the system, and the first capacitor is attempting to be energized. The circuit for the single capacitor switching has the capacitor installed in a series with the system impedance, as in Figure 2.6. The sudden capacitor switching will cause the transient system to voltage. That a transient can reach a double-rated voltage is illustrated in Figure 2.7 [13].

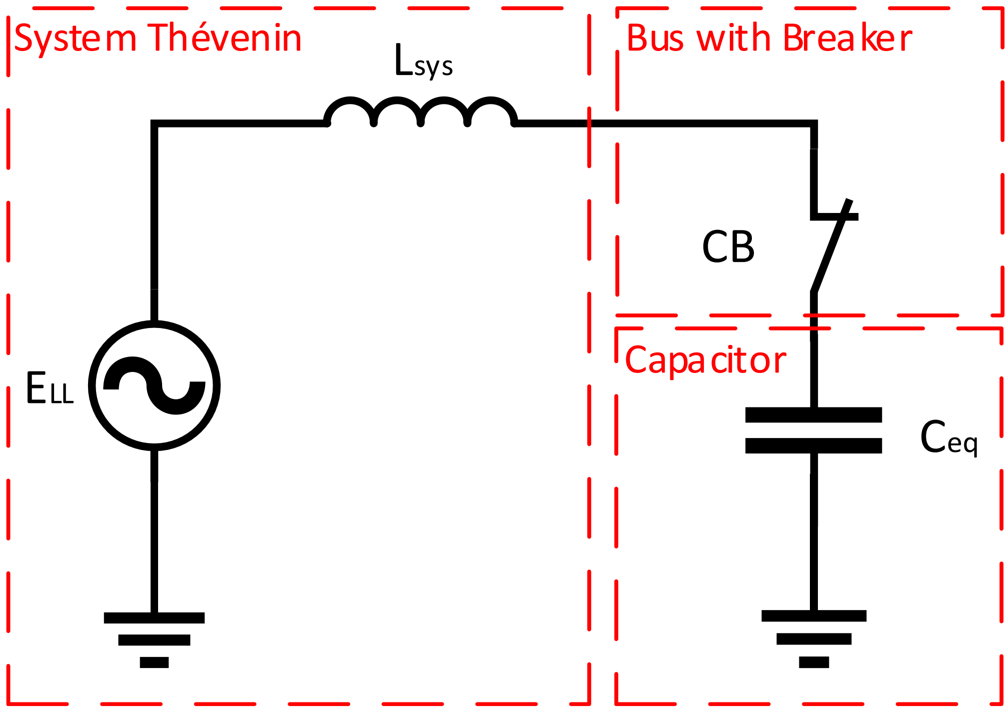


Figure 2.6 Single Capacitor Switching Model

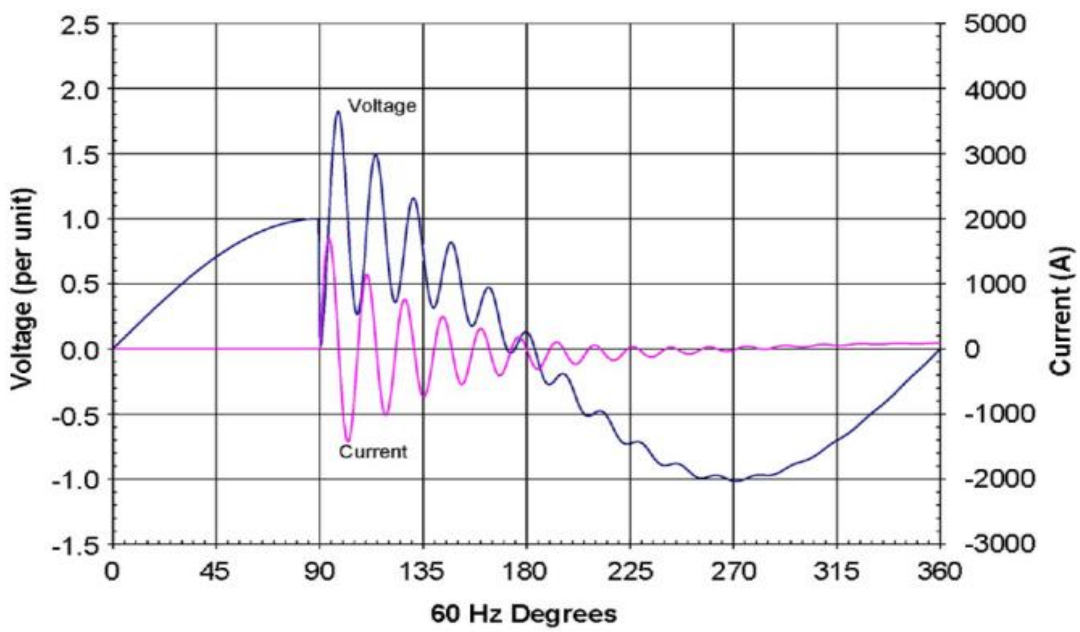


Figure 2.7 Single Capacitor Switching Effect on the System [13]

Moving to back-to-back switching, this type of switching occurs when there is already an online/energized capacitor and another capacitor is attempting to become energized. The circuit of back-to-back switching is shown in Figure 2.8, where the capacitors are parallel to the system inductance. While the inductance between the capacitors is cable inductance, when the first capacitor is energized and the other one is switched back-to-back with the first capacitor, a huge transience will occur, as shown in Figure 2.9 [13].

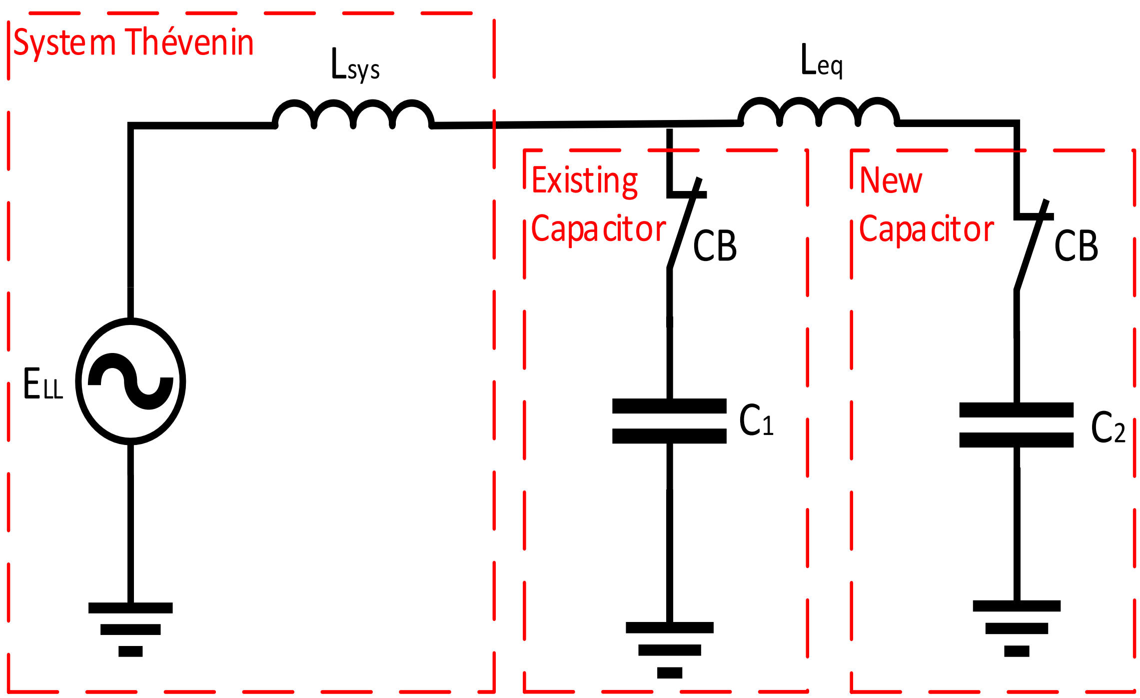


Figure 2.8 Back-to-Back Capacitor Switching Model

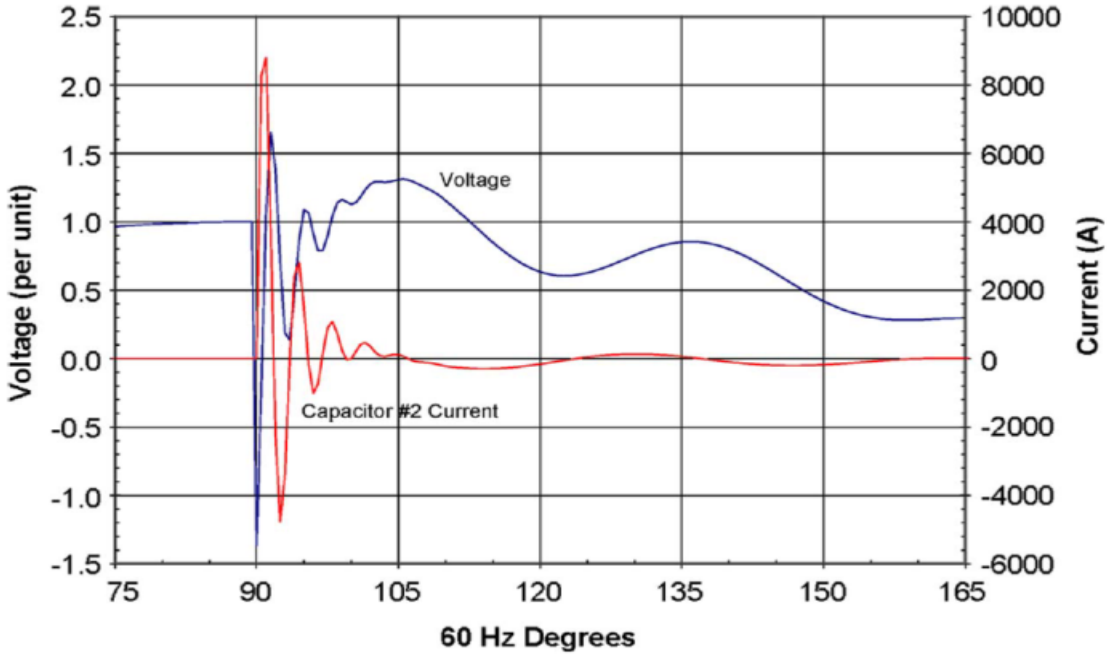


Figure 2.9 Back-to-Back Switching Effect on the System Voltage [13]

Usually, the power system doesn't have a single capacitor but have multiple capacitors, parallely installed. However, some facilities are using fixed capacitors, which will be switched once during the capacitor's life. While others are using step capacitors which will be switched when needed to correct the power factor, if a large induction motor is started. In both cases, capacitor switching transient is an issue. If, after a few years, the load expanded and more capacitors are needed to overcome the low power factor issue and avoid penalties, the fixed capacitors will have back-to-back switching with the newly installed capacitors. For the switchable capacitor case, it will be always in switching mode, which means a back-to-back switching case always occurs.

The solutions have been illustrated before, however, these solutions will not prevent the transient events. It will only limit and minimize these transient events impacts.

Furthermore, the only solution to prevent the transient events due to capacitor switching is to increase the system inductance by installing a reactor, in series with the capacitor.

As stated before, the PFC capacitors can be used as harmonics filters by installing a reactor in series with the capacitor. Therefore, this solution will help the system with two issues, the capacitor switching transient and the harmonics resonance [13] [14].

2.4 Optimal Capacitor Design

Capacitor optimal sizing and installation has been an important research area in the last few years, due to the huge advantages it provides. As discussed previously, capacitor advantages can be summarized as follows [11]:

1) Correcting the power factor, which will reduce and help avoid the penalties paid to the utility company. Worldwide the low power factor has became an issue for the utility company, which has caused a drop in the transmission system voltage, due to the high reactive power consumption by the facility. Correcting the system voltage will cost the utility a lot.
2) Providing the reactive power at a certain bus will minimize the energy losses and lead to an increase in the system capacity; thus, increasing the system reliability. As the reactive power current will be minimized, the system capacity will increase. As the line will be less loaded, the generated heat by the cable will be minimized, enhancing reliability.
3) Providing the required reactive power at a certain bus will lead to minimizing the reactive power provided by the utility company, which will lead to minimizing the

voltage drop and improving its profile. This will curtail a lot of costs in correcting the system voltage.

With all these capacitor advantages, there are issues that must be considered during capacitor applications [13]:

1) Capacitor rating design following international standards (IEEE Std 18-2012) to overcome excess current and voltage issues, otherwise the capacitor could fail in times of other electrical system failures.

2) Capacitor protection requirement which includes the overcurrent protection, capacitor discharge protection and voltage unbalance protection. These protections are requirements of the NEC. Starting with overcurrent, the breakers/fuses are required to isolate the capacitor from storing additional energy, in case of the capacitor's failure. In terms of capacitor discharge, it is known as the energy storage device, which requires discharging whenever isolated from the system. Finally, unbalance protection is initiated if one of the capacitors fail and the fuse isolates it from the system. This will cause other capacitors to be stressed and lead to an overvoltage condition. Usually, the overvoltage condition has two settings: one for alarming the system operator about the condition and one is to trip if the overvoltage condition exceeds the acceptable value.

3) Conductor and disconnect switch rating design following the NEC. Especially, the conductors have to be properly sized to overcome the overcurrent issues due to transient events.

4) Capacitor selection criteria, such as fixed or switched capacitors (IEEE Std 1036-2010). The fixed capacitors are installed to correct the power factor. However, the switched capacitors come online when large motors are started, and the power factor drops below the acceptable limit. Hence, most of the facilities are merged with both, but this could be selected based on the load requirement.

5) Capacitor design criteria, including the physical and electrical locations to meet the desired capacitor ratings, at the lowest cost. The physical location is important for accessing the capacitor easily, for maintenance as well as to assess the environmental conditions impacting its lifetime. However, the electrical location must be properly selected to avoid other electrical issues, such as connecting the capacitor to a bus that already has other power electronic devices. This will cause harmonics and resonance issues.

6) Harmonics calculations for the series and parallel resonance, to check whether the system requires harmonics filters, following the international standards (IEEE Std 519-2014). As stated before, it is better to have capacitors connected to buses without any direct connection with the power electronic devices, otherwise high resonance will amplify the harmonics at that bus.

7) Capacitor switching transient can be classified into two types. These are single capacitor switching and back-to-back switching. As discussed, there are two ways of switching the capacitor and the most severe is back-to-back switching. The most available switching mode in the industry is the back-to-back switching, due to the

nature of the load and future expansions which require adding more capacitors to avoid the low power factor penalties.

8) Capacitor fault current can be ignored due to the fast discharging rate of the capacitor, which will contribute to the fault for less than a cycle. This will not impact the system.

With all these application advantages and issues taken into consideration, a thorough and deep analysis shall be conducted to include all the factors in the problem formulation. The problem is mainly derived from reliability and economic factors. Based on that, engineering solutions are being used to put the problem into one single objective function and formulate this function to include all factors. The optimal solution of this objective function will be the desired solution.

There are a lot of papers and researches about the optimal capacitor design. Some enhanced the formulation and updated the objective function and others concentrated on the optimization technique and algorithm for better results. Now is the time to go over them to demonstrate optimal capacitor design objective functions. For this, case studies were presented and the optimization techniques that had been used [17–52]. The following sections will cover the optimal capacitor approaches dividing the design objective into three sections. These sections are case studies/system testing, problem formulation/factors consideration and design methodology.

One of the cases that implemented capacitor installation is installing capacitor banks on distribution feeders [20] [21] [22] [23]. The papers [20] [21] covered the utilization of capacitors to improve the voltage profile and power loss minimization. While [22] [23] did the optimal size and installation for the same benefits, however, the cases were different. The paper [22] considered the unbalanced effect of the three feeders. While [23] considered the fixed and switched capacitors in the case study, and another reference [24] used the capacitor directly with the induction motor to supply the required reactive power to the motor.

Other references [25] [26] [27] considered the radial distribution system as a case study for capacitor installation. The papers targeted the optimal size and location considering voltage limitation, power factor penalty and losses reduction, which translated the problem to be a cost objective function. However, the difference between them was in the algorithm formulation, where they considered different optimization approaches. Finally, reference [28] uses the capacitor to improve the voltage profile and minimize the system losses for the charging stations, used to charge electric vehicles. The improper locating of the charging stations will cause some voltage issues. These issues can be resolved using the capacitors.

The problem formulation enhancement started since 1990, when a paper was written to find the optimal size, location and the control settings in one objective function [29]. Followed by another reference which considered the nonlinear loads' effect on the capacitor design and problem formulation [30]. Another reference [31] put forth a new formulation to control the design and removal of the capacitors to correct the power factor, based on the system's needs, while the paper [32] conducted the same analysis for capacitor installation, but on conductors that considered the mutual coupling effect, with the interest to avoid the highest cost by installing the capacitors.

Another reference [33] considered the voltage and current harmonics in the problem constraints and reflected on the objective function which would impact the cost related to the power and energy losses due to the harmonics. Reference [34] included the harmonics analysis as well the nonlinear and unbalanced loads section of the optimal capacitor installation problem, with an enhanced objective function involving the cost of harmonics distortion. While reference [35] had the same approach but used different optimization techniques to compare the results. The technique used was the particle swarm optimization. The load uncertainty and time-varying loads factors were included in the problem formulation in [36]. The optimized solution was found using GA for both the fixed and switchable capacitors.

Moving on to the following papers [37] [38] [39], which included all the previous constraints or most of them with one additional factor to enhance the solution methodology. Paper [37] included fixed, switchable and combination as an option to meet the desired solution, while [38] considered the distributed generators production in the objective function. Finally, [39] included the resonance limits in the problem constraints. These factors impacted the objective function's desired solution.

Until now, the literature was reviewing the factors considered to enhance the objective function. Currently, it is time to go over the optimal capacitor design methodology. The paper [40] was written in 1988, it used feeder taps to collect the reactive power data which probably helped in sizing the capacitors. Another reference [41] used simulated annealing to set the solution algorithm for fixed and switched capacitors. Then, a more beneficial result was found using Tabu Search (TS) in [42], followed by using a graph search algorithm in [43]. The paper [44] used GA and fast energy loss computation for optimal design. While [45] used the deterministic approach with mixed integer linear programming after linearizing the objective function. Both papers explained the design methodology with an illustrated example.

Another reference [46] used a new optimization type called micro-genetic algorithm (MGA) with the fuzzy logic approximation technique. The fixed and switchable capacitors control the reactive power and power factor values. The paper [47] used the placement and replacement concept. The decision is made based on the cost of conducting the optimization using a GA. Another paper [48] used the heuristic constructive algorithm (HCA) and the ant colony search algorithm (ACSA) was used in [49].

Paper [50] used the reconfiguration placement methodology. The concept of this method is to consider the varying nature of loads, integrated with the GA for faster and more accurate results. Moving to [51], the paper used evolutionary algorithm (EA) as an optimization technique and [52] considered the optimal capacitor location as a multi-objective function, accounting for several aspects to guide the installation.

The following three papers [53] [54] [55] use different design methodologies with the same objective function. Paper [53] used the cuckoo search algorithm (CSA) for optimal design on a radial distribution system. While [54] used particle swarm optimization (PSO) with a backward-sweep-forward-sweep (BSFS) load flow for the distribution systems. Finally, paper [55] used the crow search algorithm to solve the developed objective functions.

2.5 Power Factor Correction (PFC) Capacitors Reliability Impact

As mentioned before, capacitor installation will influence the system reliability. There are three papers published about the optimal capacitor design considering reliability calculations [56] [57] [58]. The cost and system reliability comparisons are shown in Figure 2.10, where the reliability will be low, and the system failures will be high due to low system reliability. By increasing the system reliability, the losses will be reduced to a certain limit that will make investing in system reliability cost much more than the actual reliability enhancement.

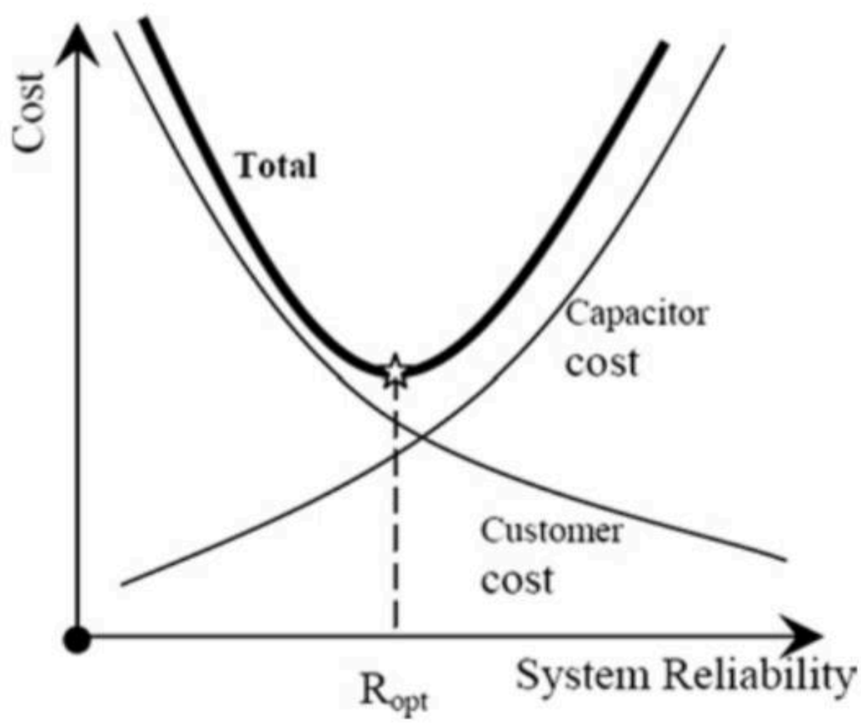


Figure 2.10 System Reliability vs. Total Cost [56]

The reliability enhancement concept in optimal capacitor design comes from line loading. As capacitors will supply reactive power in the system, the main line supplying the system will be less loaded. Thus, it will minimize the heat generated in the line and minimize the failure possibility in the line as well; this will lead to a reliability enhancement.

The paper [56] talked about the reliability enhancement of the radial distribution systems after installing the capacitors. It was representing the problem as cost and included it in the objective function. Another paper [57] included the switchable capacitors in the solution methodology, which will impact the load parameters. Then, it calculated the reliability indices System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Average Energy Not Served (AENS) for the connected customers. Finally, reference [58] did a multi-objective optimization problem for the reliability indices SAIDI, SAIFI, and AENS. Then, it included the cost of the optimization and accounting for the reliability cost enhancement part of the optimization.

As noted, all papers considered the enhancement to the system as being implemented through the capacitor installation. However, there are a lot of applications issues negatively impacting the system reliability which were not considered. For more details on these applications, they are described in this thesis and available in [14] [13].

2.6 Conclusions of Literature Gaps and This Thesis Focus

After going through the literature reviews, it can be concluded that the gaps to be investigated are:

1) Capacitor switching transient was not addressed in any optimal design problem before.

2) Capacitor installation will lead to system enhancements and the reliability will improve as proven by several papers. However, some factors impacting the system reliability were not addressed. These are factors related to the capacitor switching transient which causes system failure and power loss.
3) Future load growth/expansion and planning impact to capacitor switching transient, accounting for back-to-back switching for the added capacitors.

Thus, this thesis will concentrate on these factors and include them in the problem formulation with different case studies. In addition, it will consider all previously covered factors in the problem formulation, such as the avoided penalty, energy loss minimization, and voltage profile. The problem formulation and methodology chapter will examine the objective function formulation.

CHAPTER 3

PROBLEM FORMULATION

3.1 Capacitor-Switching Transient Events

The objective of this thesis is to conduct an optimal design planning for the PFC capacitor installations, including transient switching events. These events will disturb the system and cause failures. According to ANSI C37.0732, the breaker has a limit to ensure continuous operation. These limits are divided into transient frequency and inrush current. Table 3.1 presents the limits of the breaker according to ANSI requirement, as follows:

Table 3.1 Max Operation Limits for Circuit Breakers

Operating Voltage (kV)	Max. Current (kA)	Max. Frequency (Hz)
$V_{max} < 15$	15	2000
$15 < V_{max} < 72$	16	3360
$120 < V_{max} < 145$	16	4250
$169 < V_{max} < 362$	20	4250

These limits were designed at this rate based on the breakers are available in the market. For example 132kV system operation voltage rating available breakers in the market are limited to protect up to 16kA inrush current and 4250Hz frequency.

To calculate these limits, the system is divided into two operation modes. These modes are single capacitor switching and back-to-back switching, presented previously and shown in Figure 3.1 and 3.3.

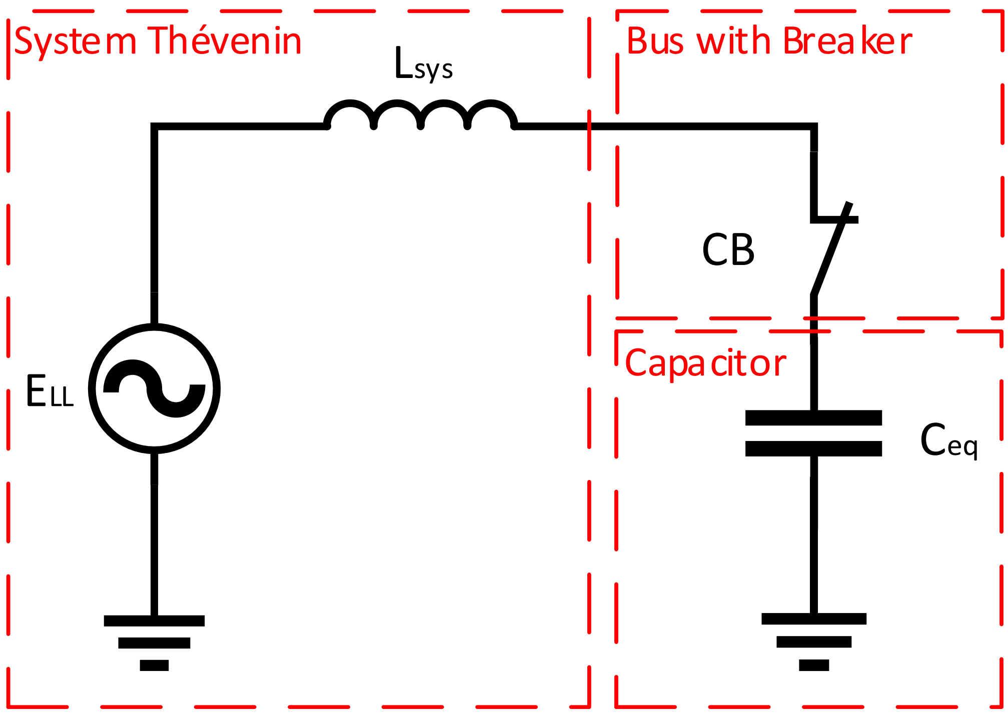


Figure 3.1 Single Capacitor Switching Model

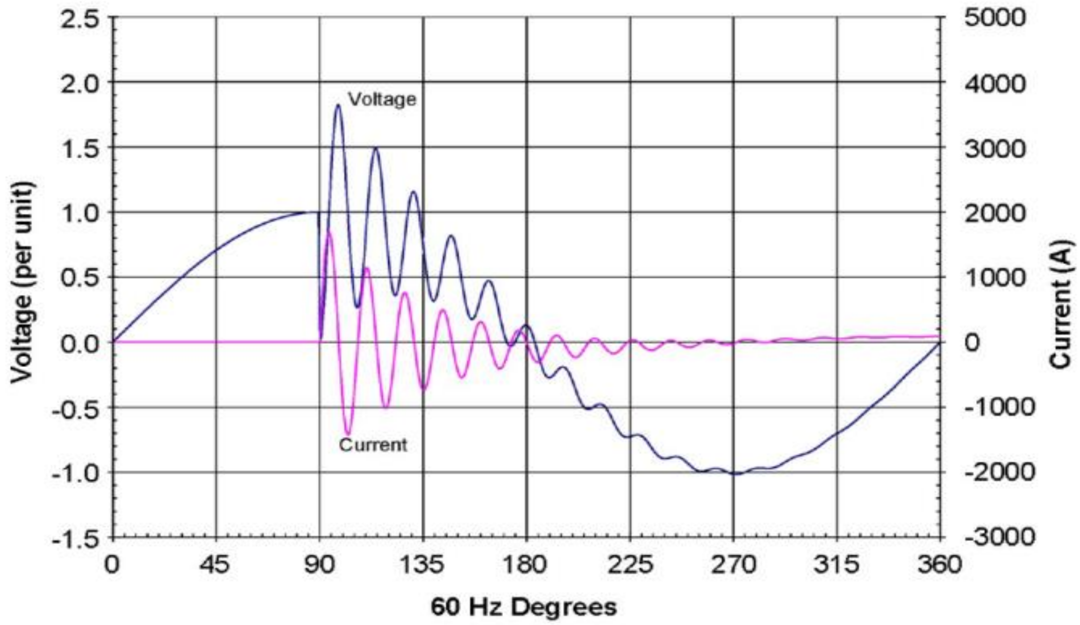


Figure 3.2 Single Capacitor Switching Effect on the System [13]

For single capacitor switching, the capacitor banks are installed in serious and parallel to meet the required system design rating. That final capacitor value is used in the resonance equations as follow [59]:

$$i_{\max peak} = \frac{\sqrt{2}E_{LL}}{\sqrt{3}}\sqrt{\frac{C_{eq}}{L_{sys}}} \tag{3.1}$$

$$f = \frac{1}{2\pi\sqrt{C_{eq}L_{sys}}} \tag{3.2}$$

Where, E_{LL} is the system voltage. C_{eq} is the equivalent installed capacitor in a single switching model. L_{sys} is the system impedance. The system inductance can be calculated by conducting the load flow analysis on the system. While the voltage rating is the system operating voltage. The details of these parameters are shown in Figure 3.1 for single switching mode.

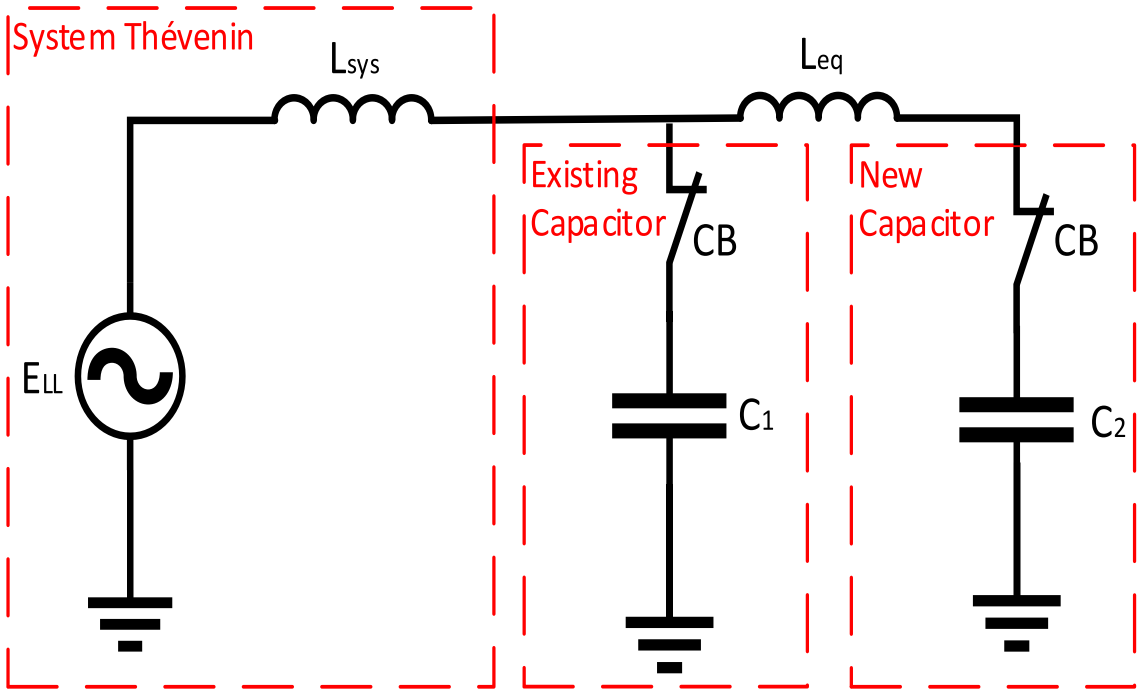


Figure 3.3 Back-to-Back Capacitor Switching Model

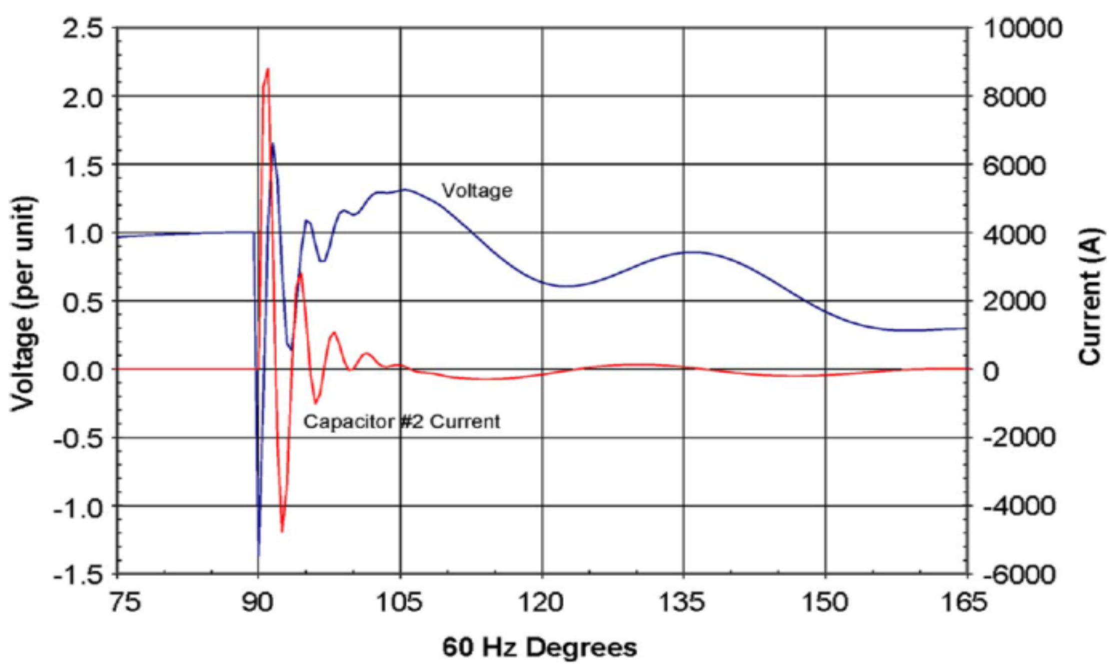


Figure 3.4 Back-to-Back Switching Effect on the System Voltage [13]

Moving to back-to-back capacitor switching mode, which happens if there is an available capacitor banks that are connected. Then, another capacitor bank connected to the same bus has been energized. This will lead to tremendous raise in the transient overvoltage limit and could cause major system losses.

Back-to-back capacitor switching is happening due to system expansions which cause a drop in the power factor and more banks installed in parallel to compensate for that increase. Also, there are some facilities are installing banks in parallel to be energized based on induction motors energization to control the power factor.

To calculate the transient events for back-to-back capacitor switching, use the resonance equations as follows [59]:

$$i_{\max peak} = \frac{\sqrt{2}E_{LL}}{\sqrt{3}} \sqrt{\frac{C_1 C_2}{L_{eq}(C_1 + C_2)}} \tag{3.3}$$

$$f = \frac{1}{2\pi \sqrt{\frac{C_1 C_2 L_{eq}}{(C_1 + C_2)}}} \tag{3.4}$$

Where E_{LL} is the system voltage. C_1 and C_2 are the two equivalent installed capacitors in the back-to-back switching model. Finally, L_{eq} is the cable inductance running between the two capacitors banks in the back-to-back switching model. The details of these parameters are shown in Figure 3.3.

These equations are used to identify the impact of the power factor energization on the system behavior. Single capacitor switching impacts the system resonance as shown in Figure 3.2. However, back-to-back switching resonance impact to the system looks more severe from Figure 3.4, as compared to Figure 3.2.

The system inductance can be calculated using the proposed formulation. Then, it will be used in the previous transient equations. The proposed formulation will calculate the per unit values of the accumulative inductance of a selected system. Then, the following equation will be able to find the system inductance in Henry:

$$L = \frac{X_{pu} \times V_{base}^2}{S_{base} \times 2\pi f} \tag{3.5}$$

Where, X_{pu} is the per unit inductance for the selected test system which can be found using load flow analysis. V_{base} is the base voltage and S_{base} is the base apparent power for the selected system. f is 50 Hz or 60 Hz for the system. The system frequency selected to be 60 Hz in this thesis.

To find the capacitance used for transient calculations, select the required MVAR rating for the installed capacitor and calculate the capacitance in F, using the following equation:

$$C = \frac{VAR\ Rating}{2\ \pi\ f \times V^2} \tag{3.6}$$

Where, V is the system rated voltage f is the system frequency selected to be 60 Hz in this thesis.

3.2 Reliability Impact

As reviewed in the literature, the capacitor installation will enhance the system reliability by minimizing the system loading, which will reduce the heat generated; thus, the reliability will be improved. It is like adding another power line in parallel. This will increase the system capacity and minimize the failure rate. This reduction in the system capacity comes from the reactive power supplied reduction from the upstream.

This reliability enhancement could be calculated as cost (ECOST) function to include in the objective function. The following equation could be used:

$$ECOST_N = L_N C_N \lambda_N \tag{3.7}$$

Where, L is the load, C power cost and λ is the failure rate for bus N [56].

As the supplied energy is reduced, the current through the line will be reduced as well. This will cause a difference in the line current between the old and the new. This difference can be calculated as follows:

$$\alpha_N = \frac{I_{new-N}}{I_{old-N}} \tag{3.8}$$

Where (α) is the relation difference between the new current after installing capacitors and the old current before the installation for bus N.

Then, the final failure rate will be enhanced and can be calculated using the following equation for bus N:

$$\lambda_{new-N} = \alpha_N(\lambda_{old-N} - \lambda_{best-N}) + \lambda_{best-N} \tag{3.9}$$

Where, λ_{old} is the initial failure rate before the capacitor installation and λ_{best} is the new failure rate at full capacitor compensation, which is approximately 85% of the initial failure rate [56]. This means the failure rate will drop by 15% after installing the capacitors for every bus N.

This thesis is concentrating on the reliability cost impact and not finding the reliability indices as the objective function is targeting the avoided cost maximization.

3.3 Failure Rates

The system reliability will be enhanced by installing capacitor banks. However, it will be reduced as well. The capacitors will generate series and parallel resonances and will case transient to the system due to capacitor switching. The paper [14] [13] mentioned the failures had occurred to the systems until they realize the transient issue. The capacitor-switching transient is considered as the hidden capacitor failures. However, it was not considered before in the reliability calculations.

The solution for the capacitor-switching transient is increasing the inductance of the line. This will resolve two issues: 1) Transient events; 2) Resonance issues. Installing the capacitor in series with damping reactors to increase the line inductance will let the power factor correction capacitor behave as harmonic filters.

Even though the failure rate will be enhanced by adding inductance but still it will be lower than not considering the impact at all. The damping reactors have a failure rate by itself. In addition, installing more equipment in the system will reduce the reliability.

The failure rate of transient switching will be divided into two situations. First, considering the transient and installing damping reactors to overcome resonance magnification to transient events. Second, not considering the transient will case more failures in the system. The breaker failure is assumed to be 2 f/y. This approximation is for studying purposes, even though it's more than this. Especially that in the industry, no one will return the system after the second failure without full and detail investigation to the system.

The failure rates with the repair time for all the components in the circuit shown in Figure 3.5 are taking from IEEE gold book for reliability calculations and presented in Table 3.2 [60] [61].

Table 3.2 Electrical System Components Failure Rates

Component	Failure Rate	Repair Time
Line/Cable	0.0141	40.4
Damping Reactor	0.04	150
Capacitor	0.17443	2.3
Circuit Breakers (Considering Transient)	0.003	129
Circuit Breakers (Not Considering Transient)	2	129

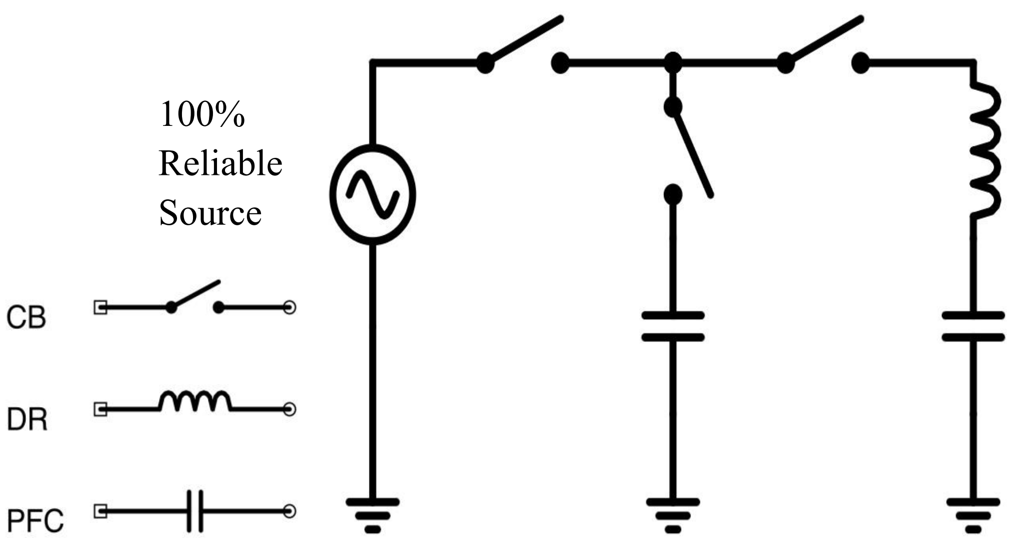


Figure 3.5 Monte Carlo Simulation Evaluated Circuit

3.4 Objective Function

The objective function is a cost function that drives the problem solution. This thesis objective function is a maximization problem formulation that optimizes the system design to find the most achievable avoided cost.

This thesis is formulated to include all previous advantages and disadvantages, in addition to the new factors addressed in this thesis literature which were not considered before. The factors considered under the thesis are:

1) Reliability factors including installation advantages, such as reliability enhancement, and disadvantages, such as failures due to capacitor resonance magnification for transient events.
2) Energy loss minimization due to capacitor reactive power supply directly to the load.
3) The capacitor installation cost including cabling, building, capacitors, and breakers. In addition to damping reactors whenever needed.
4) The avoided penalty due to the low power factor. Low power factor is impacting the electrical grid negatively which lead to system losses and low voltage profile. Thus, correcting the system from these impacts is a very high cost which caused the utility companies and the countries to put a regulation on paying penalties for low power factors.
5) Future load growth and system expansions due to increase in power demand.

Based on the previous explanation, the finalized objective function will be a maximization solution is as follow:

$$Maximize(C_{tot}) = C_{RC} + C_{ELM} - C_{install} \tag{3.10}$$

Where, ($C_{install}$) is the capacitor installation cost, (C_{ELM}) is energy loss minimization cost and (C_{RC}) reliability impact (Failure) cost.

Followed by another function to include the total penalty avoided (C_{PFC}) to the previous solution (C_{tot}), as follows:

$$Maximize(C_{avoided}) = C_{tot} + C_{PFC} \tag{3.11}$$

The previous equations contain main four cost contributors which are calculated as a part of the optimization solution, as follows:

$$C_{PFC} = kvarh\ cost\ \times\ 8760\ \times\ P\ (\tan(\cos^{-1} 0.95) - \tan(\cos^{-1} PF_{before})) \tag{3.12}$$

$$C_{ELM} = \left(kwh\ cost \times \left(P_{af} - P_{bef}\right) +\ kvarh\ cost\ \times \left(Q_{af} - Q_{bef}\right)\right) \times\ 8760 \tag{3.13}$$

$$C_{RC} = (kwh\ cost\ \times\ P\ +\ kvarh\ cost\ \ \times\ Q)\ \times\ \lambda_{new-N}\ \times\ 8760 \tag{3.14}$$

$$C_{install} = Mvar\ cost\ \times\ Required\ Mvar +\ mH\ cost\ \times\ Required\ mH \tag{3.15}$$

Where, $kvarh\ cost$ is the reactive power cost in Table 3.3, P is the real power at each bus, Q is the reactive power at each bus, PF_{before} the bus power factor before capacitor installation, $kwh\ cost$ is the real power cost in Table 3.3, P_{af}/P_{bef} & Q_{af}/Q_{bef} the supplied real & reactive powers at each bus before and after capacitor installation, λ_{new-N} the accumulative failure rate found after applying MCS, $Mvar\ cost$ is the capacitor cost in Table 3.3, $mH\ cost$ is the added inductance cost in Table 3.3, $Required\ Mvar$ and

$Required\ mH$ are the required PFC capacitors and damping reactors calculated using the proposed formulation after conducting the load flow.

Table 3.3 Problem Economic Data

Discount rate	5.0%
Capacitor cost (installation + equipment)	\$87500/MVAR
Inductor cost (installation + equipment)	\$30000/1 mH
Capacitor power cable	\$3200/capacitor
Capacitor or inductor building	\$675000/capacitor
Energy cost [62]	\$0.0479/kwh
Reactive power cost [62]	\$0.0133/kvarh

3.5 Problem Constraints

The previous objective function will be subjected to following constraints:

1) Transient limit constraints for the inrush current and frequency.
2) Voltage profile limits.
3) The targeted power factor as a minimum to be 95%.

Thus, the problem constraints are summarized as, power factor limit constraints to be at 0.95 minimum, operation constraints for the voltage limits to be always within 5% of the rated voltage, and protection constraints for the capacitor-switching transient, as specified in ANSI C37.0732. The summary of the problem constraints are as follow:

$$PF_N \geq PF_{Target} \quad (for\ every\ PQ\ bus\ N\ ) \tag{3.16}$$

$$0.95 \ \leq V_i \ \leq 1.05 \quad i \ \in [1, N]\ for\ bus\ N \tag{3.17}$$

$$f_N \ < f_{max} \quad for\ bus\ N\ the\ operating\ voltage \tag{3.18}$$

$$i_N < i_{max} \quad for\ bus\ N\ the\ operating\ voltage \tag{3.19}$$

3.6 Genetic Algorithm (GA)

Genetic Algorithm (GA) is a famous population-based technique [63], using the strongest/fittest chromosomes to move towards a better/fitter generation. The next generated chromosomes are controlled by the crossover and mutation techniques. This process is repeated until the global optimum chromosome is identified. The algorithm starts after receiving the initial generation from the initialization process.

Selection is the first step in GA, which is randomly selecting two chromosomes and comparing their fitness. The fittest will be copied to the next population or selected to be the first parent. This process is repeated until the required population is met, so the same chromosome can be copied, more than once, to the next population.

The next step is the crossover which is a method of sharing information between chromosomes. The crossover method used in this thesis is $BLX - \alpha$ and it is represented by the following equations:

$$\boldsymbol{let}: k = \frac{1}{2} \times \ population\ length \tag{2.2}$$

$$c_1 = \min(population\ (2 \times k - 1), population\ (2 \times k, b)) \tag{2.3}$$

$$c_2 = \max(population\ (2 \times k - 1), population\ (2 \times k, b)) \tag{2.4}$$

$$I = c_2 - c_1 \tag{2.5}$$

$$c_{min} = c_1 - I\ \times \alpha \tag{2.6}$$

$$c_{max} = c_2 - I\ \times \alpha \tag{2.7}$$

$$population\ (2 \times k - 1) = c_{min} + (c_{max} - c_{min}) \times rand\ (0,1) \tag{2.8}$$

$$population\ (2 \times k) = c_{min} + (c_{max} - c_{min}) \times rand\ (0,1) \tag{2.9}$$

Where, c_1, c_2, c_{min}, c_{max} and I are the parameters used for $BLX - \alpha$ crossover technique. Population length is the total number of solutions available in one population, α is the crossover factor and it is usually between 0 to 2. While $rand\ (0,1)$ is a randomized number between 0 to 1.

Following this is the mutation, which is a simple change in the chromosome to play with its structural variability. It plays the role of exploring to avoid missing any genetic materials. There are several mutation methods, but this thesis uses the non-uniform mutation method. The non-uniform mutation is applied as follows:

$$\boldsymbol{let}: k = population\ length \tag{2.10}$$

$$\Delta = \left(1 - rand\ (0,1)\right)^{\left(\left(\frac{1-iter}{ITER}\right)^{beta}\right)} \tag{2.11}$$

$$randsample\ either\ 1\ or\ 0 \tag{2.12}$$

$$\boldsymbol{if\ 1}: Population\ (k) = Population\ (k) - \Delta \times (Population\ (k) - limit(1)) \tag{2.13}$$

$$\boldsymbol{if\ 0}: Population\ (k) = Population\ (k) + \Delta \times (limit(2) + Population\ (k)) \tag{2.14}$$

Where, $rand\ (0,1)$ is a randomized number between 0 to 1, $limit(1)$ is the lowest value limit specified, $limit(2)$ the highest value limit specified, $iter$ is the current iteration number, while $ITER$ is the last iteration number where the optimization is supposed to stop. Finally, $beta$ is the non-uniform mutation constant chosen by the user and it is usually 2.

The final step in GA is conducting a final check on the new generation and checking it with the previous generation. There are several ways to make sure the fittest will go to the next generation. This thesis randomly selects two chromosomes and compares their fitness; the fittest will advance to the next generation.

3.7 Sine and Cosine Algorithm (SCA)

Stochastic analysis to find the optimal solution is the way for population-based optimization techniques. It generates a random solution to be evaluated by the objective function to determine its fitness. It's using its best values to guide the remaining towards the optimal. Over a course of iterations, it will be able to reach to the global optimal.

Sine and cosine optimization technique is one of the population-based techniques. It has been presented and explained in details in the paper [64]. This name was selected due to the presence of sine and cosine in the optimization function, using its signal wave behavior to move towards the optimum value.

Optimization algorithms have two phases, exploration and exploitation [64], using the unit circle as an example to represent the search space, while the best solution is the center. Exploration outside the unit circle to find new search spaces and exploitation inside the unit circle to move towards the optimal, are the technique used by SCA in the equations below [64]:

$$X_i^{t+1} = \begin{cases} X_i^t + r_1 \times \sin r_2 \times |r_3 P_i^t - X_i^t|, \; r_4 < 0.5 \\ X_i^t + r_1 \times \cos r_2 \times |r_3 P_i^t - X_i^t|, \; r_4 \geq 0.5 \end{cases} \tag{3.20}$$

Where, X_i^t is the current solution position and P_i^t is the best solution obtained, so far. r_1, r_2, r_3, and r_4 are SCA parameters.

SCA parameters will use the main rule to move towards the optimal. Where, r_1 is to direct the next movement, either to be inside or outside the region, and r_2 is a random value between [0, 2π] which indicates one cycle. r_3 is an added random weight ranged between [0, 2] to P_i^t, to be emphasized or deemphasized. Finally, sine and cosine are randomly selected, based on the equal probability r_4.

The effect of SCA parameter r_1 on exploration and exploitation can be calculated as follows:

$$r_1 = a - t \times \frac{a}{T} \tag{3.21}$$

Where, a is a constant value equal to 2, t is the current iteration and T is the maximum number of iterations.

The SCA parameters vary the search space between [-2, 2]. When the range is between [-1, 1], the search space will be exploited, and it will be explored when the return value is more than 1 or less than -1. The SCA parameters' effect on exploration and exploitation are shown in Figure 3.6, where the blue dot is P_i, the green dot is X_i, the black shaded area is the exploited area and the explored area is shaded with orange. Figure 3.7 shows the shrinking behavior in SCA signals towards the exploitation range [-1, 1] after half of the iterations have passed.

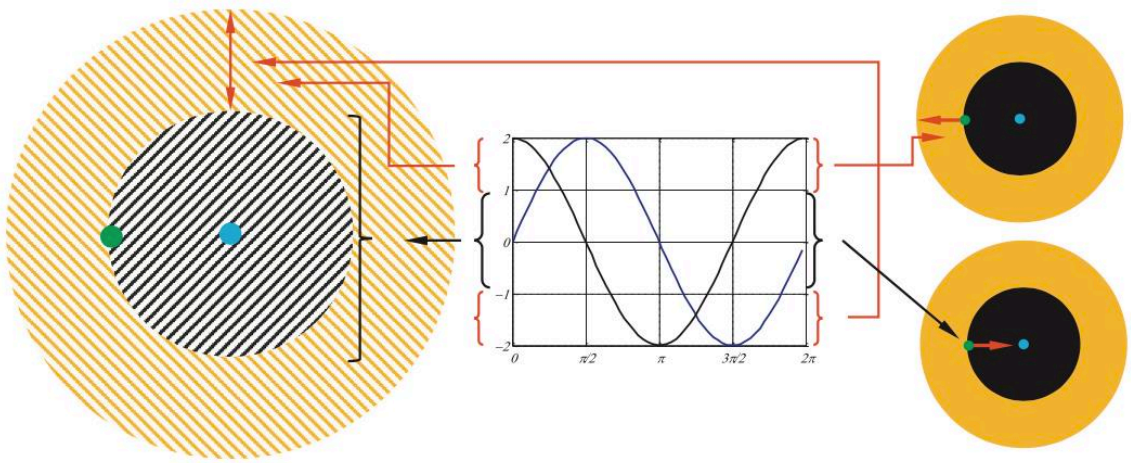


Figure 3.6 SCA Exploration and Exploitation

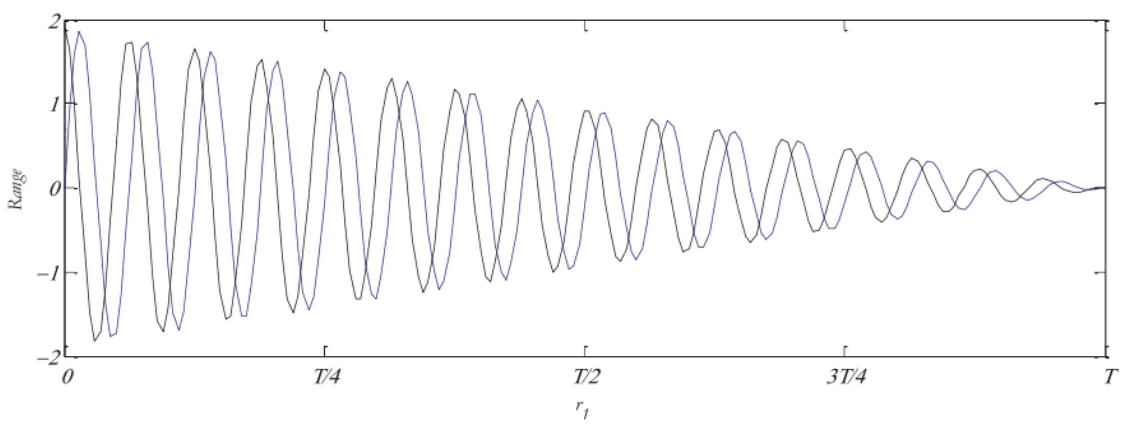


Figure 3.7 SCA Signals Shrinks towards Exploitation Area

3.8 Grey Wolf Optimization (GWO)

The grey wolf optimization (GWO) is selected to be used in this thesis to verify the robustness of the proposed formulation. It is explained in [65], which is inspired by the grey wolves' hunting mechanism. The scientific name of the grey wolf is the Canis lupus. The wolves are live in groups. Each group or pack contains 5–12 wolves on average. The group is divided into four dominance levels. These levels are alpha (α), beta (β), delta (δ) and omega (ω). The dominance levels are classified based on the rules and responsibilities of each level.

Alpha is the leader of the pack. The strength and hunting techniques are not the leader's main responsibilities, its primary role is to manage the pack. Each leader has a backup for helping and providing advice to the leader when needed. In addition, the backup takes care of the pack and handles the leadership responsibilities when the leader (alpha) disappears or passes away. The third dominance level is deltas. They are subordinates and they are distributed to do several activities such as hunting, taking care of injured partners, scouting the area and guarding the pack. The final dominance level is Omegas. They are dominated by rest of the grey wolf levels.

This optimization technique was developed based on the hunting strategy and social behavior of the grey wolves. The hunting strategy of grey wolves can be summarized in four main steps [65]:

1) Tracking the prey slowly.
2) Approaching the prey without being noticed.
3) Encircling the prey to close all escaping paths and stop movement.
4) Attacking the prey from the best spot.

So, it is a TAEA technique (Tracking, Approaching, Encircling and Attacking). The same strategy is used to find or to hunt for the optimal solution. The dominance level, as compared to the algorithm level is shown in Table 3.4 below, and in Figure 3.8.

Table 3.4 Algorithm Levels vs. Wolves Dominance Levels (GWO)

Grey Wolves Dominance Levels	Algorithm Levels in One Population
Alpha (α)	Best candidate solution
Beta (β)	Second candidate solution
Delta (δ)	Third candidate solution
Omegas (ω)	Remaining population

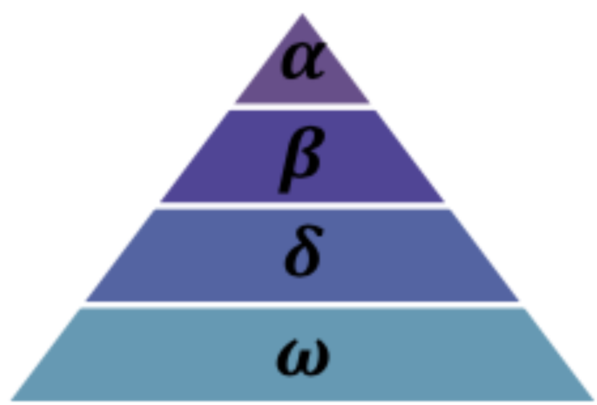


Figure 3.8 Grey Wolves Dominance Level

These were represented as a mathematical model for optimization and finding the optimal solution. The GWO uses the concept of the hunting. As the alpha (α), beta (β) and deltas

(δ) are the top three dominance levels, they guide the hunt. However, omegas (ω) follow the lead of these three. The hunting strategy of grey wolves is modeled mathematically as alpha (α) the best solution in the population, beta (β) the second-best solution, and delta (δ) as the third best. The mathematical equations are as follows:

$$D_\alpha^t = |C_1^t \cdot X_\alpha^t - X^t| \tag{3.22}$$

$$D_\beta^t = |C_2^t \cdot X_\beta^t - X^t| \tag{3.23}$$

$$D_\delta^t = |C_3^t . \cdot X_\delta^t - X^t| \tag{3.24}$$

$$X_1^t = X^t - A_1^t \cdot D_\alpha^t \tag{3.25}$$

$$X_2^t = X^t - A_2^t \cdot D_\beta^t \tag{3.26}$$

$$X_3^t = X^t - A_3^t \cdot D_\delta^t \tag{3.27}$$

$$X^{t+1} = (X_1^t + X_2^t + X_3^t)/3 \tag{3.28}$$

Where, X_α^t is the best candidate solution, X_β^t is the second best, X_δ^t is the third best, t represents the iteration, so, X^t will represent the current solution or as a hunting concept, represented through the wolf position. The encircling behavior during prey hunting is represented mathematically as $X_{1,2,3}^t$ and $D_{\alpha,\beta,\delta}^t$. Finally, $A_{1,2,3}^t$ and $C_{1,2,3}^t$ are coefficients vectors. The coefficient vectors can be calculated three times for each candidate solution α, β and δ using:

$$A = 2a \cdot r - a \tag{3.29}$$

$$C = 2 \cdot r \tag{3.30}$$

Where, r is a random variable between [0, 1] that is generated six times. These six results are broken down to three times for A, and three times for C. While a is a value starting from 2 and decreasing linearly to 0, to make sure the possible areas of solutions are scanned. The calculation of a depends on the iteration number and can be calculated as follows:

$$a = 2 - (current\ iter.) \times (2/Max\ iter.) \tag{3.31}$$

The concept of position update using the previous equations for GWO is shown in Figure 3.9. While the next expected grey wolf movements towards the prey (best solution) is shown in Figure 3.10.

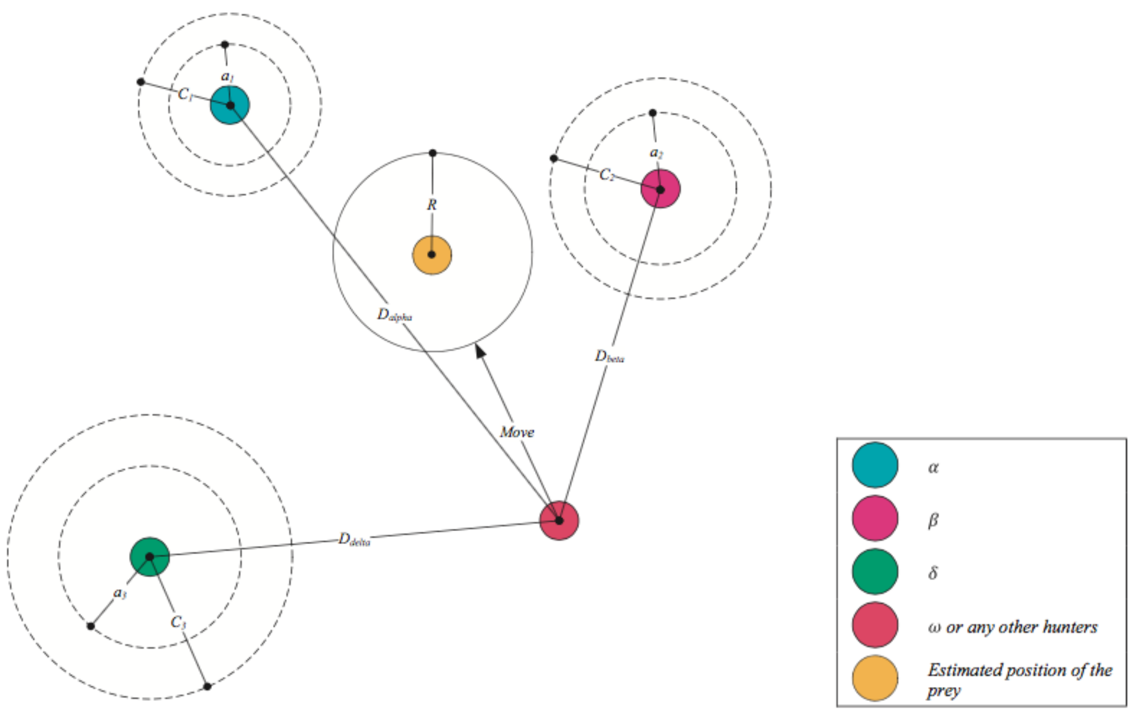


Figure 3.9 Position Update in GWO

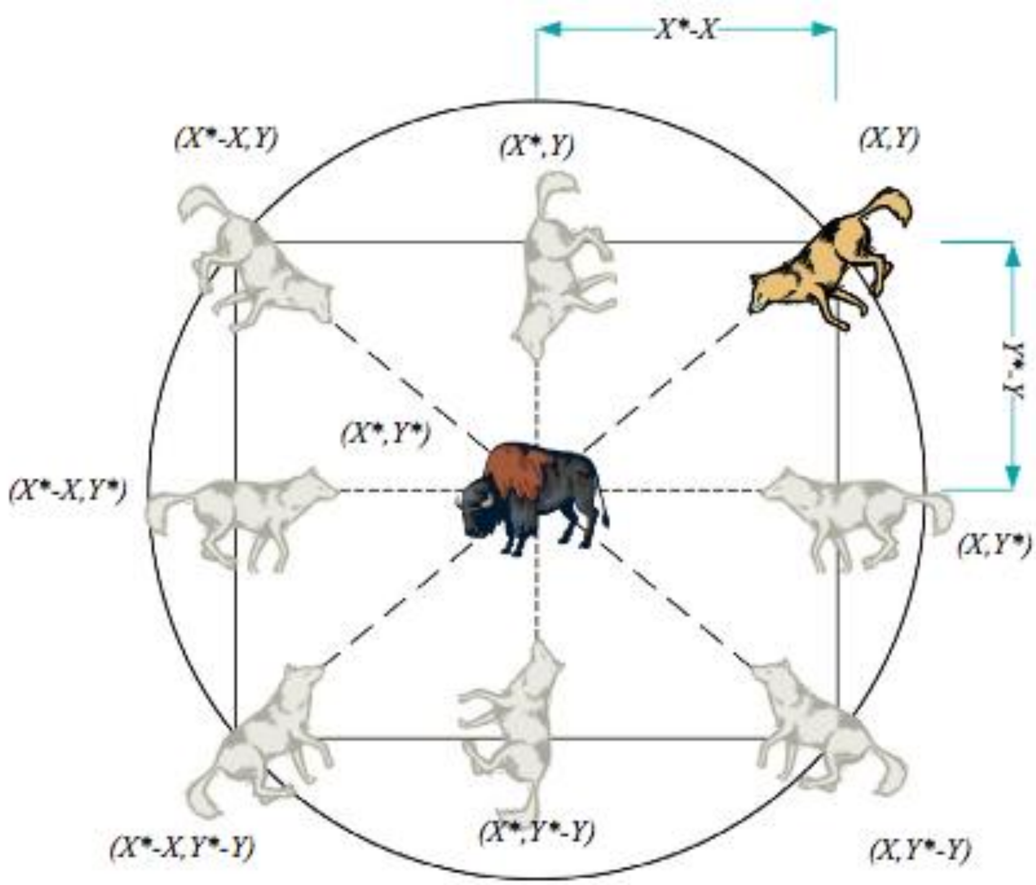
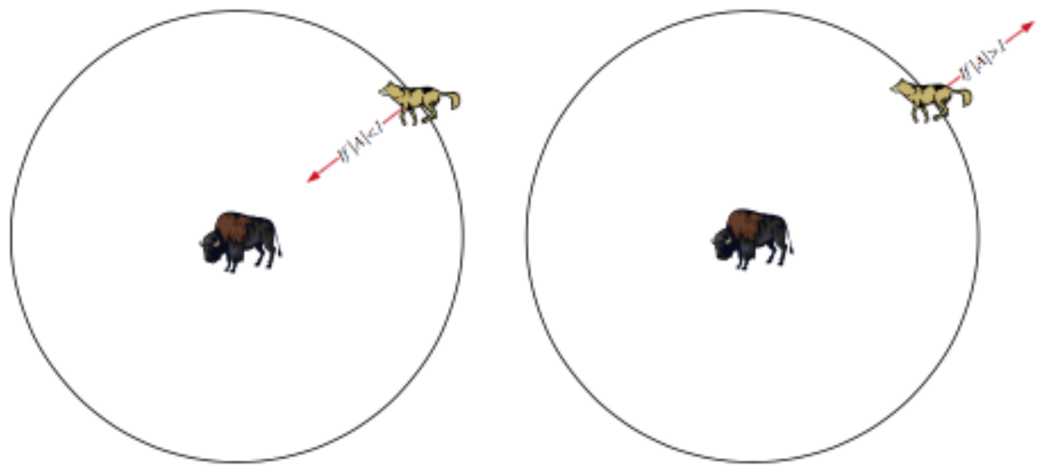


Figure 3.10 Next Expected Movement for the Grey Wolf

Till now, three steps have been mathematically modeled: tracking, approaching and encircling. Moving to the final step in the hunting strategy of grey wolves, attacking the prey. In mathematical representation, this is considered as finding the optimal solution. GWO is a population-based optimization technique. The solution of the optimization technique is divided into two phases: exploration and exploitation. Exploration is moving away from the targeted solution to search the area for other better solutions—searching for preys in terms of the hunting concept. While exploitation, is moving towards the targeted solution, which is attacking the prey.

As explained before a is linearly decreasing from 2 to 0 over several iterations. This will affect the area of the coefficient A from $[-a, a]$. Which means, if A more than 1 and less than -1, the movement will be away from the targeted solution to explore the area. While if, A is between [-1, 1], the next movement will be towards the targeted solution as exploitation. The movements are clarified in Figure 3.11.



(a) **(b)**

Figure 3.11 (a) Exploitation or Attacking vs. (b) Exploration or Searching

3.9 Black Wolf Optimization (BWO)

The enhanced GWO is called black wolf optimizer (BWO) in this thesis. GWO is a great technique and proved its quality with regards to other problems [66] [67] [68] [69]. However, GWO didn't perform as expected in this problem. So, an enhancement was proposed which significantly improved the results.

The grey wolves could be black due to the marriage between the grey wolves and dogs. The black colored grey wolves are called black wolves. Due to the merged genetics, the outcome could be something with a different mind and smarter. This concept is used to enhance the results of the GWO. The assumption made is that the black wolf is part of the subordinates, which will support in hunting preys.

This will be modeled mathematically. It is known that the alpha (α) is the leader and beta (β) is the vice leader. In GWO, alpha (α) and beta (β) were the two best solutions and the best hunters. As mentioned before, they are leaders in managing the pack, but it doesn't mean that they are the best in hunting. However, deltas (δ) are the subordinates and the pack hunters with the best hunter star ($Star$) among the pack as well. Star ($Star$) is the best hunter, the fastest and the most intelligent. Star ($Star$) always has the best movements and helps when the time comes to catch the prey (see Table 3.5).

The black wolf, mathematically, is the global optimal which is the best-obtained solution over all iterations. So, equation (3.28) will have a slight improvement, as follows:

$$X^{t+1} = (X_1^t + X_2^t + X_3^t + X_{Star}^t)/4 \tag{3.32}$$

Where, X_{Star}^t is the global optimal. The remaining steps and equations are similar to the GWO.

Table 3.5 Algorithm Levels vs. Wolves Dominance Levels (BWO)

Grey Wolves Dominance Levels	**Algorithm Levels**
Star ($Star$)	Global Optimal (Best among all populations)
Alpha (α)	Best candidate solution in the population
Beta (β)	Second candidate solution in the population
Delta (δ)	Third candidate solution in the population
Omegas (ω)	Remaining population

CHAPTER 4

PROPOSED METHODOLOGY

4.1 Overview

The problem will start by conducting the Monte Carlo Simulation for the specified circuit in order to get the failure rates considering and not considering transient events. Then, the load flow will be conducted using Newton Raphson for the selected system. The constraints parameters are checked after the load flow. Once a bus will be identified as violating power factor limit, the bus will be selected for initialization process. The initialization will randomize the capacitor values taking into consideration the remaining constraints. If the voltage limits were violated for a certain number of times, the upstream transformer taps will be adjusted accordingly and the following scenarios are repeated until the limits are met. Below is the summery of the previous explanation where TTR is the Transformer Turns Ration:

$If\ V > 1.05\ of\ system\ voltage$

$$\gg\ \boldsymbol{Increase}\ the\ transformer\ tap - ratio\ by\ 1\%$$

$$Transformer\ Tap\ Ratio\ (TTR) = TTR + 0.01 \tag{4.1}$$

$If\ V < 0.95\ of\ system\ voltage$

$$\gg\ \boldsymbol{Decrease}\ the\ transformer\ tap - ratio\ by\ 1\%$$

$$Transformer\ Tap\ Ratio\ (TTR) = TTR - 0.01 \tag{4.2}$$

If the transient limits were violated (frequency, inrush current or both) for a certain number of times, the following equation with 10% added a factor (in order not to be in the limit) is used to calculate the required inductance to be added (Damping Reactors (DR)):

$$DR = \frac{1}{(2\pi f)^2 \times 0.9 \times MVAR} \tag{4.3}$$

where $MVAR$ is the capacitor rating and f is the maximum transient frequency limit for a certain voltage as per ANSI C37.0732 requirements.

Once all constraints are passed for a certain bus with the randomized capacitor value, the total cost and the avoided costs will be calculated as per the previous explanation. Then, it will be added to the first generation as part of the optimization process.

4.2 Monte Carlo Simulation

Monte Carlo Simulation (MCS) is a well-known stochastic technique [70] [71]. It randomizes the samples of complex system parameters to explore the system behavior. For example, if the failure rates and repair times of a breaker and a cable supplying the load are known, then these rates can be used in the MCS to find the overall circuit failure rate and repair time. There are several techniques to do that, but the MCS is very simple even for complicated systems. However, it's very slow and takes a long simulation time because it simulates the failure for each equipment individually. Then, it starts counting the parallel and series behaviors of the system to find the final failure rate and repair time.

It is a great stochastic approach to quantify the system failures. It requires the failure rate for all the system components with the time needed to repair that equipment. This data are available in IEEE gold book for all electrical equipment. It was presented previously and represented in here in Table 4.1.

These data will be used in the proposed formulation to conduct Monte Carlo Simulation for 100 years in order to quantify the failure rate for the circuit before and after installing capacitor banks. In addition, it will quantify the failure rate for the circuit with considering and without considering transient events. The circuit in Figure 4.1 will be used for Monte Carlo Simulation.

Table 4.1 Electrical System Components Failure Rates

Component	Failure Rate	Repair Time
Line/Cable	0.0141	40.4
Damping Reactor	0.04	150
Capacitor	0.17443	2.3
Circuit Breakers (Considering Transient)	0.003	129
Circuit Breakers (Not Considering Transient)	2	129

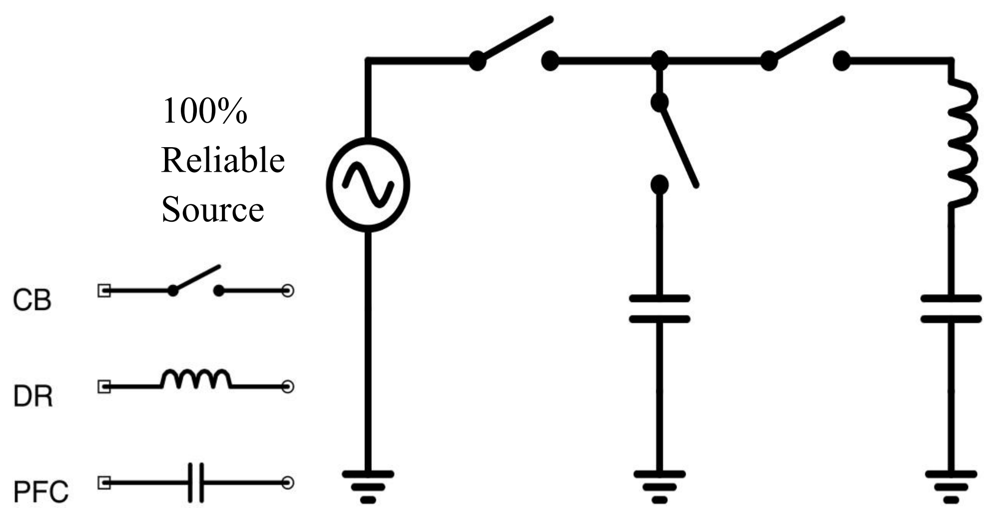


Figure 4.1 Monte Carlo Simulation Evaluated Circuit

4.1 Initialization

Initialization is the step before starting the optimization process where the first generation is randomly collected in order to use them in the optimization process. Randomizing the capacitance value is the starting point for the initialization. The capacitance values are represented in MVAR. Randomization process takes a long time to find the suitable values if the search range was not set properly due to the huge number of buses with their different configurations. So, the following equation used to minimize the randomization process by only concentrating on the maximum capability of the bus MVAR. The used equation is shown below:

$$Q_{shunt}\ (Mvar) = \ rand\ (0,1)\ \times\ Q_{load} \tag{4.4}$$

Where Q_{shunt} is the randomized capacitance is value in MVAR and Q_{load} is the actual reactive power consumption of the selected bus. While $rand\ (0,1)$ is a randomized value between [0, 1].

The finalized steps for initialization are as follow and Figure 4.2 is the flow chart summarizing these steps:

1) **Start** the initialization process.
2) **Conduct** optimal load flow using Newton Raphson method.
3) **Identify** the buses violating power factor limit ($PF\ <\ 0.95$).
4) **Set** K_v, K_f, K_s equal to 1.
5) **Initialize** the system capacitor values using equation 4.4 for each bus.
6) **Evaluate** $PF \geq\ 0.95$; if **NO** go to step 5 to initialize again.

7) **Evaluate** $0.95 \leq V_{pu} \leq 1.05$:

   a) If **NO Evaluate** $K_v > FK_v$:

   - If **NO** get back to step 5 to initialize again.
   - If **YES** modify transformer tap-ratio as shown in equation 4.1 and 4.2, then, get back to step 4 to set the system parameters again

   b) If **YES** get back to step 5 for initialization again.

8) **Evaluate** transient constraints $f < 3360$ and $I < 16kA$; if **NO** install damping reactor using equation 4.3 and get back to step 4 to initialize again.

   a) If **NO Evaluate** $K_f > FK_f$:

   - If **NO** get back to step 5 to initialize again.
   - If **YES** modify transformer tap-ratio as shown equation 4.1 and 4.2, then, get back to step 4 to set the system parameters again.

   b) If **YES** get back to step 5 for initialization again.

9) **Copy** the capacitor values for each bus as a solution for the first iteration.

10) **Evaluate** $K_s > FK_s$:

    a) If **NO** get back to step 5 to initialize again.

    b) If **YES** go to step 11.

11) **End** the initialization process.

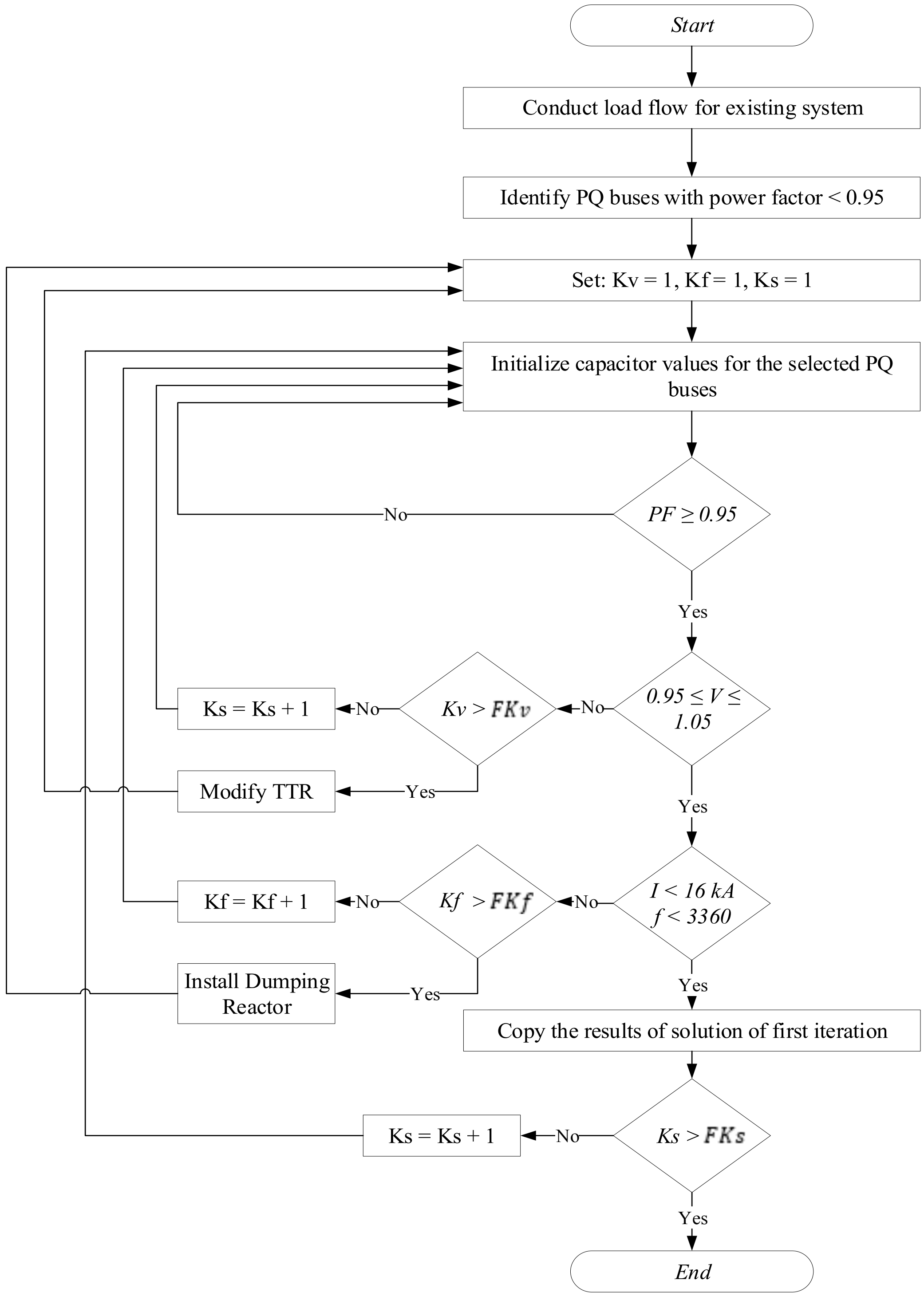


Figure 4.2 Initialization Process Flow Chart

4.2 Genetic Algorithm (GA)

Initial values will be used in GA to be processed in its steps. Starting from parents' selection, $BLX - \alpha$ crossover, and mutation. Finalized steps are as below:

1) **Update** the best capacitor value obtained so far for each bus.
2) **Update** crossover and mutation factors.
3) **Select** two random values from the population.
4) **Compare** their fitness.
5) **Select** the fittest as the first parent.
6) **Select** another two random values from the population.
7) **Compare** their fitness.
8) **Select** the fittest as the second parent.
9) **Evaluate** the crossover probability to do $BLX - \alpha$ crossover as per equations between 2.2 and 2.9.
10) **Evaluate** the mutation probability to do non-uniform mutation as per the equations from 2.10 to 2.14.
11) **Check** the limits constraints.
12) **While** the maximum number of iterations not reached or the stopping criteria not matched repeat the steps from 1 to 11.

4.3 Sine Cosine Algorithm (SCA)

SCA starts optimization for the first generation after initialization and evaluating the search agents using the objective function. SCA steps are as follows:

1) **Update** the best capacitor value obtained so far for each bus (P_i).
2) **Update** SCA parameters r_1, r_2, r_3, and r_4.
3) **Evaluate** Sine function (3.20) if $r_4 < 0.5$.
4) **Evaluate** cosine function (3.20) if $r_4 \geq 0.5$.
5) **Update** the search agent's position, which is the new capacitor value.
6) **Check** the limits constraints.
7) **Evaluate** the new capacitor values for each bus using the objective function.
8) **Copy** the fittest values comparing the previous and the current iteration to the new iteration.
9) **While** the maximum number of iterations not reached or the stopping criteria not matched repeat the steps 1 to 8.

4.4 Gray Wolf Optimizer (GWO)

Once the initialization completed and first looped values over the iterations received with its fitness. GWO starts optimizing flowing these steps:

1) **Update** the best capacitor value obtained so far for each bus.
2) **Update** the parameters a, r_1 and r_2.

3) **Evaluate** A_1, A_2, A_3, C_1, C_2, and C_3.

4) **Sort** the population values to have the fittest on the top.

5) **Update** X_α^t as best, X_β^t as second best and X_δ^t as third best.

6) **Evaluate** D_α^t, D_β^t, and D_δ^t.

7) **Evaluate** X_1^t , X_2^t , and X_3^t .

8) **Update** the search agent's position, which is the new capacitor value using (3.28).

9) **Check** the limits constraints.

10) **Evaluate** the new capacitor values for each bus using the objective function.

11) **Copy** the fittest values comparing the previous and the current iteration to the new iteration.

12) **While** the maximum number of iterations not reached or the stopping criteria not matched repeat the steps 1 to 11.

4.5 Black Wolf Optimizer (BWO)

Similarly, BWO starts optimizing as follow:

1) **Update** the best capacitor value obtained so far for each bus (X_{Star}^t).

2) **Update** the parameters a, r_1 and r_2.

3) **Evaluate** A_1, A_2, A_3, C_1, C_2, and C_3.

4) **Sort** the population values to have the fittest on the top.

5) **Update** X_α^t as best, X_β^t as second best and X_δ^t as third best.

6) **Evaluate** D_α^t, D_β^t, and D_δ^t.

7) **Evaluate** X_1^t , X_2^t , and X_3^t .

8) **Update** the search agent's position, which is the new capacitor value using (3.32).

9) **Check** the limits constraints.

10) **Evaluate** the new capacitor values for each bus using the objective function.

11) **Copy** the fittest values comparing the previous and the current iteration to the new iteration.

12) **While** the maximum number of iterations not reached or the stopping criteria not matched repeat the steps 1 to 11.

4.6 Optimization Output

The previously explained optimization techniques with their steps are to select the most appropriate capacitor values that will meet the highest avoided cost as formulated in the objective function. The required transformer tap-ratio settings and the damping reactor value are selected and sized based on the constraints valuation as per the explanation in chapter 3.

All these parameters are involved in the objective to find the total paid and avoided cost as explained in problem formulation section. Then, the ranking process will be conducted and the lower fitness values will be excluded from moving to the next iteration. This will be repeated until the end of the selected iterations or until the cost converges and doesn't change for a certain number of iterations.

Finally, the capacitor MVAR values had led to the best-avoided cost will be selected as the best sizes. The result will include the transformers tap ratios values and the damping reactors sizes. Likewise, the reliability calculations will be presented as well.

CHAPTER 5

CASE STUDIES AND LOAD MODELING

5.1 Case Studies and System Parameters

The proposed formulation will be evaluated and tested on two different systems. These systems are Graver's test system and IEEE-30 test system. The date of these two systems are available in the Appendix A and Appendix B of this thesis and in [62] and [72]. Graver's test system is a simple system used to test the proposed formulation and prove the hypotheses made in this thesis. The system consists of 5 buses. Three of these buses have generators and two are load points. However, this simple system is not enough to check the system robustness. Thus, IEEE-30 test system is used which contains 30 buses divided into 21 load buses, 6 generator buses and the remaining are distribution points. The two systems one-line diagrams are showing all buses in detail in Figure 5.1 and Figure 5.2.

These two systems will be tested as 69kV network configuration system for distribution. The transient constraints classified in ANSI C37.0732 according to the system voltage. Which limited 69kV to 16kA inrush switching current and 3360Hz resonance frequency.

In back-to-back switching model, there is cable connected between the two installed capacitor. That line has an inductance (L_{eq}) and selected to be $16\mu H$ [59]. System voltage has a limit to control the tap ratios. It is selected to be in per unit limits $+/-\ 5\%$. And as stated before the power factor is limited to 0.95 at each bus. The generators can be used to modify the power factor. Thus, only load buses will be considered in this case studies.

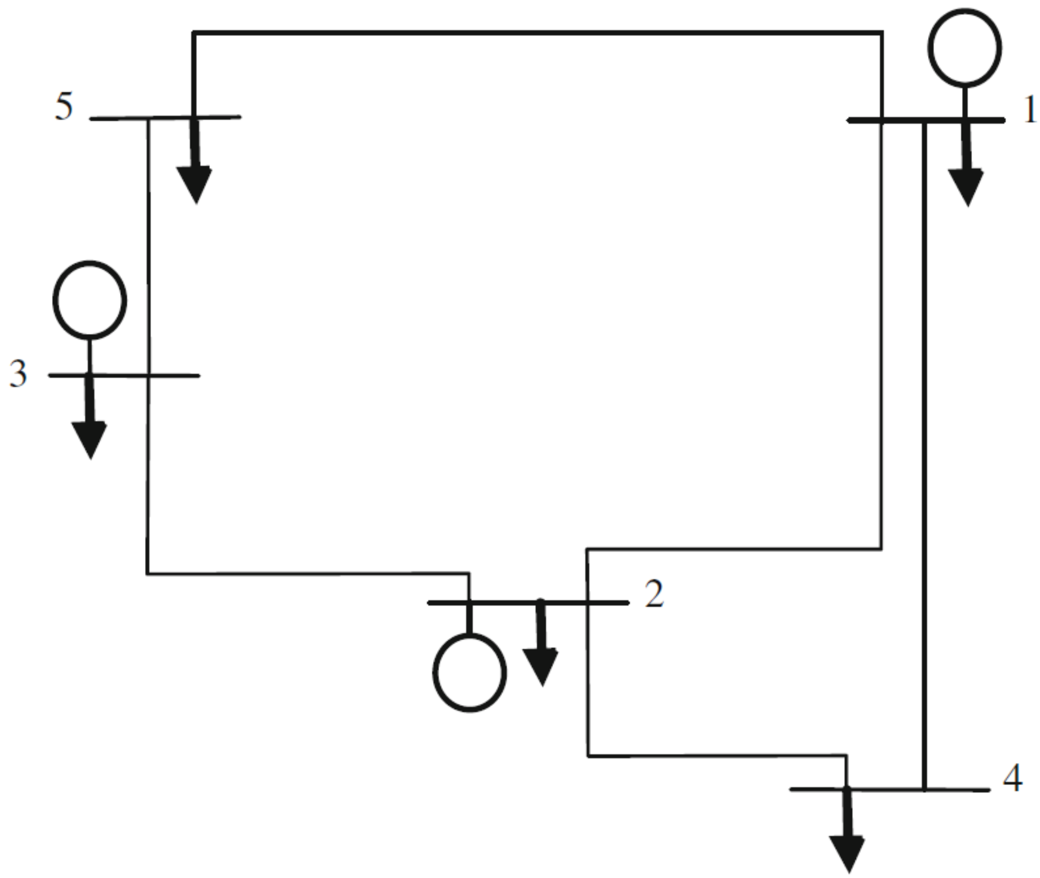


Figure 5.1 Garver's Test System

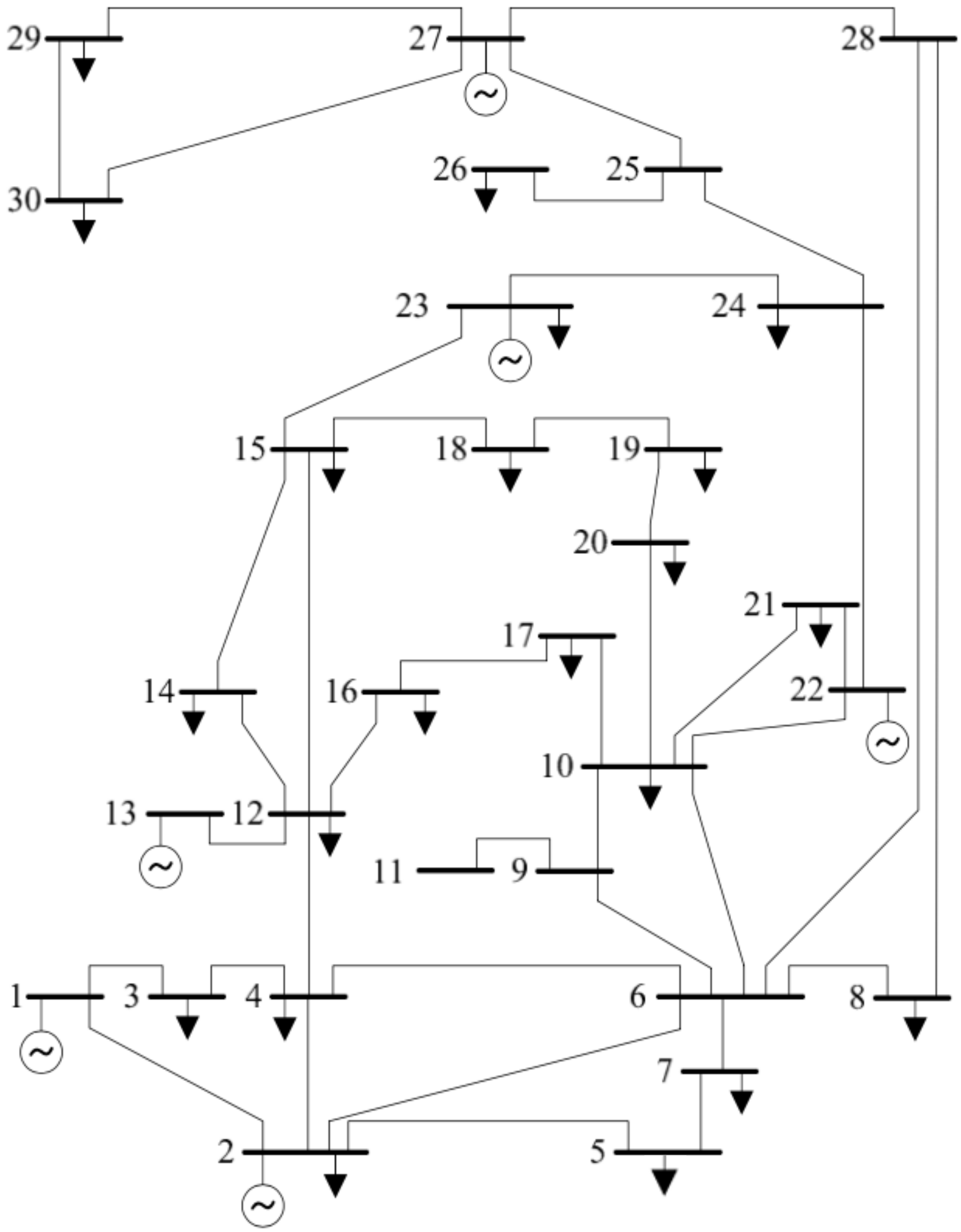


Figure 5.2 IEEE-30 Bus Test System

5.2 Load Modeling and System Expansion

To include the future expansion and check the robustness of the proposed formulation, the problem formulated to be planning issue. In addition, as stated before the future expansion will impact the power factor due to the increase in the reactive power consumption. Thus, in order to solve the issue, another power factor correction capacitor will be installed in a back-to-back with the existing capacitor. This will cause a transient issue to the system and will impact the reliability. In addition, it will cause the problem to be more difficult and this will evaluate the problem formulation under excessive load changes.

The system load growth is approximated by Electricity and Co-Generation Regulatory Authority (ECRA) historical data presented in the yearly report. The planning will be done for 10 years, every 5 years considered a cycle. So, ECRA data used to forecast the load for the next 10 years using the simple moving average technique with 5 years planning horizon. The load growth data is shown in Table 5.1.

Table 5.1 Load Growth Factor for 10 Years

Year	Growth Factor	Year	Growth Factor
Year 1	6.1100%	Year 6	6.3300%
Year 2	6.4300%	Year 7	6.3200%
Year 3	6.2700%	Year 8	6.3250%
Year 4	6.3500%	Year 9	6.3225%
Year 5	6.3100%	Year 10	6.3238%

Table 5.2 Load Growth Factor at End of Year N

Year 5	1.36
Year 10	1.84

5.3 PFC Design Planning

After including the expected load growth of future expansion, this expansion was averaged to two cycles for 10 years planning. Each cycle is planning for 5 years. Thus, the total cost shall be calculated to include all avoided costs in each year including the discount rate stated as 5%. The discount rate is to calculate the Net Present Value (NPV). NPV for realistic study and evaluation, the planning problem has to be represented as a dynamic type.

The investment cost is paid once in the first year only. So, the discount rate will have no impact. However, the avoided penalty, energy loss minimization, and failure costs will be impacted by the discount rate. These costs are continues for several years which require being planned using the dynamic type planning to get the NPV. The following equations are used to calculate each cost including the discount rate:

$$\sum_{t=1}^{T}(1+d)^{-t'-0.5} \times C_{PFC} \tag{5.1}$$

$$\sum_{t=1}^{T}(1+d)^{-t'-0.5} \times C_{ELM} \tag{5.2}$$

$$\sum_{t=1}^{T}(1+d)^{-t'-0.5} \times C_{RC} \tag{5.3}$$

$$t' = current\ year - 1 \tag{5.4}$$

where T is the final year in the planning cycle and d is the discount rate. While C_{PFC}, C_{ELM}, and C_{RC} with the installation/investment cost are calculated as follow:

$$C_{PFC} = kvarh\ cost \times 8760 \times P\ (\tan(\cos^{-1} 0.95) - \tan(\cos^{-1} PF_{before})) \quad (5.5)$$

$$C_{ELM} = \left(kwh\ cost \times \left(P_{af} - P_{bef}\right) + kvarh\ cost \times \left(Q_{af} - Q_{bef}\right)\right) \times 8760 \quad (5.6)$$

$$C_{RC} = (kwh\ cost \times P + kvarh\ cost \times Q) \times \lambda_{new-N} \times 8760 \quad (5.7)$$

$$C_{install} = Mvar\ cost \times Required\ Mvar + mH\ cost \times Required\ mH \quad (5.8)$$

5.4 Overall Problem Solution Methodology

The problem will go through a lot of checking steps and simulations. To simplify the problem solution, the finalized steps are as below and the flowchart in Figure 5.3:

1) **Start** the problem solution.
2) **Simulate** the new system failure rates using Monte Carlo Simulation (MCS).
3) **Start** planning for PFC capacitors design on the proposed case study for $year = 1$.
4) **Conduct** optimal load flow using Newton Raphson method.
5) **Identify** the buses violating power factor limit ($PF < 0.95$).
6) **Initialize** the capacitor value for each bus.
7) **Conduct** Initialization process as explained in Chapter 4.
8) **Optimize** the system parameters using the proposed optimization techniques over the selected number of iterations as explained in Chapter 4.
9) **Conduct** load flow and find Thevenin impedance at the identified PQ buses.

10) **Evaluate** the optimized solutions against problem constraints at each PQ bus:

- If the solution didn't pass one of the constraints get back to step 8.
- If the solution passed all constraints, move to step 11.

11) **Print** the results for $Year\ N$.

12) **While** the number of years is still less than 10 years, repeat the steps from 1 to 11 after including the load growth factor.

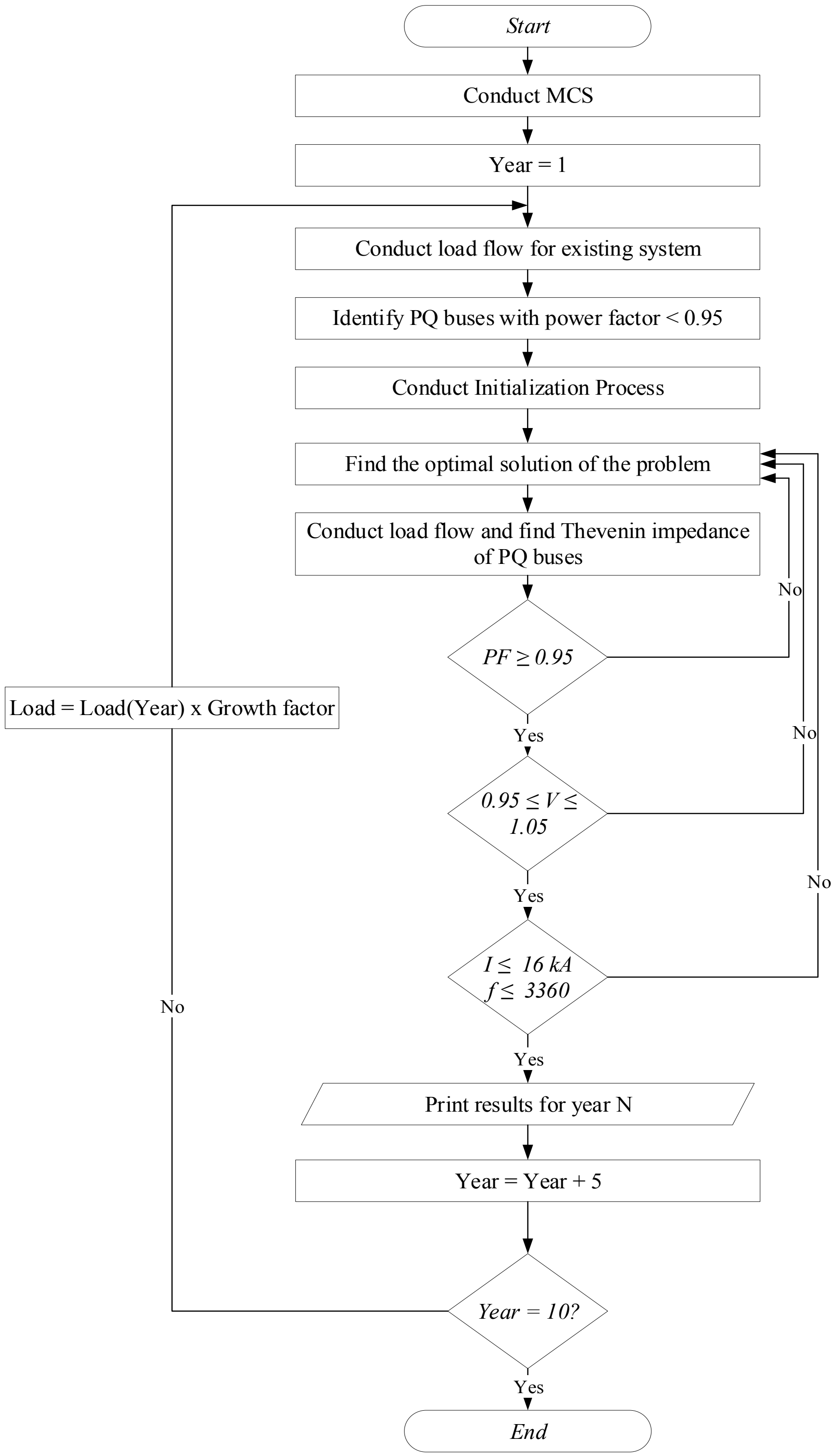


Figure 5.3 Summarized flow chart of the problem

CHAPTER 6

RESULTS AND DISCUSSIONS

To prove the difference and requirement of including the reliability analysis, the case studies divided into two main sections. First, without including the failure and reliability analysis. Second, after including them. In addition, each case study will be presented separately and will be divided to subsections to see the difference in considering and not considering the transient resonance.

6.1 Load Flow Results and System Expansion

The load flow conducted for the system twice, which is before considering the future expansion and after the consideration. The consideration of the future expansion requires incomer (main) lines expansion to accommodate the added load. Since the added load will not be more than double of the existing load as per Table 6.1 presented previously for 10 years load growth. An additional circuit shall be added in parallel to the existing otherwise the system will not be capable to accommodate the new load. In the following subsections, the load flow presented for both case studies.

6.1.1 Graver's Test System

Before starting the initialization, the load flow must be conducted to identify the buses are violating the power factor constraints. The power factor constraints have been set to 0.95

as stated before. So, the buses violating that limit will be selected. In addition, an assumption was made that all generator buses can be utilized to provide the required MVAR. Thus, only the load buses with no generation and violating the power factor limit were selected. The load flow results are shown below for Graver's test system.

Table 6.1 Load Flow Results (Original System)

BUS #	V (PU)	LOAD (MW)	LOAD (MVAR)	PF (PU)	PF (+ OR -)
4	0.937	48	23.2	0.90035	Lagging
5	0.954	72	34.8	0.90035	Lagging

The load buses are violating the power factor are bus 4 and 5. The power factor found to be 0.90035 for both buses. In addition, the voltage limits are being violated as well in bus 4. The per unit voltage is 0.937 which is below the acceptable limit 0.95. The system voltage selected to be 69kV. This drop in the voltage limit means the bus voltage become 64.653kV, which will impact other equipment operation.

The system expanded as the load growth shows the system load will increase by 36% after 5 years. This was conducted by adding another circuit in parallel with the first one. The data used for the load flow are including the impedance of the lines between the buses. The impedance of the line divided by two mathematically. However, physically means another circuit with the same size added in parallel to accommodate the new load. The concept is explained mathematically as follow:

$$\frac{1}{Z_{eq}} = \frac{1}{Z_1} + \frac{1}{Z_2} \gg Z_{eq} = \frac{Z_1 \times Z_2}{Z_1 + Z_2}$$

Assuming the same cable size, rating and materials used for the new cable. This means the two cables impedances are the same. The equation will become as follow:

$$Z_{eq} = \frac{Z^2}{2Z} = \frac{Z}{2}$$

So, dividing the line impedance by two equivalent to adding another identical circuit (line) in parallel with the existing circuit.

The load flow for 5 years expansion considering 36% load growth shown in the following table.

Table 6.2 Load Flow Results for 5 Years (Double Circuits=Z/2 to Accommodate the New Load)

BUS #	V (PU)	LOAD (MW)	LOAD (MVAR)	PF (PU)	PF (+ OR -)
4	0.959	65.28	31.552	0.90035	Lagging
5	0.970	97.92	47.328	0.90035	Lagging

The system voltage enhanced due to the added circuit. So, it is not violating the voltage limits anymore. The circuit divided the line impedance by 2, which means the voltage drop is minimized. This resulted in voltage drop enhancement.

The system expansion for the other 5 years, which lead to 84% load expansion, will be accommodated by the added circuit as the added circuit capable to handle up to double of the existing load. Due to this reason, the load flow will be the same and will not have a change in the final results. The results presenting the load flow for the 10 years case was skipped.

6.1.2 IEEE-30 Bus Test System

For the IEEE-30 is same as graver's concept. Graver's used for an easier explanation because the system is small and easy to do the calculations. The IEEE-30 is used to check the problem formulation and optimization robustness. The load flow results for the original system are shown in the below Table.

Table 6.3 Load Flow Results (Original System)

BUS #	V (PU)	LOAD (MW)	LOAD (MVAR)	PF (PU)	PF (+ OR -)
3	1.022	2.4	1.2	0.89443	Lagging
4	1.013	7.6	1.6	0.97855	Lagging
6	1.012	0	0	1.00000	Leading
7	1.004	22.8	10.9	0.90220	Lagging
9	1.051	0	0	1.00000	Leading
12	1.058	11.2	7.5	0.83091	Lagging
14	1.043	6.2	1.6	0.96828	Lagging
15	1.039	8.2	2.5	0.95653	Lagging
16	1.045	3.5	1.8	0.88929	Lagging
17	1.039	9	5.8	0.84057	Lagging
18	1.028	3.2	0.9	0.96265	Lagging
19	1.025	9.5	3.4	0.94152	Lagging
20	1.029	2.2	0.7	0.95293	Lagging
21	1.03	17.5	11.2	0.84227	Lagging
22	1.036	0	0	1.00000	Leading
23	1.029	3.2	1.6	0.89443	Lagging
25	1.022	0	0	1.00000	Leading
26	1.004	3.5	2.3	0.83571	Lagging
27	1.029	0	0	1.00000	Leading
28	1.011	0	0	1.00000	Leading
29	1.01	2.4	0.9	0.93633	Lagging

The load flow results identified 10 buses are below the acceptable power factor limits, which will lead to penalties from the utilities. These buses are 3, 7, 12, 16, 17, 19, 21, 23, 26 and 29.

As explained before, the system will be expanded with 36% load growth within the next 5 years and 84% after 10 years. The load flow for the first system expansion including the incomer lines increase to be double circuits is shown below.

Table 6.4 Load Flow Results for 5 Years (Double Circuits=Z/2 to Accommodate the New Load)

BUS #	V (PU)	LOAD (MW)	LOAD (MVAR)	PF (PU)	PF (+ OR -)
3	1.02	3.264	1.632	0.89443	Lagging
4	1.01	10.336	2.176	0.97855	Lagging
6	1.005	0	0	1.00000	Leading
7	0.998	31.008	14.824	0.90220	Lagging
9	1.041	0	0	1.00000	Leading
12	1.058	15.232	10.2	0.83091	Lagging
14	1.046	8.432	2.176	0.96828	Lagging
15	1.041	11.152	3.4	0.95653	Lagging
16	1.045	4.76	2.448	0.88929	Lagging
17	1.037	12.24	7.888	0.84057	Lagging
18	1.032	4.352	1.224	0.96265	Lagging
19	1.029	12.92	4.624	0.94152	Lagging
20	1.031	2.992	0.952	0.95293	Lagging
21	1.03	23.8	15.232	0.84227	Lagging
22	1.032	0	0	1.00000	Leading
23	1.03	4.352	2.176	0.89443	Lagging
25	1.02	0	0	1.00000	Leading
26	1.008	4.76	3.128	0.83571	Lagging
27	1.024	0	0	1.00000	Leading
28	1.003	0	0	1.00000	Leading
29	1.009	3.264	1.224	0.93633	Lagging

6.2 Case Studies Results without Including Failure Analysis

This section will be divided into four subsections. These sections are:

1) Graver's Test System without Considering Transient Resonance.
2) Graver's Test System Considering Transient Resonance.
3) IEEE-30 Bus Test System without Considering Transient Resonance.
4) IEEE-30 Bus Test System Considering Transient Resonance.

In addition, in each subsection, all four proposed optimization techniques are being used to compare the proposed approach.

6.2.1 Graver's without Considering Transient Resonance

To illustrate the transient issue, the case studies solved without considering the transient events prior the consideration and after the consideration. This section will go over the case without considering transient resonance in the problem formulation and its impact on the system.

The following tables 6.5, 6.6, 6.7 and 6.8 are showing the results of the problem formulation solved by four optimization techniques. As stated before, the optimization will start after the initialization process. It will keep checking the constraints continuously while playing with the system parameters for better results. But the capacitor switching transient constraints will not be considered and there will be no impact on the final cost.

These tables are showing the results for different optimization techniques. These techniques are GA, SCA, GWO and BWO, which have been explained previously in this thesis. The table is expressing the results in two cycles to calculate the objective functions at each one. In addition, the time to complete that algorithm was calculated to evaluate the technique robustness in finding the best result fast. Also, power factor results at each bus were presented along with the objective function to check the accuracy of the result. To have a fare comparison between the techniques by evaluating the results accuracy and operation time, the number of iterations on Graver's test system was set to 500 and the limit to stop if no change on the results is 200.

First table 6.5 is presenting GA results, which shows high accuracy in the power factor with final result of 0.95 at both buses. This high accuracy in results implies on the objective function final result, which approaches $17,224,000 avoided cost. The system operation time to reach this high accuracy results was a bit fast and acceptable.

Table 6.5 Graver's No Transient Case Study GA (500 Iterations, 200 Stop)

Technique	**GA**			
Year	1		6	
Time (s)	62.1		41.6	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95000	0.95000	0.95000	0.95000
Frequency (KHz)	0.50	0.52	13.1	10.7
Inrush Current (KA)	1.10	1.55	6.82	8.36
Capacitor (MVAR)	10.10	15.15	3.56	5.35
Damping Reactor (mH)	N/A	N/A	N/A	N/A
Installation Cost ($)	-3,565,000		-2,136,200	
ELM Cost ($)	1,155,200		556,650	
PFC Avoided Penalty ($)	13,045,000		4,602,900	
Total ($)	10,636,000		3,023,400	
Accumulated Cost ($)	10,636,000		**17,224,000**	

Moving to second table 6.6 that provide the details of SCA optimization technique on Graver's test system. This technique operation time is incredible and the speed is faster than GA for sure. However, the result accuracy is very low especially this is an easy system and the result supposes to be 100% accurate. This revealed to a negative impact on the objective function results and reduces the total avoided cost on both cycles to $17,088,000.

Table 6.6 Graver's No Transient Case Study SCA (500 Iterations, 200 Stop)

Technique	**SCA**			
Year	1		6	
Time (s)	51.3		39.3	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95110	0.95010	0.95040	0.95020
Frequency (KHz)	0.54	0.52	13.3	10.7
Inrush Current (KA)	1.11	1.55	6.75	8.39
Capacitor (MVAR)	10.35	15.18	3.43	5.40
Damping Reactor (mH)	N/A	N/A	N/A	N/A
Installation Cost ($)	-3,589,900		-2,129,100	
ELM Cost ($)	1,167,700		547,900	
PFC Avoided Penalty ($)	13,045,000		4,455,800	
Total ($)	10,623,000		2,874,600	
Accumulated Cost ($)	10,623,000		**17,088,000**	

GWO results were presented on the third table 6.7, which shows lower accuracy results compared to SCA even. However, the operation time was fast, even faster than SCA. The results accuracy indicated on the objective function result by decreasing the avoided cost to be $16,998,000.

Table 6.7 Graver's No Transient Case Study GWO (500 Iterations, 200 Stop)

Technique	GWO			
Year	1		6	
Time (s)	40.7		40.6	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95070	0.95090	0.95010	0.95020
Frequency (KHz)	0.54	0.51	13.32	10.9
Inrush Current (KA)	1.10	1.57	6.73	8.24
Capacitor (MVAR)	10.26	15.5	3.42	5.10
Damping Reactor (mH)	N/A	N/A	N/A	N/A
Installation Cost ($)	-3,607,700		-2,102,000	
ELM Cost ($)	1,173,300		530,770	
PFC Avoided Penalty ($)	13,045,000		4,350,800	
Total ($)	10,611,000		2,779,600	
Accumulated Cost ($)	10,611,000		**16,998,000**	

Finally, the proposed BWO optimization technique results were presented on table 6.8. The technique shows low operation time with high results accuracy. It considered to be best technique in finding the result. The objective function result was similar to GA results. However, the operation time is faster than GA.

Table 6.8 Graver's No Transient Case Study BWO (500 Iterations, 200 Stop)

Technique	**BWO**			
Year	1		6	
Time (s)	60.2		32.9	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95000	0.95000	0.95000	0.95000
Frequency (KHz)	0.50	0.52	13.1	10.7
Inrush Current (KA)	1.10	1.55	6.82	8.36
Capacitor (MVAR)	10.10	15.15	3.56	5.35
Damping Reactor (mH)	N/A	N/A	N/A	N/A
Installation Cost ($)	-3,565,000		-2,136,200	
ELM Cost ($)	1,155,200		556,650	
PFC Avoided Penalty ($)	13,045,000		4,602,900	
Total ($)	10,636,000		3,023,400	
Accumulated Cost ($)	10,636,000		**17,224,000**	

In conclusion, it is very clear from the results that GA and the proposed BWO, enhanced GWO, got best results in this case study. These techniques are proven on many problems, however, in this problem few techniques perform well. Even GWO didn't perform well compared to the enhanced BWO. But it is notable that the operation time for these techniques is much faster than the others. So, GWO and SCA are excellent techniques for simple problems and can find the results very fast compared to the remaining. The following figures are showing the optimization techniques performance summery. The first cycle is shown in Figure 6.1 and the second cycle is shown in Figure 6.2.

The following figures 6.1 and 6.2 were added to simplify the performance of the utilized optimization techniques. As stated before BWO performance was the best by comparing time and accuracy.

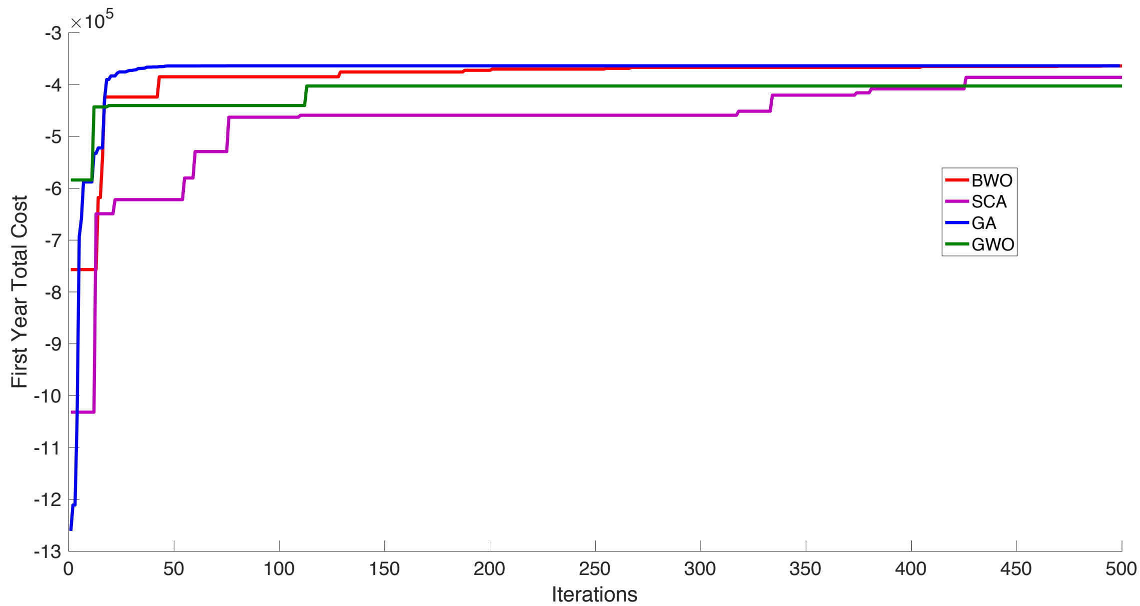


Figure 6.1 Graver's Summery Optimization Results for First Cycle No Transient Constraints

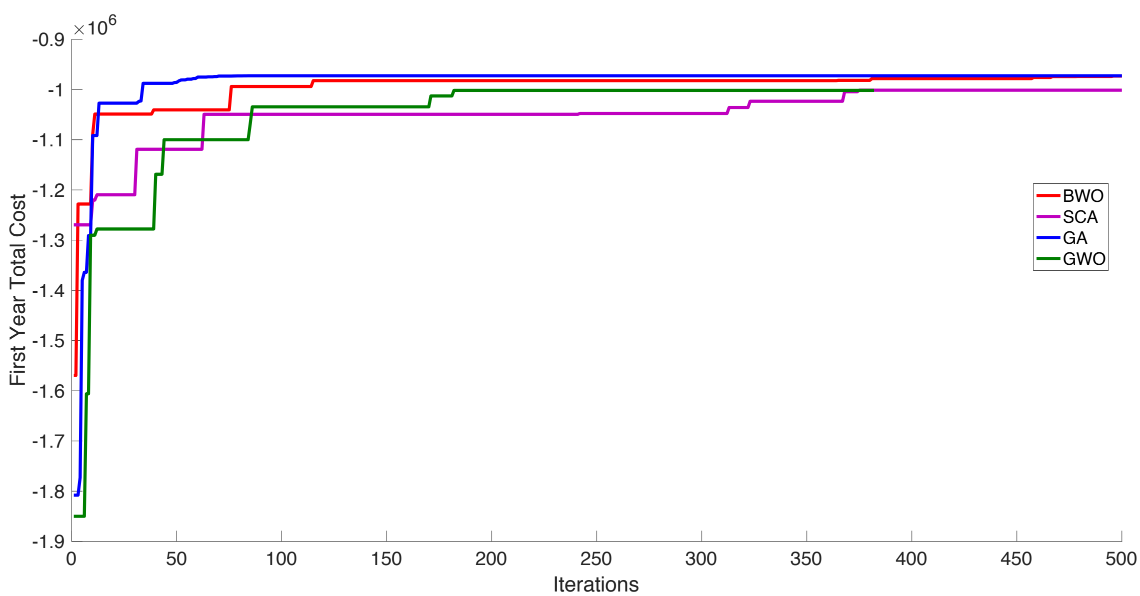


Figure 6.2 Graver's Summery Optimization Results for Second Cycle No Transient Constraints

This case study was to evaluate the objective function without considering the transient switching events. Looking to GA and BWO as best results, the first cycle the transient resonant frequency and current didn't violate the limits of 3360 Hz and 16kA as specified in ANSI C37.0732 for the 69kV system. Even the power factor is exactly on the border and set to be 0.95 to avoid the penalties, the avoided penalties in the first 5 years were calculated to be $13,045,000 for both buses. To achieve this capacitor banks installed on both buses 4 and 5 rated 10.1 MVAR and 15.15 MVAR respectively. This installation cost is $3,565,000 and represents 28% only from the total avoided cost. In addition, it led to total energy loss minimization of $1,155,200. This equivalent to 32.2% of the total installation cost. The total saved or avoided cost is $10,636,000 in the first 5 years cycle which is almost 3 times the installation cost.

For the second 5 years cycle, the forecasted load expansion was 84% from the base load. This will require another capacitor to be installed in parallel with the first one and will case a back-to-back switching model. This model transient resonance impact is much worse than the single capacitor-switching model. As shown in GA and BWO results, another capacitor rated 3.56 MVAR and 5.35 MVAR installed on buses 4 and 5 respectively. As noted the frequency limit was violated. However, damping reactors installations were not considered. This led to only considering the capacitors in the installation cost. The installation cost found to be $2,136,200.

Moving to the total avoided cost due to PFC installation, it is $4,602,900 which is more than double of the installation cost. This installation led as well to minimize the energy losses by $556,650 reflecting 26.1% of the total instillation. All these investments and avoided costs with the previous cycle total avoided cost led to a total of $17,084,700. The total installation cost in 10 years cycle represents 33.37% of the total avoided cost. Which means a little investiment led to huge cost avoidance that would be paid for the grid if these capacitors were not installed. This shows the importance of conducting such studies in each plant to check the power factor and try to avoid penalties by installing capacitor banks at the point of common coupling.

6.2.2 Graver’s Considering Transient Resonance

This section is having same scenarios as the previous section. However, the problem formulation modified to consider the transient resonance events and do the necessary modifications. The modifications due to capacitors switching transient will impact the final cost because it will lead to damping reactors installation. The following tables 6.9, 6.10, 6.11 and 6.12 will go over all optimization techniques are selected in this thesis for the newly enhanced formulation.

Same as before, to have a fair evaluation of the results accuracy and operation time, the system was set to do 500 iterations and 200 as a limit to stop. The system and proposed formulation will be evaluated on all techniques GA, SCA, GWO and BWO.

Similar to the previous case, GA operation time a bit slower than other techniques, however, GA has a high accuracy results. The objective function results after including the transient resonance constraints impacted. The installation cost increased in the second cycle due to damping reactor installation, which impacted the objective function results and revealed to $17,121,000 as total avoided cost.

Table 6.9 Graver's No Transient Case Study GA (500 Iterations, 200 Stop)

Technique	**GA**			
Year	1		6	
Time (s)	68.1		65.7	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95000	0.95000	0.95000	0.95000
Frequency (KHz)	0.50	0.52	2.94	2.60
Inrush Current (KA)	1.10	1.55	1.53	2.03
Capacitor (MVAR)	10.10	15.15	3.56	5.34
Damping Reactor (mH)	0	0	2.0	1.7
Installation Cost ($)	-3,565,000		-2,240,200	
ELM Cost ($)	1,155,200		556,440	
PFC Avoided Penalty ($)	13,045,000		4,604,200	
Total ($)	10,636,000		2,920,500	
Accumulated Cost ($)	10,636,000		**17,121,000**	

Also for SCA, similar to previous results in the previous case, SCA operation time is low and the results accuracy is low as well. The accuracy impacted the damping reactor installation as well and revealed to decrease in the avoided cost to $16,993,000.

Table 6.10 Graver's No Transient Case Study SCA (500 Iterations, 200 Stop)

Technique	**SCA**			
Year	1		6	
Time (s)	62.7		54.6	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95060	0.95030	0.95120	0.95020
Frequency (KHz)	0.55	0.52	2.73	2.87
Inrush Current (KA)	1.10	1.56	1.49	2.23
Capacitor (MVAR)	10.24	15.26	3.79	5.31
Damping Reactor (mH)	0	0	2.2	1.4
Installation Cost ($)	-3,304,500		-2,257,400	
ELM Cost ($)	1,165,300		568,740	
PFC Avoided Penalty ($)	13,045,000		4,471,500	
Total ($)	10,623,000		2,782,800	
Accumulated Cost ($)	10,623,000		**16,993,000**	

Third table 6.11 provides the results for GWO, which shows fast operation time and low accuracy. However, still the accuracy is better that SCA but not up to the mark. This revealed to avoided cost equals to $17,010,000.

Table 6.11 Graver's No Transient Case Study GWO (500 Iterations, 200 Stop)

Technique	**GWO**			
Year	1		6	
Time (s)	42.8		33.5	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95030	0.95050	0.95000	0.95000
Frequency (KHz)	0.55	0.52	2.69	2.89
Inrush Current (KA)	1.10	1.56	1.39	2.21
Capacitor (MVAR)	10.16	15.31	3.52	5.20
Damping Reactor (mH)	0	0	2.4	1.4
Installation Cost ($)	-3,585,000		-2,227,900	
ELM Cost ($)	1,163,500		544,250	
PFC Avoided Penalty ($)	13,045,000		4,484,700	
Total ($)	10,624,000		2,801,000	
Accumulated Cost ($)	10,624,000		**17,010,000**	

Finally, the fourth table 6.12 shows the proposed BWO results. The accuracy is high and result is similar to GA. However, the operation time is faster than GA. BWO is considered as best optimization technique for the second case as well.

Table 6.12 Graver's No Transient Case Study BWO (500 Iterations, 200 Stop)

Technique	**BWO**			
Year	1		6	
Time (s)	66.78		61.51	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95000	0.95000	0.95000	0.95000
Frequency (KHz)	0.50	0.52	3.01	2.98
Inrush Current (KA)	1.10	1.55	1.57	2.32
Capacitor (MVAR)	10.10	15.15	3.56	5.35
Damping Reactor (mH)	0	0	1.9	1.3
Installation Cost ($)	-3,565,000		-2,229,000	
ELM Cost ($)	1,155,200		556,250	
PFC Avoided Penalty ($)	13,045,000		4,598,900	
Total ($)	10,636,000		2,926,100	
Accumulated Cost ($)	10,636,000		**17,127,000**	

As noticed previously and from this section results as well, GA and BWO are the best perfumers. Even the proposed BWO performed better than GA. See the figures 6.3 and 6.4 below to see the summarized comparison between all techniques.

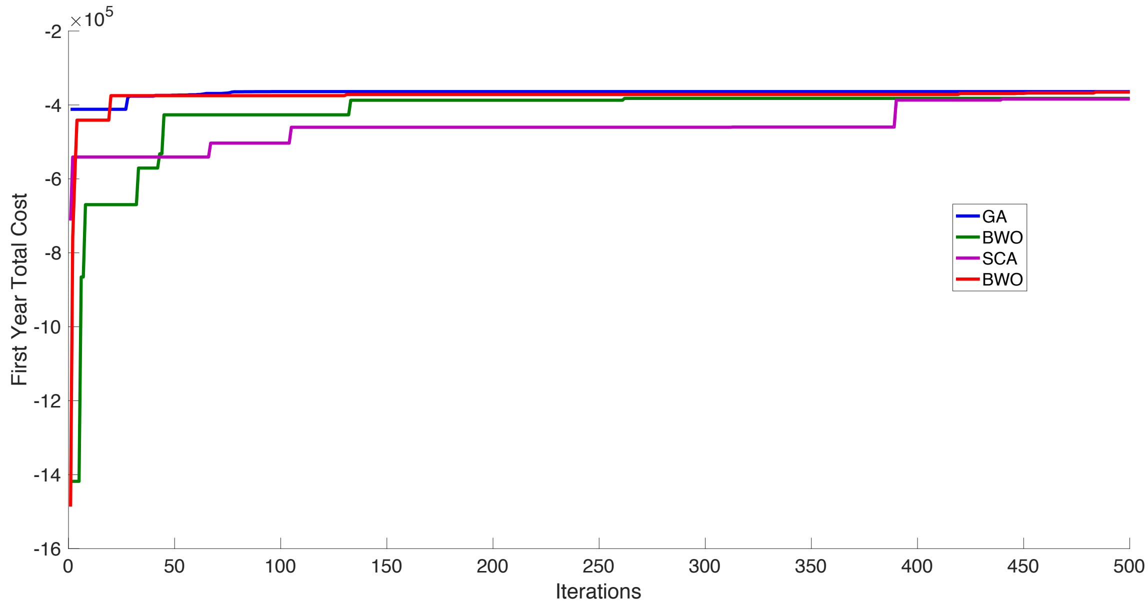


Figure 6.3 Graver's Summery Optimization Results for First Cycle Considering Transient Constraints

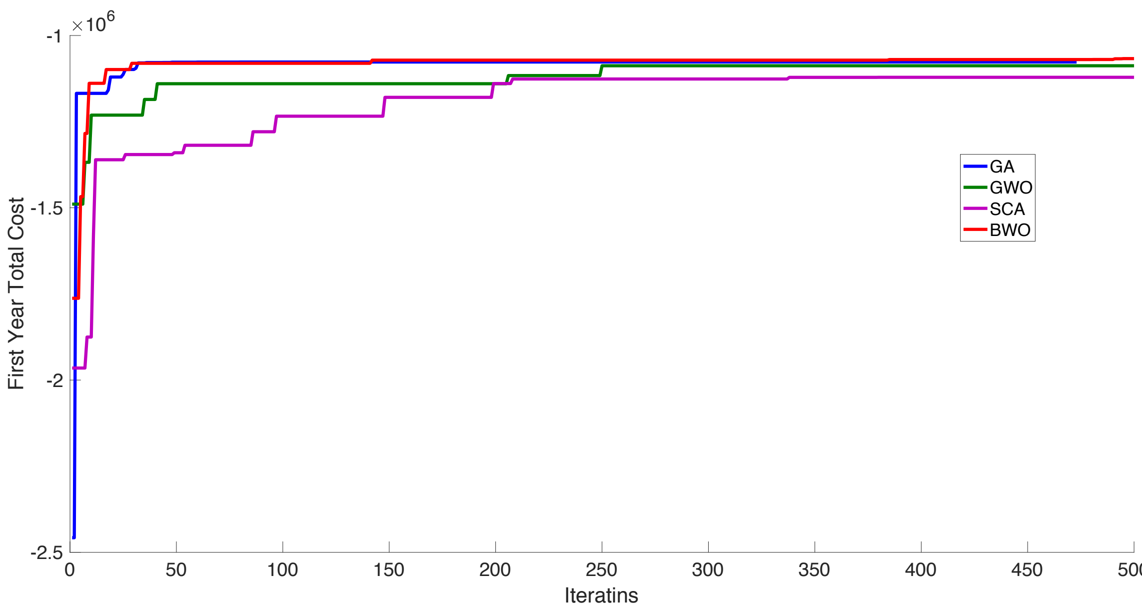


Figure 6.4 Graver's Summery Optimization Results for Second Cycle Considering Transient Constraints

Going to the details in reviewing the problem formulation in BWO as it produces the best results, the transient resonance considered and damping reactors installed in series with the added capacitors to avoid these events. The total cost of capacitors for the first cycle is

$3,565,000 without damping reactors. Reactors were not installed because the transient limits parameters were within the acceptable limits. The ELM cost is $1,155,200, PFC avoided penalty is $13,045,000 and the total accumulated cost is $10,636,000. This similar to previous case because the capacitor switching transient limits were within the acceptable values. This avoided installing damping which will increases the installation cost.

For the second cycle, the capacitor installed and capacitor switching transient limits were violated. This led to additional installations for damping reactors to avoid the transient's impacts on the system. The damping reactors installed on both buses and rated 1.9mH for bus 4 while bust 5 calculated to be 1.3mH. This led to making the transient frequency to be 3.01kHz and 2.98kHz for bus 4 and 5 respectively. These values are within the acceptable ANSI standard values. The total installation cost becomes $2,229,000. Thus, the total accumulated avoided cost reduces to be $17,127,000 compared to the previous case.

Even though the system has violated the capacitor switching transient limits, installing capacitors to avoid the penalties will lead to more cost saving. The total expected cost avoided is 3 times the installation cost.

6.2.3 IEEE-30 without Considering Transient Resonance

The same problem formulation was done on Graver's test system will repeated on IEEE-30. The reason for conducting the study on IEEE-30 is to check the robustness formulation and optimization techniques on more complicated systems and difficult case studies.

The problem formulation tested on IEEE-30 using all optimization techniques and the results are shown in the following tables 6.13, 6.14, 6.15, 6.16, 6.17, 6.18, 6.19, 6.20 and

6.21. The transient limits were not considered in this subsection. So, if the capacitor switching transient limits were violated, no cost impact will be considered.

Based on the analysis, the identified buses that are violating power factor limit 0.95 are 10 buses, which are 3, 7, 12, 16, 17, 19, 21, 23, 26 and 29. Similar to Graver's test system and in order to have fair analysis between the optimization techniques, the algorithm was limited to 1000 iterations and 400 no result change limit to stop.

The first two tables 6.13 and 6.14 are showing the results using GA technique for both cycles that covers the 10 years planning period. It is very clearly noticed that after moving to more difficult and complicated system, the accuracy reduced. The algorithm installed more capacitors than needed which contributed to additional installation cost and reduces the avoided cost. In addition, the operation time of IEEE-30 bus is much more compared to Graver's test system. However, still GA provided good accuracy results considering the system complexity. The total avoided cost after the second cycle and at the end of year 10 is $13,599,400.

Table 6.13 IEEE-30 No Transient Case Study for GA First Cycle (1000 Iterations, 400 Stop)

Technique	**GA**				
Year	1				
Time (s)	3428.35				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9535	0.9506	0.9501	0.9510	0.9508
Frequency (KHz)	3.36	1.18	0.95	1.84	0.96
Inrush Current (KA)	0.40	1.1	0.98	0.33	0.74
Capacitor (MVAR)	0.6	4.7	5.2	0.9	3.9
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9505	0.9511	0.9535	0.9521	0.9541
Frequency (KHz)	2.51	0.72	2.20	0.78	2.40
Inrush Current (KA)	0.2	1.10	0.35	0.25	0.09
Capacitor (MVAR)	0.4	7.5	0.8	1.6	0.2
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Table 6.14 IEEE-30 No Transient Case Study for GA Second Cycle (1000 Iterations, 400 Stop)

Technique	**GA**				
Year	6				
Time (s)	2630.04				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9527	0.9516	0.9510	0.9502	0.9512
Frequency (KHz)	55.1	18.7	18.1	45.0	21.0
Inrush Current (KA)	1.63	4.80	4.96	2.00	4.27
Capacitor (MVAR)	0.2	1.8	1.9	0.3	1.4
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9514	0.9507	0.9543	0.9537	0.9559
Frequency (KHz)	58.4	15.4	45.7	32.3	82.6
Inrush Current (KA)	1.54	5.84	1.96	2.78	1.09
Capacitor (MVAR)	0.2	2.6	0.3	0.6	0.1
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Moving to the following tables 6.15 and 6.16 for SCA optimization. As usual, SCA operation time is very low and leads to much lower results accuracy in both cycles. This leads to worse planning as more capacitors were installed in the first cycle and caused an increase in the initial investment cost which caused less capacitors to be installed in the second cycle. This contributed to additional capacitor installation and impacted the total avoided cost to be $15,328,750.

Table 6.15 IEEE-30 No Transient Case Study for SCA First Cycle (1000 Iterations, 400 Stop)

Technique	**SCA**				
Year	1				
Time (s)	1518.7				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9907	0.9509	0.9524	0.9664	0.9562
Frequency (KHz)	2.06	1.1	0.90	1.40	0.80
Inrush Current (KA)	0.65	1.20	1.04	0.44	0.90
Capacitor (MVAR)	1.6	5.5	5.9	1.6	5.6
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9530	0.9507	0.9543	0.9657	0.9559
Frequency (KHz)	1.90	0.68	1.96	0.63	1.95
Inrush Current (KA)	0.26	1.14	0.39	0.31	0.12
Capacitor (MVAR)	0.7	8.5	1.0	2.5	0.3
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Table 6.16 IEEE-30 No Transient Case Study for SCA Second Cycle (1000 Iterations, 400 Stop)

Technique	**SCA**				
Year	6				
Time (s)	2786.3				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9527	0.9516	0.9510	0.9502	0.9512
Frequency (KHz)	2.06	24.3	20.7	1.40	0.80
Inrush Current (KA)	0.65	3.70	4.34	0.44	0.90
Capacitor (MVAR)	0	0.9	1.3	0	0
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
PF (PU) (OLD/NEW)	0.9514	0.9507	0.9543	0.9537	0.9559
Frequency (KHz)	1.90	18.4	70.7	0.63	1.95
Inrush Current (KA)	0.26	4.9	1.27	0.31	0.12
Capacitor (MVAR)	0	1.6	0.1	0	0
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

For GWO technique, the operation time is almost equivalent to SCA. However, the accuracy is much lower. The total avoided cost at the end of year 10 is $13,715,590. Even though more capacitors were installed in first cycle, still the second cycle considered installing capacitors are more than needed on the other buses, which reduces the final cost even further.

Table 6.17 IEEE-30 No Transient Case Study for GWO First Cycle (1000 Iterations, 400 Stop)

Technique	**GWO**				
Year	1				
Time (s)	1554.4				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9870	0.9856	0.9624	0.9766	0.9715
Frequency (KHz)	2.48	0.83	0.89	1.48	0.85
Inrush Current (KA)	0.54	1.56	1.04	0.41	0.82
Capacitor (MVAR)	1.1	9.5	5.9	1.4	4.9
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9702	0.9612	0.9803	0.9578	0.9874
Frequency (KHz)	1.34	0.70	1.72	0.76	1.30
Inrush Current (KA)	0.37	1.13	0.44	0.26	0.18
Capacitor (MVAR)	1.4	8.4	1.3	1.7	0.7
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Table 6.18 IEEE-30 No Transient Case Study for GWO Second Cycle (1000 Iterations, 400 Stop)

Technique	**GWO**				
Year	6				
Time (s)	1927.8				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9699	0.9698	0.9510	0.9697	0.9627
Frequency (KHz)	2.48	0.83	21.4	1.48	19.4
Inrush Current (KA)	0.54	1.56	4.20	0.41	4.62
Capacitor (MVAR)	0	0	1.2	0	1.6
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9635	0.9524	0.9632	0.9694	0.9825
Frequency (KHz)	1.34	17.1	1.72	27.8	1.30
Inrush Current (KA)	0.37	5.24	0.44	3.23	0.18
Capacitor (MVAR)	0	1.9	0	0.9	0
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Finally, the proposed BWO technique still shows best results among others. Even though the operation time is slower than SCA and GWO but still faster than GA. In addition, the accuracy was higher than GA even. This leads to proper planning results and final avoided cost to be $14,204,000. This high avoided cost was not achieved by spending additional initial investment on installing more capacitors in the first cycle and avoid the installation in the second cycle. This was achieved by doing proper planning and spending what actually need to be spent.

Table 6.19 IEEE-30 No Transient Case Study for BWO First Cycle (1000 Iterations, 400 Stop)

Technique	**BWO**				
Year	1				
Time (s)	2890.2				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9556	0.9500	0.9502	0.9603	0.9503
Frequency (KHz)	3.29	1.19	0.95	1.69	0.96
Inrush Current (KA)	0.41	1.09	0.98	0.36	0.73
Capacitor (MVAR)	0.63	4.63	5.21	1.07	3.88
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9525	0.9501	0.9510	0.9528	0.9570
Frequency (KHz)	2.26	0.73	2.25	0.78	2.20
Inrush Current (KA)	0.22	1.06	0.34	0.25	0.10
Capacitor (MVAR)	0.49	7.42	0.76	1.61	0.23
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Table 6.20 IEEE-30 No Transient Case Study for BWO Second Cycle (1000 Iterations, 400 Stop)

Technique	**BWO**				
Year	6				
Time (s)	1533.8				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9551	0.9502	0.9511	0.9682	0.9501
Frequency (KHz)	53.5	19.3	18.1	34.7	21.3
Inrush Current (KA)	1.67	4.65	4.96	2.58	4.22
Capacitor (MVAR)	.21	1.66	1.90	0.58	1.36
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9507	0.9509	0.9812	0.9535	0.9519
Frequency (KHz)	92.6	15.1	32.3	32.5	2.20
Inrush Current (KA)	0.97	5.93	2.78	2.76	0.10
Capacitor (MVAR)	0.06	2.71	1.02	0.59	0
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Table 6.21 IEEE-30 No Transient Case Study Cost Summery (1000 Iterations, 400 Stop)

Technique	**GA**	**SCA**	**GWO**	**BWO**
Year	**First Cycle (1)**			
Installation Cost ($)	-9,039,500	-9,687,000	-9,958,250	-9,050,600
ELM Cost ($)	1,475,500	1,525,800	1,585,600	1,478,000
PFC Avoided Penalty ($)	13,118,000	13,118,000	13,118,000	13,118,000
Penelty without PFC ($)	13,118,000	13,118,000	13,118,000	13,118,000
Total ($)	5,554,400	4,957,200	4,745,700	5,545,800
Accumulated Cost ($)	5,554,400	4,957,200	4,745,700	5,545,800
Year	**Second Cycle (6)**			
Installation Cost ($)	-7,604,500	-3,054,050	-3,202,800	-6,987,200
ELM Cost ($)	2,197,400	1,967,900	408,290	2,231,700
PFC Avoided Penalty ($)	4,413,000	1,771,100	1,806,500	4,362,800
Total ($)	-994,100	684,950	-988,010	-392,710
Accumulated Cost ($)	**13,599,400**	**15,328,750**	**13,715,590**	**14,204,000**

As summery, the first look at the accumulated cost, it is concluding SCA as best optimization technique. However, the installations in Tables 6.15 and 6.16 showing high capacitor values installed in the first cycle, which cause the second cycle to have few buses without accounting them for capacitors installation. This will avoid additional buildings for the new capacitors and their costs were avoided. In planning problems, this is considered not acceptable. The planning supposes to meet the required load growth and not assuming higher load. SCA spent more in the first cycle and installed more than needed. This proves lower performance form SCA compared to others. So, best results came from BWO.

The problem formulation solution was same as Graver's test system but the case study was more difficult as it has 10 buses require capacitors to correct the power factor and avoid penalties. The total avoided penalties were \$13,118,000 for the first cycle and \$4,362,800 for the second cycle. While the installation was \$9,050,600 and \$6,987,200 for both cycles without considering transient, which means no reactors were installed.

The total accumulated cost found to be \$5,545,800 for the first cycle and \$14,204,400 for the second cycle. The accumulated cost in the second cycle includes the avoided penalties for both cycles and the ELM as well for both cycles. The capacitors installed in the second cycle but still, the capacitor installed in the first cycle contributed to the final avoided payment.

6.2.4 IEEE-30 Considering Transient Resonance

The previous subsection didn't include the transient limits as part of the problem constraints that cause no damping reactors were installed. These rectors costs were not included part of the installation cost. The following tables 6.22, 6.23, 6.24, 6.25, 6.26, 6.27, 6.28, 6.29 and 6.30 will solve the problem considering these transient limits and the damping reactor cost will be included.

Similar to the previous case and in order to have fair evaluation between the techniques, the iterations will be limited to 1000 and 400 to stop without any change to the most optimal value.

In general, this section will show the impact on the cost by including the transient resonance to the constraints. Which will increases the installation cost, as damping reactors will be installed to protect the system from these events. The system will be tested on GA, SCA, GWO and the proposed BWO. Since the discussions are similar to all previous cases on all techniques result accuracy and operation time, the details discussions for IEEE-30 bus test system will be summarized at the end of this section.

Table 6.22 IEEE-30 Considering Transient Case Study for GA First Cycle (1000 Iterations, 400 Stop)

Technique	**GA**				
Year	1				
Time (s)	2610.34				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9535	0.9506	0.9501	0.9510	0.9508
Frequency (KHz)	1.93	1.18	0.95	1.84	0.96
Inrush Current (KA)	0.23	1.10	0.98	0.33	0.74
Capacitor (MVAR)	0.6	4.7	5.2	0.9	3.9
Damping Reactor (mH)	13.7	0	0	0	0
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9505	0.9511	0.9535	0.9521	0.9541
Frequency (KHz)	2.51	0.72	2.19	0.78	2.40
Inrush Current (KA)	0.20	1.07	0.35	0.25	0.09
Capacitor (MVAR)	0.4	7.5	0.8	1.6	0.2
Damping Reactor (mH)	0	0	0	0	0

Table 6.23 IEEE-30 No Transient Case Study for GA Second Cycle (1000 Iterations, 400 Stop)

Technique	**GA**				
Year	6				
Time (s)	2688.37				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9527	0.9516	0.9510	0.9502	0.9512
Frequency (KHz)	2.76	2.82	2.28	3.04	2.71
Inrush Current (KA)	0.08	0.72	0.63	0.14	0.55
Capacitor (MVAR)	0.2	1.8	1.9	0.3	1.4
Damping Reactor (mH)	39.8	4.4	6.3	21.8	6.0
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9514	0.9507	0.9543	0.9537	0.9559
Frequency (KHz)	3.16	2.64	2.62	2.43	2.83
Inrush Current (KA)	0.08	1.00	0.11	0.21	0.04
Capacitor (MVAR)	0.2	2.6	0.3	0.6	0.1
Damping Reactor (mH)	34.1	3.4	30.3	17.7	84.9

Table 6.24 IEEE-30 Considering Transient Case Study for SCA First Cycle (1000 Iterations, 400 Stop)

Technique	**SCA**				
Year	1				
Time (s)	1750.52				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9763	0.9615	0.9645	0.9891	0.9554
Frequency (KHz)	1.57	1.05	0.88	1.32	0.93
Inrush Current (KA)	0.28	1.24	1.05	0.45	0.76
Capacitor (MVAR)	0.91	5.97	6.03	1.74	4.11
Damping Reactor (mH)	13.7	0	0	0	0
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9538	0.9509	0.9562	0.9862	0.9697
Frequency (KHz)	2.13	0.72	2.13	0.65	1.68
Inrush Current (KA)	0.23	1.07	0.35	0.30	0.13
Capacitor (MVAR)	0.56	7.48	0.84	2.33	0.40
Damping Reactor (mH)	0	0	0	0	0

Table 6.25 IEEE-30 No Transient Case Study for SCA Second Cycle (1000 Iterations, 400 Stop)

Technique	**SCA**				
Year	6				
Time (s)	2663.16				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9593	0.9550	0.9547	0.9715	0.9501
Frequency (KHz)	1.57	2.97	2.54	1.32	2.95
Inrush Current (KA)	0.28	0.53	0.55	0.45	0.52
Capacitor (MVAR)	0	1.06	1.35	0	1.13
Damping Reactor (mH)	0	5.7	6.4	0	5.9
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9507	0.9520	0.9533	0.9589	0.9619
Frequency (KHz)	2.13	2.61	3.05	0.65	1.68
Inrush Current (KA)	0.23	1.04	0.11	0.30	0.13
Capacitor (MVAR)	0	2.77	0.24	0	0
Damping Reactor (mH)	0	3.3	26.6	0	0

Table 6.26 IEEE-30 Considering Transient Case Study for GWO First Cycle (1000 Iterations, 400 Stop)

Technique	**GWO**				
Year	1				
Time (s)	3127.4				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9584	0.9572	0.9694	0.9520	0.9522
Frequency (KHz)	1.84	1.10	0.86	1.82	0.95
Inrush Current (KA)	0.24	1.18	1.08	0.33	0.74
Capacitor (MVAR)	0.66	5.44	6.34	0.92	3.96
Damping Reactor (mH)	13.8	0	0	0	0
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9547	0.9657	0.9668	0.9515	0.9598
Frequency (KHz)	2.06	0.67	1.93	0.79	2.05
Inrush Current (KA)	0.24	1.16	0.39	0.25	0.11
Capacitor (MVAR)	0.60	8.83	1.02	1.59	0.27
Damping Reactor (mH)	0	0	0	0	0

Table 6.27 IEEE-30 No Transient Case Study for GWO Second Cycle (1000 Iterations, 400 Stop)

Technique	**GWO**				
Year	6				
Time (s)	2663.16				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9657	0.9516	0.9521	0.9504	0.9519
Frequency (KHz)	2.35	3.33	3.33	2.93	2.68
Inrush Current (KA)	0.11	0.59	0.49	0.13	0.54
Capacitor (MVAR)	0.36	1.07	0.84	0.29	1.38
Damping Reactor (mH)	35.4	4.6	5.5	24.2	6.2
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9514	0.9523	0.9508	0.9546	0.9541
Frequency (KHz)	2.78	3.17	0.87	2.49	2.09
Inrush Current (KA)	0.10	0.79	0.06	0.22	0.03
Capacitor (MVAR)	0	1.46	0	0.63	0
Damping Reactor (mH)	0	3.6	0	16.2	0

Table 6.28 IEEE-30 Considering Transient Case Study for BWO First Cycle (1000 Iterations, 400 Stop)

Technique	**BWO**				
Year	1				
Time (s)	2897.2				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9551	0.9500	0.9514	0.9533	0.9501
Frequency (KHz)	3.31	1.19	0.94	1.80	0.96
Inrush Current (KA)	0.41	1.09	0.98	0.33	0.73
Capacitor (MVAR)	0.62	4.63	5.27	0.94	3.87
Damping Reactor (mH)	0	0	0	0	0
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9500	0.9501	0.9623	0.9500	0.9688
Frequency (KHz)	2.58	0.73	2.01	0.79	1.71
Inrush Current (KA)	0.19	1.06	0.38	0.24	0.13
Capacitor (MVAR)	0.38	7.41	0.95	1.56	0.39
Damping Reactor (mH)	0	0	0	0	0

Table 6.29 IEEE-30 No Transient Case Study for BWO Second Cycle (1000 Iterations, 400 Stop)

Technique	**BWO**				
Year	6				
Time (s)	2160.1				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9563	0.9504	0.9531	0.9626	0.9500
Frequency (KHz)	2.62	2.68	2.31	2.38	2.52
Inrush Current (KA)	0.09	0.66	0.66	0.16	0.5
Capacitor (MVAR)	0.24	1.70	1.98	0.56	1.36
Damping Reactor (mH)	38.6	5.1	5.9	22.9	7.1
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9550	0.9503	0.9560	0.9512	0.9612
Frequency (KHz)	2.45	2.39	3.29	2.63	1.71
Inrush Current (KA)	0.1	0.92	0.1	0.22	0.13
Capacitor (MVAR)	0.45	2.64	0.19	0.58	0
Damping Reactor (mH)	37.0	4.1	26.4	15.6	0

Table 6.30 IEEE-30 Considering Transient Case Study Cost Summery (1000 Iterations, 400 Stop)

Technique	**GA**	**SCA**	**GWO**	**BWO**
Year	**First Cycle (1)**			
Installation Cost ($)	-9,449,900	-9,849,800	-9,787,700	-9,059,100
ELM Cost ($)	1,475,500	1,661,700	1,659,500	1,484,400
PFC Avoided Penalty ($)	13,118,000	13,118,000	13,118,000	13,118,000
Penelty without PFC ($)				
Total ($)	5,144,000	4,930,200	4,990,200	5,543,700
Accumulated Cost ($)	5,144,000	4,930,200	4,990,200	5,543,700
Year	**Second Cycle (6)**			
Installation Cost ($)	-15,047,000	-5,392,000	-8,133,100	-11,816,000
ELM Cost ($)	2,197,400	1,909,000	2,073,400	2,211,800
PFC Avoided Penalty ($)	4,413,000	2,650,700	2,5151,800	4,392,600
Penelty without PFC ($)				
Total ($)	-8,436,300	-832,260	-3,543,900	-5,211,600
Accumulated Cost ($)	**6,157,600**	**13,948,000**	**11,234,000**	**9,391,200**

As explained before by seeing the numbers only, SCA and GWO look like as best solutions. However, installing more than the system need for the first cycle is not acceptable in planning formulation. Thus, it is concluded that BWO has the best solution.

The problem formulation included the transient constraints. It is noted in GA, which is the second-best performer technique, bus 3 violated the transient limits from the first cycle even and before connecting the system in the back-to-back configuration. However, BWO managed to modify the bus power factor without exceeding transient limits. This led to a high increment in GA installation cost compared to BWO.

In general IEEE-30 test system was in a serious problem from transient events. Even, the second cycle led to high damping reactors installations. The total installation cost in BWO for capacitors and damping reactors was $9,059,100 for the first cycle, which is mainly buildings and capacitors. However, the second cycle when it was included damping reactors, the total cost become $11,816,000. The total accumulated cost becomes $9,391,200 for the second cycle.

The following figures are showing the summary of the optimization techniques performance. The first two figures are showing the first and second cycle comparison for all techniques. It shows BWO perform better in the first cycle and SCA spent a lot, which causes it become the worst. For the second cycle, SCA didn't require to spend a lot which causes it avoiding the back-to-back switching model and buildings cost. As stated before, this is not acceptable in planning problems as the problem set for 5 years planning horizon.

The second three figures are the summary of the comparison between all techniques and an individual figure for the best two techniques. These techniques are BWO and GA which are shown in Figure 6.7.

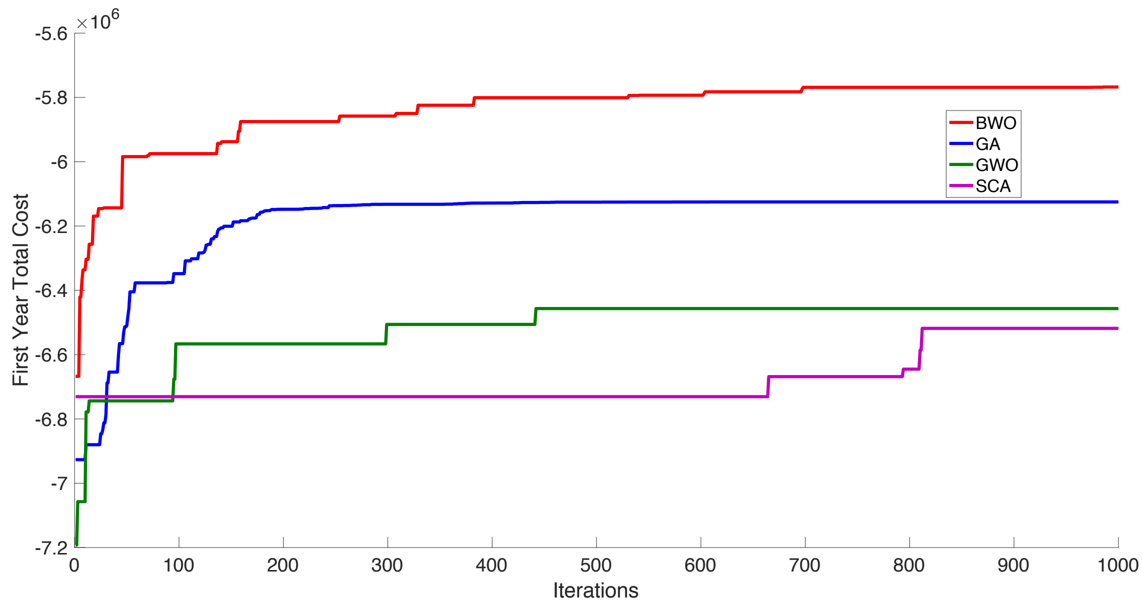


Figure 6.5 IEEE-30 Summery Optimization Results for First Cycle Considering Transient Constraints

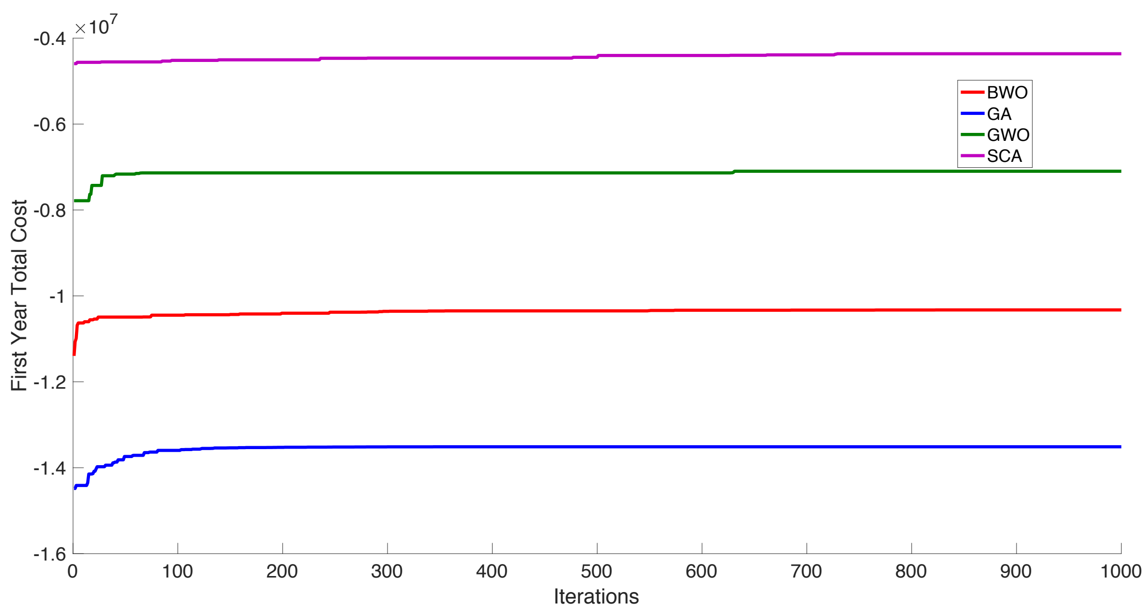


Figure 6.6 IEEE-30 Summery Optimization Results for Second Cycle Considering Transient Constraints

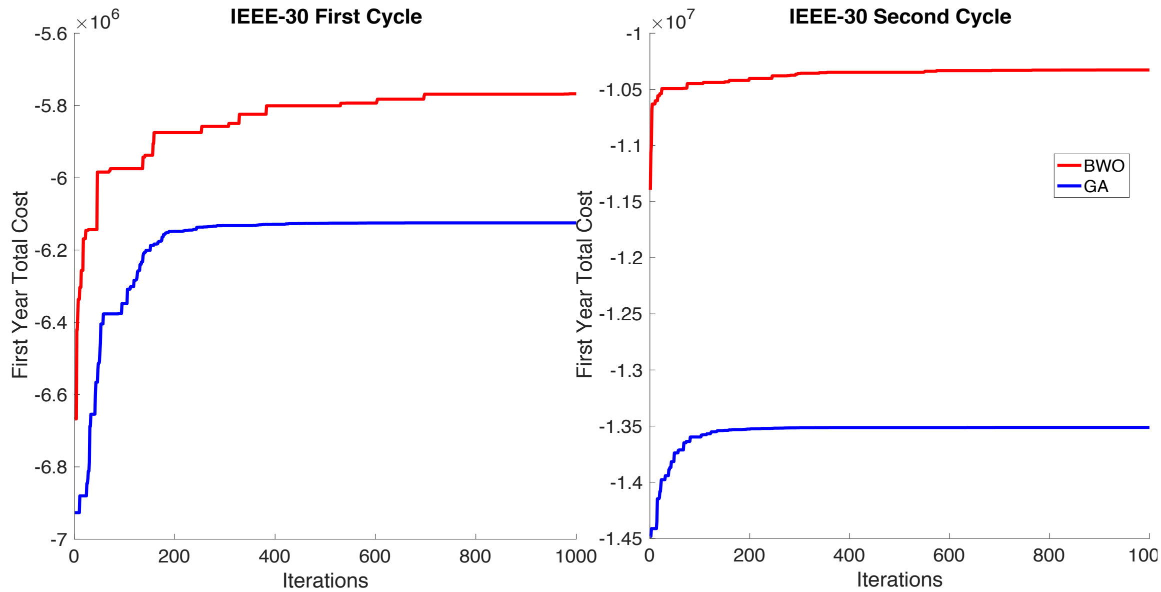


Figure 6.7 Summery Best Two Optimization Techniques (BWO vs. GA) Results

6.3 Case Studies Including Failure and Reliability Analysis

The failure analysis is very important to prove the system healthiness after adding new electrical equipment. The standard used for such study is IEEE gold book. This book has a historical data for all electrical equipment failure rates with their expected repair time. This book will be used as bases to conduct the reliability analysis in this thesis.

The data taken from IEEE gold book has to be simulated on the system circuit. There are several simulation techniques to get the overall failure rate and repair time of the system after adding this new equipment. These techniques such as Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), Markov Model, and Monte Carlo Sampling (MCS). The technique is used in this thesis is MCS which already explained in Chapter 3 under this thesis.

The previous researchers were done on this topic was only considering the positive impacts of PFC capacitors installation on system reliability. This enhancement due to reducing the main power line loading which will reduce the heat losses and improve the reliability. However, capacitors by itself are impacting the system resonance and cause transient issues. This will lead to negative reliability issues as well. In addition, they also have a failure rate which will impact the overall system failure rate. These factors were not considered before. This section will do the reliability analysis on the system after adding PFC capacitors and prove the proposed hypothesis.

This section will be divided into four subsections. These sections are:

1) Monte Carlo Simulation.
2) Graver's Test System without Considering Transient Resonance.
3) Graver's Test System Considering Transient Resonance.
4) IEEE-30 Bus Test System without Considering Transient Resonance.
5) IEEE-30 Bus Test System Considering Transient Resonance.
6) Reliability Impact of Failure Cost.

Likewise, in each subsection, the best two proposed optimization techniques found in the previous section will be used. These techniques are GA and proposed BWO.

6.3.1 Monte Carlo Simulation

Monte Carlo Sampling/Simulation (MCS) is used in this thesis to simulate the system failure rates. The explanation was done in chapter 3 section 3.5. The same concept is done on more complicated systems. MCS will sample each equipment failure according to the failure rates and repair time is taken from IEEE gold book.

The first step before going to system failure analysis is to do the MCS. The reason for starting with MCS and not making it built within the optimization process is to minimize the simulation time. MCS is taking a long sampling time. If this sampling was built within the optimization, MCS will run with every iteration.

MCS will start under this section for failure analysis even prior starting the initialization for optimization activity. The electrical circuit used for this simulation after assuming the power supply provided is 100% reliable is shown in Figure 6.8 and the data used are taking from IEEE gold book and shown in the table below.

Table 6.32 Electrical System Components Failure Rates

Component	Failure Rate	Repair Time
Line/Cable	0.0141	40.4
Damping Reactor	0.04	150
Capacitor	0.17443	2.3
Circuit Breakers (Considering Transient)	0.003	129
Circuit Breakers (Not Considering Transient)	2	129

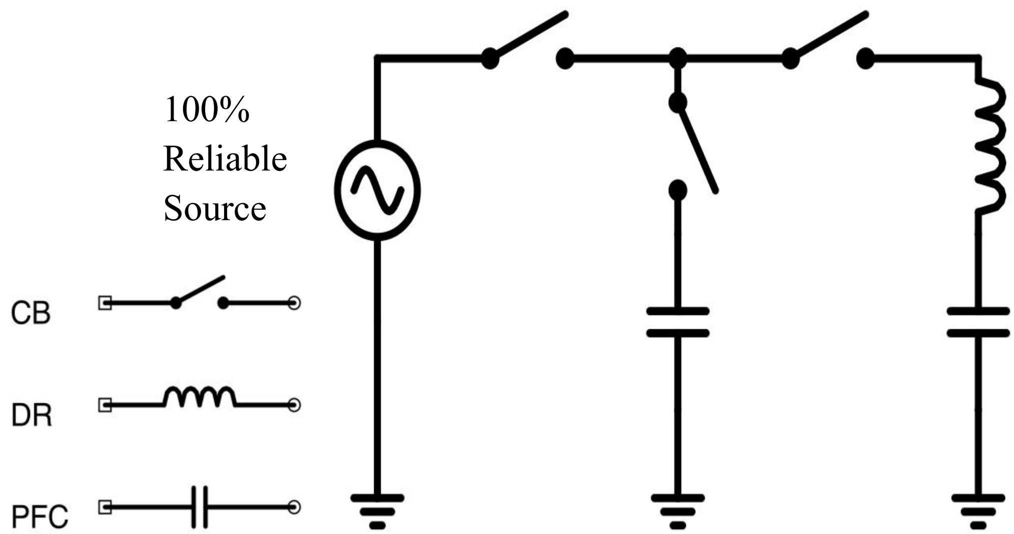


Figure 6.8 Monte Carlo Simulation Evaluated Circuit

The only impacted failure rate is circuit breaker failure rate which is going to fail more than expected if the transient was not considered. The failure rates approximated to be 2 failures per year. Even though the failures could be much more than this but this approximation was done for the purpose of checking the validated of the study in including the transient events part of the reliability calculations. The results of MCS are shown below with the figure of the failure rate change during MCS iterations.

Table 6.33 Monte Carlo Sampling/Simulation Results

Case	Not Violating Transient Limit (f/y)	Violating Transient Limit (f/y)
Not Considering Transients	0.0042	0.0373
Considering Transients	0.0042	0.0047

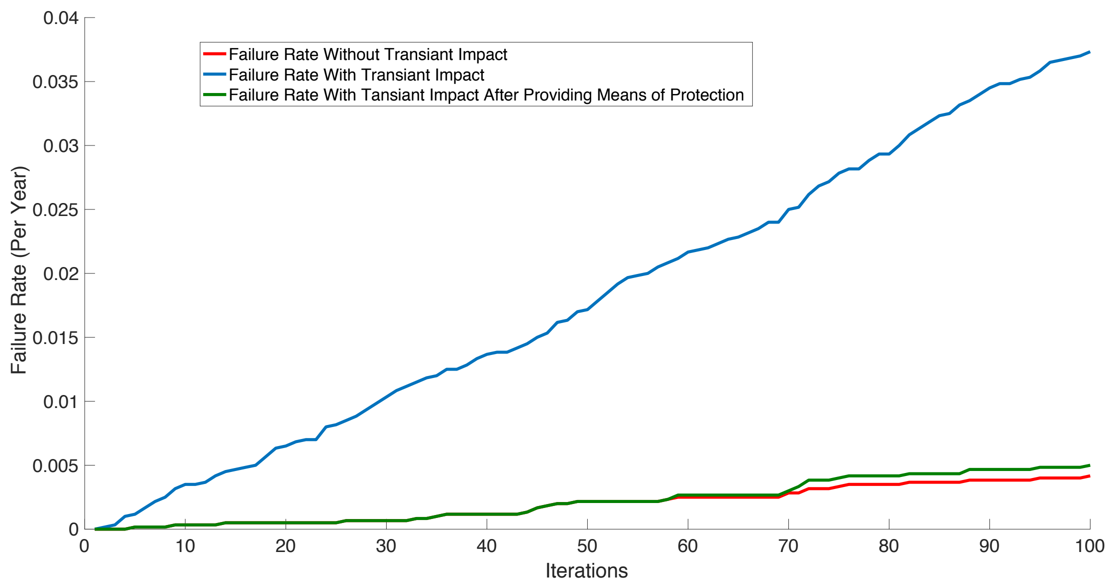


Figure 6.9 Failure Rate Change during MCS Iteriatons

The simulation was done twice, considering and not considering transient events. The system could have transient resonance event and there is a potential without transient events especially for single switching model. So, both situations were evaluated. If the transient events were not considered, the failure rate is 0.0042 failure per year. However, if the transient limits violated and it was not considered as part of the installation planning to have proper protection, the failure rate become 0.0373 failure per year.

If the transient events were considered during the planning study, the proper engineering solutions were used which is damping reactors in this case. The failure rate if there was no violation of transient limits will be same as if the transient was not considered and it will be 0.0042 failure per year. However, if there was a transient limits violation, the failure rate per year will become 0.0047 f/y. This slight increase came from damping reactor which is increasing the probability of electrical system failure.

These calculations proving the hypothesis made in the failure analysis and reliability impact after PFC installation in the electrical system. Which focuses on the system failure increase after capacitor installations.

6.3.2 Graver's without Considering Transient Resonance

This study is same as the previous study in considering and not considering transient switching events. However, this study will include the reliability analysis and the failure cost. The total accumulated cost calculated previously was \$10,636,000. The calculated failure cost using the formulation explained in Chapter 4 is \$54,340 for this cycle which led to \$10,581,000 as accumulated cost.

For the second cycle and when the transient is not considered, the failure rate will increase due to the unnecessary tripping coming from the bad system design to overcome the transient events. Since the failure rate is increased, it causes an increase in the total failure cost approximated to be paid yearly to be \$658,180.

The actual failure cost could be more than this because the assumption was made that the breaker/fuses failures are only twice a year. The failures could be much higher than this assumption. However, the purpose of this assumption is to prove the transient events on the failure rate and the system reliability.

The following tables are for GA and BWO. As shown GA and BWO produces exactly the same results. However, BWO is slower in convergence as it can be seen in Figures 6.10 and 6.11 due to the exploration and exploitation factor which reduces from 2 to 1. This factor causes the technique to search for the optimal result around the area over the total number of iterations. So, sometime the result can't be achieved fast and it has to go over all the iteration numbers to approach the best solution.

Table 6.34 Graver's Test System No Transient with Reliability Case Study for GA

Technique	**GA**			
Year	1		6	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95000	0.95000	0.95000	0.95000
Frequency (KHz)	0.55	0.52	13.14	10.73
Current (KA)	1.10	1.55	6.82	8.36
Size (MVAR)	10.10	15.15	3.56	5.34
Damping Reactor (mH)	N/A	N/A	N/A	N/A
Installation Cost ($)	-3,564,800		-785,830	
ELM Cost ($)	1,155,200		556,440	
PFC Avoided Cost ($)	13,045,000		4,604,200	
Failure Cost ($)	-54,340		-658,180	
Total Cost ($)	-2,464,000		-887,570	
Avoided Loss ($)	10,581,000		3,716,600	
Accumulated Cost ($)	10,581,000		**14,298,000**	

Table 6.35 Graver's Test System No Transient with Reliability Case Study for BWO

Technique	BWO			
Year	1		6	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95000	0.95000	0.95000	0.95000
Frequency (KHz)	0.55	0.52	13.14	10.73
Current (KA)	1.10	1.55	6.82	8.36
Size (MVAR)	10.10	15.15	3.56	5.34
Damping Reactor (mH)	N/A	N/A	N/A	N/A
Installation Cost ($)	-3,564,800		-785,830	
ELM Cost ($)	1,155,200		556,440	
PFC Avoided Cost ($)	13,045,000		4,604,200	
Failure Cost ($)	-54,340		-658,180	
Total Cost ($)	-2,464,000		-887,570	
Avoided Loss ($)	10,581,000		3,716,600	
Accumulated Cost ($)	10,581,000		**14,298,000**	

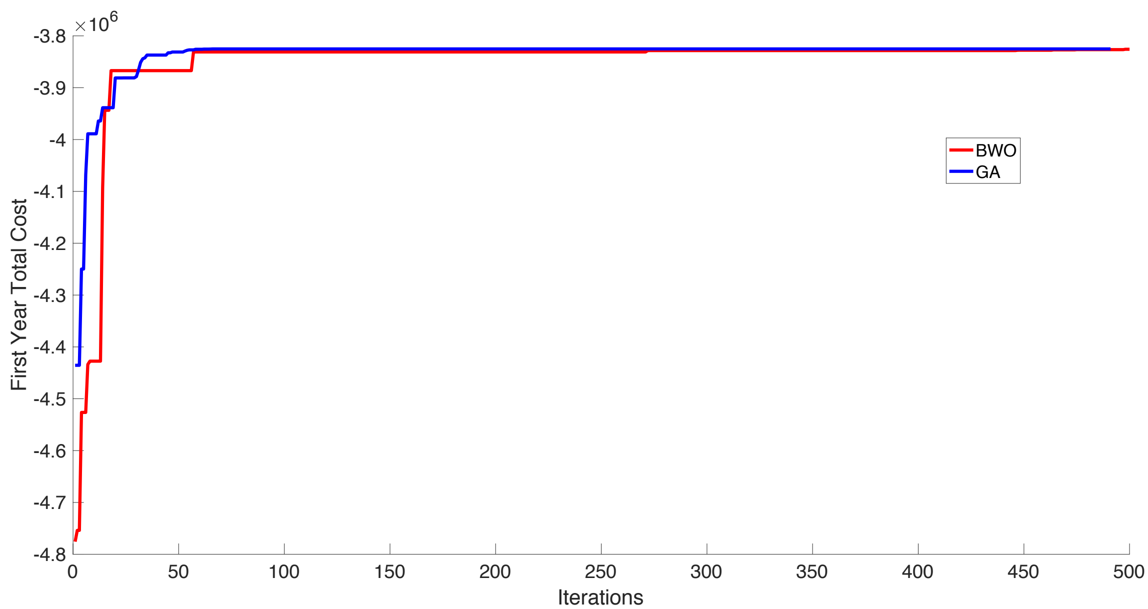


Figure 6.10 Graver's Summery Optimization Results for First Cycle No Transient with Reliability

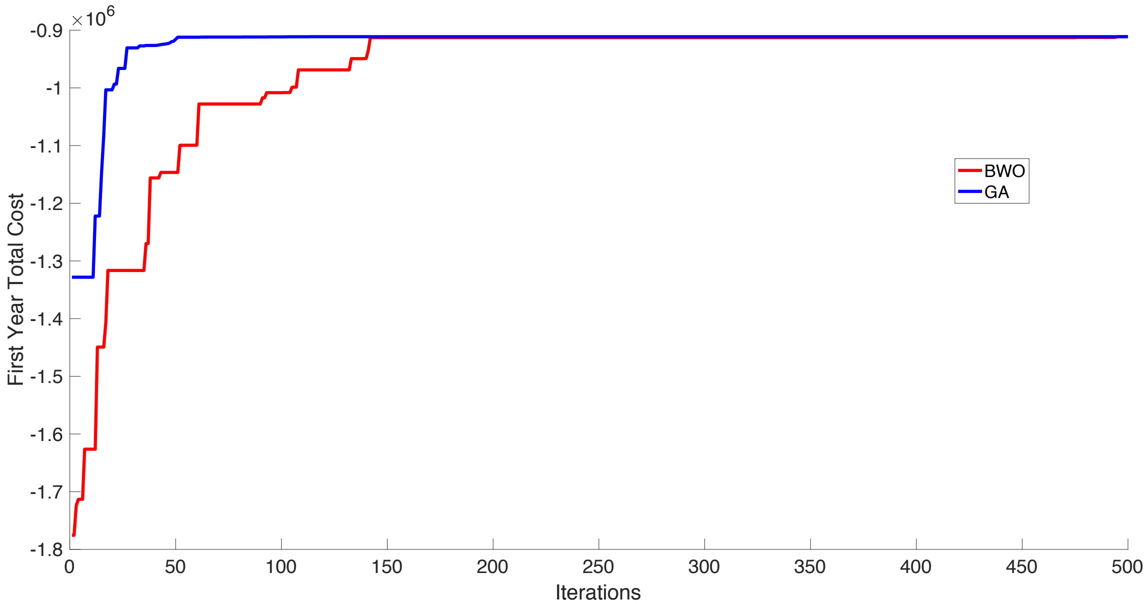


Figure 6.11 Graver's Summery Optimization Results for Second Cycle No Transient with Reliability

6.3.3 Graver's Considering Transient Resonance

This section will consider the transient resonance and see the reliability impact to the failure cost. From an optimization point of view, BWO performer slightly better than GA. This slight difference came from the damping reactor size selected by BWO was 1.9mH for bus 4, which is smaller and meets ANSI requirement. However, GA was 2.3mH, which is slightly bigger than the damping reactor was sized by BWO. This difference leads to a mall cost difference in the Accumulated cost to be $14,766,000 in GA and $14,773,000 for BWO. The full analysis results can be seen in below tables and figures.

Moving to problem formulation, it was updated to include the reliability and failure cost calculations. The transient constraints were considered and damping reactors were sized to protect the system from these events. The total failure cost in the second cycle, when transient limits were violated, become $82,807. It was $658,180 in the previous case when transient limits were not considered.

Table 6.36 Graver's Test System Considering Transient and Reliability Case Study for GA

Technique	GA			
Year	1		6	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95000	0.95000	0.95000	0.95000
Frequency (KHz)	0.55	0.52	2.274	2.976
Current (KA)	1.10	1.55	1.42	2.32
Size (MVAR)	10.10	15.15	3.56	5.34
Damping Reactor (mH)	0	0	2.3	1.3
Installation Cost ($)	-3,564,800		-888,930	
ELM Cost ($)	1,155,200		556,210	
PFC Avoided Cost ($)	13,045,000		4,600,700	
Failure Cost ($)	-54,340		-82,808	
Total Cost ($)	-2,464,000		-415,540	
Avoided Loss ($)	10,581,000		4,185,200	
Accumulated Cost ($)	10,581,000		**14,766,000**	

Table 6.37 Graver's Test System Considering Transient and Reliability Case Study for BWO

Technique	BWO			
Year	1		6	
Location (Bus)	4	5	4	5
OLD PF (PU)	0.90035	0.90035	0.90035	0.90035
NEW PF (PU)	0.95000	0.95000	0.95000	0.95000
Frequency (KHz)	0.55	0.52	3.014	2.975
Current (KA)	1.10	1.55	1.57	2.32
Size (MVAR)	10.10	15.15	3.56	5.34
Damping Reactor (mH)	0	0	1.9	1.3
Installation Cost ($)	-3,564,800		-886,520	
ELM Cost ($)	1,155,200		556,440	
PFC Avoided Cost ($)	13,045,000		4,604,200	
Failure Cost ($)	-54,340		-82,807	
Total Cost ($)	-2,464,000		-412,890	
Avoided Loss ($)	10,581,000		4,191,300	
Accumulated Cost ($)	10,581,000		**14,773,000**	

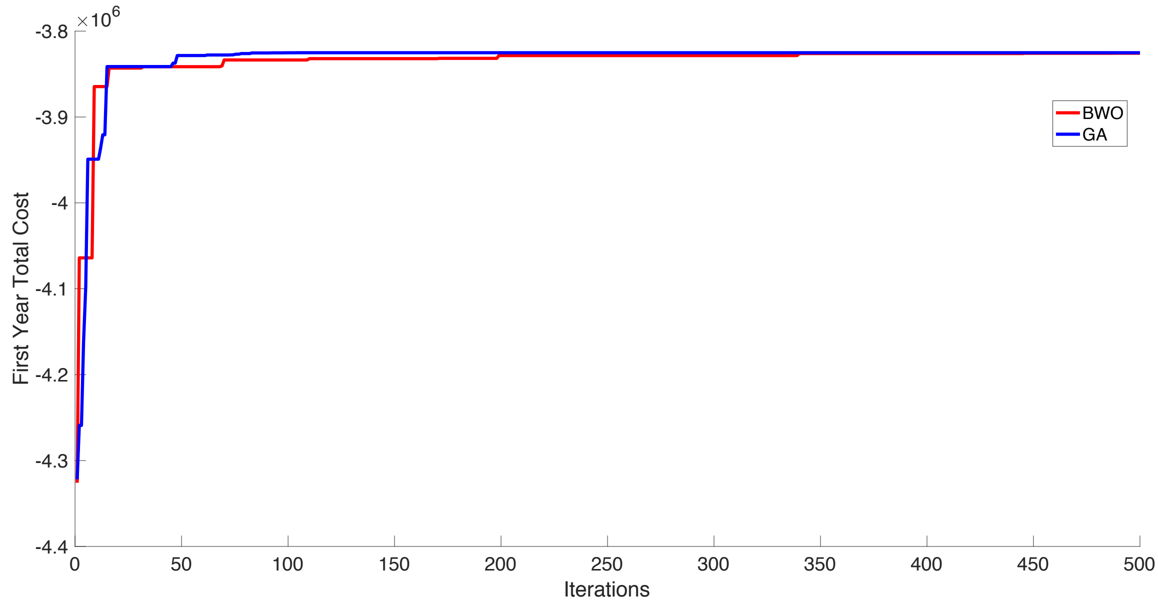


Figure 6.12 Graver's Summery Optimization Results for First Cycle Considering Transient and Reliability

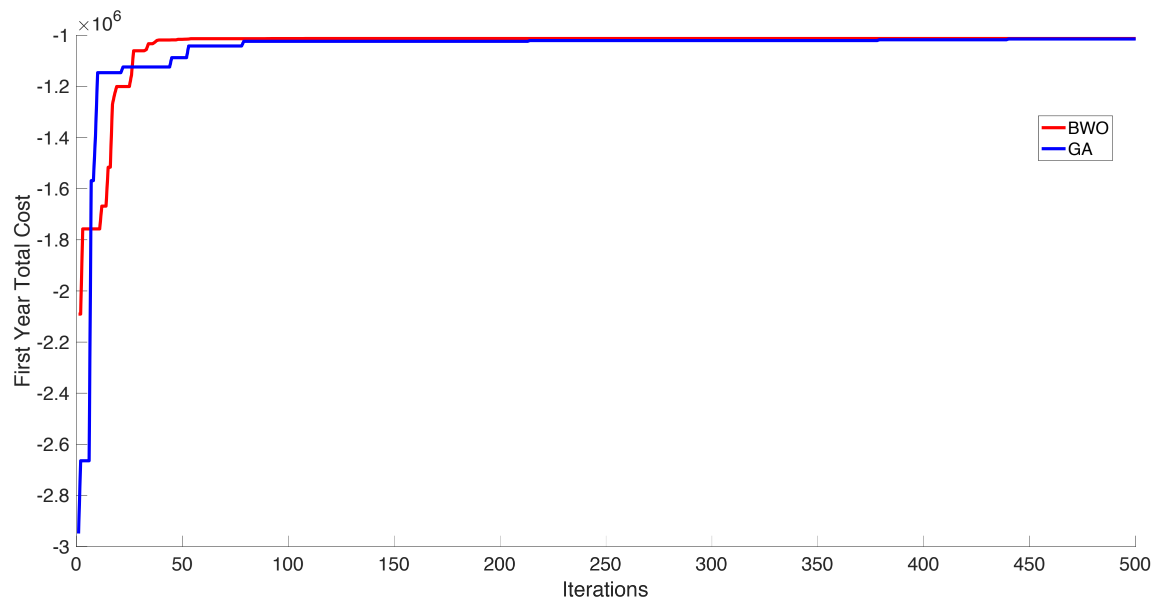


Figure 6.13 Graver's Summery Optimization Results for Second Cycle Considering Transient and Reliability

6.3.4 IEEE-30 without Considering Transient Resonance

The problem formulation for IEEE-30 bus test system will be duplicated from the Graver's test system. This case study was added to check the robustness of the optimization technique and problem formulation.

The optimization techniques were used are GA and BWO and the produces the same final results. The tables below are showing the results of IEEE-30 bus system with no transient constraints and considering the reliability calculations. Thus, the planning problem considers the damping reactor installation, which leads to an increase in the system failure cost. The failure cost reached to $661,860 in the second cycle when transient events start appearing after it was $64,171 in the first cycle.

Table 6.38 IEEE-30 Test System No Transient with Reliability Case Study First Cycle

Technique	**GA & BWO**				
Year	1				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9500	0.9500	0.9500	0.9500	0.9500
Frequency (KHz)	3.49	1.19	0.95	1.86	0.96
Inrush Current (KA)	0.40	1.1	0.98	0.33	0.74
Capacitor (MVAR)	0.56	4.64	5.20	0.89	3.87
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9500	0.9500	0.9500	0.9500	0.9500
Frequency (KHz)	2.58	0.73	2.27	0.79	2.74
Inrush Current (KA)	0.20	1.10	0.34	0.25	0.09
Capacitor (MVAR)	0.38	7.41	0.75	1.57	0.16
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Table 6.39 IEEE-30 Test System No Transient with Reliability Case Study Second Cycle

Technique	**GA & BWO**				
Year	6				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9500	0.9500	0.9500	0.9500	0.9500
Frequency (KHz)	55.8	19.4	18.3	44.4	21.2
Inrush Current (KA)	1.61	4.62	4.90	2.02	4.22
Capacitor (MVAR)	0.20	1.64	1.84	0.32	1.37
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9500	0.9500	0.9500	0.9500	0.9500
Frequency (KHz)	68.0	15.3	48.4	33.4	107.3
Inrush Current (KA)	1.32	5.85	1.86	2.69	0.84
Capacitor (MVAR)	0.14	2.62	0.27	0.56	0.06
Damping Reactor (mH)	N/A	N/A	N/A	N/A	N/A

Table 6.40 IEEE-30 Test System No Transient with Reliability Case Study Cost Summery

Technique	**GA & BWO**	
Year	**First Cycle (1)**	**Second Cycle (6)**
Installation Cost ($)	-9,002,800	-814,160
ELM Cost ($)	1,469,800	485,380
PFC Avoided Penalty ($)	13,118,000	4,629,700
Failure Cost ($)	-64,171	-661,860
Total Cost ($)	-7,597,200	-991,760
Avoided Loss ($)	5,521,200	3,628,400
Accumulated Cost ($)	**5,521,200**	**9,148,300**

6.3.5 IEEE-30 Considering Transient Resonance

This subsection is covering the IEEE-30 test system case study with consideration to transient switching events. The required damping reactors will be installed whenever there will be transient events which will reduce the total failure cost.

The failure cost for the first cycle found to be $54,749 which is less than the previous case in the first cycle. The previous first cycle cost was $64,171. This cost difference came from the frequency resonance happening in bus 3. The previous case didn't consider the transient events in the problem formulation. This led to an increase in the failure rate which contributed to the failure cost.

For the second cycle, the failure cost becomes $83,263 due to the consideration of transient events compared to $661,860 in the previous case. This led to accumulated cost $1,219,300 avoidance cost compared to $9,148,300 without transient events consideration.

Table 6.41 IEEE-30 Test System Considering Transient and Reliability Case Study First Cycle

Technique	**GA & BWO**				
Year	1				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9500	0.9500	0.9500	0.9500	0.9500
Frequency (KHz)	2.00	1.19	0.95	1.86	0.96
Inrush Current (KA)	0.22	1.1	0.98	0.33	0.74
Capacitor (MVAR)	0.56	4.64	5.20	0.89	3.87
Damping Reactor (mH)	13.7	0	0	0	0
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9500	0.9500	0.9500	0.9500	0.9500
Frequency (KHz)	2.58	0.73	2.27	0.79	2.74
Inrush Current (KA)	0.20	1.10	0.34	0.25	0.09
Capacitor (MVAR)	0.38	7.41	0.75	1.57	0.16
Damping Reactor (mH)	0	0	0	0	0

Table 6.42 IEEE-30 Test System Considering Transient and Reliability Case Study Second Cycle

Technique	**GA & BWO**				
Year	6				
Location (Bus)	**3**	**7**	**12**	**16**	**17**
OLD PF (PU)	0.8944	0.9022	0.8309	0.8893	0.8406
NEW PF (PU)	0.9500	0.9500	0.9500	0.9500	0.9500
Frequency (KHz)	2.47	3.07	2.39	2.68	2.63
Inrush Current (KA)	0.71	0.73	0.64	0.12	0.52
Capacitor (MVAR)	0.20	1.64	1.84	0.32	1.37
Damping Reactor (mH)	50.9	4.0	5.9	27.4	6.5
Location (Bus)	**19**	**21**	**23**	**26**	**29**
OLD PF (PU)	0.9415	0.8423	0.8944	0.8357	0.9363
NEW PF (PU)	0.9506	0.9500	0.9501	0.9500	0.9500
Frequency (KHz)	3.35	2.80	3.05	2.61	3.35
Inrush Current (KA)	0.08	1.07	0.12	0.21	0.03
Capacitor (MVAR)	0.17	2.62	0.27	0.56	0.06
Damping Reactor (mH)	34.9	3.0	25.0	16.4	102.3

Table 6.43 IEEE-30 Test System Considering Transient and Reliability Case Study Cost Summery

Technique	**GA & BWO**	
Year	**First Cycle (1)**	**Second Cycle (6)**
Installation Cost ($)	-9,413,900	-9,042,600
ELM Cost ($)	1,469,800	487,370
PFC Avoided Penalty ($)	13,118,000	4,629,800
Failure Cost ($)	-54,749	-83,263
Total Cost ($)	-7,998,900	-8,638,800
Avoided Loss ($)	5,119,500	-4,009,300
Accumulated Cost ($)	**5,119,500**	**1,219,300**

6.3.6 Reliability Impact of Failure Cost

This subsection is covering in detail the reliability and failure cost calculations to prove the hypothesis made on the capacitor negative impact to failure cost. PFC capacitors have a lot of advantages, thus, enhancing the system reliability. The main advantage contributing to the system reliability is the reductions in main power lines energy supply which reducing the line loading. This reducing the heat dissipation produces by main power lines. This reduction is reducing the line failure possibility, thus, enhancing the system reliability.

Such enhancement to system reliability was explained in Chapter 4 and the application of those calculations is shown in the tables below. The energy reduction happening to the main power line is mainly due to minimizing MVAR consumption. So, as shown below Graver's total failure cost was $15,989 and it is reduced to $15,919 for MVAR losses and $119,140 to $118,620 for MW losses. While IEEE-30 bus reduces from $12,846 to $12,753 for MVAR losses and $84,391 to $83,837 for MW losses. The reduction due to reliability enhancement it doesn't worth to be mentioned even in these case studies. The advantage of reducing main power lines consumption to reduce heat dissipation in the line is more applicable to the radial distribution system. The radial distribution system has one main power line supplying multiple loads. The reliability enhancement in minimizing main power lines failure possibility will do a major enhancement to the system reliability compared to network configuration which used in this thesis case studies.

Moving to negative impacts due to capacitor installations. The main contribution of this thesis is considering the capacitor-switching transient events that will have a huge negative impact on failure costs. The capacitor installation will minimize penalties for lower power factor by generating MVAR to the system. In Graver's test system, failure cost due to MVAR loss is $713,120 in not considering transient events. However, when the system design properly and the precautions including damping reactors installation were taken, failure cost reduces to $137,740. This lead to a total accumulated failure to be $256,290 compared to $831,670. While IEEE-30 bus test system, the total failure cost considering transient is $222,404 compared to $810,424 without transient consideration.

Table 6.44 Graver's Test System Reliability and Failure Cost Summery

Technique	**GA & BWO**	
Case	**Not Considering Transient**	**Considering Transient**
MW Failure Cost ($)	119,140	119,140
MVAR Failure Cost ($)	15,989	15,989
MW Failure Cost - Line ($)	118,620	118,620
MVAR Failure Cost - Line ($)	15,919	15,919
MVAR Failure Cost - Capacitor ($)	713,120	137,740
MW Failure Cost Difference ($)	520	520
MVAR Failure Cost Difference ($)	713,050	137,670
Final Failure Cost ($)	831,670	256,290

Table 6.45 IEEE-30 Test System Reliability and Failure Cost Summery

Technique	**GA & BWO**	
Case	**Not Considering Transient**	**Considering Transient**
MW Failure Cost ($)	84,391	84,391
MVAR Failure Cost ($)	12,846	12,846
MW Failure Cost - Line ($)	83,837	83,837
MVAR Failure Cost - Line ($)	12,753	12,753
MVAR Failure Cost - Capacitor ($)	726,680	138,660
MW Failure Cost Difference ($)	554	554
MVAR Failure Cost Difference ($)	726,587	138,567
Final Failure Cost ($)	810,424	222,404

CHAPTER 7

CONCLUSION

7.1 Conclusion

The thesis proposes a new problem formulation that will evaluate the system condition and solve low power factor issues. This objective function of the proposed formulation is targeting to achieve the maximum avoided cost. The costs that were considered part of the objective function are low PF penalty regulation, reliability cost impact, energy loss minimization due to capacitor installation and the system installation cost.

Two (2) main factors were considered in the proposed problem formulation capacitor switching transient and reliability constraints. Capacitor will enhance system reliability by reducing the main feeder loading, however, the transient switching events will lead to tremendous negative impact. In order to reduce the system transient during capacitor energization/switching, a damping reactor has to be installed in series with the capacitor. This will protect the capacitor and avoid breakers failures. All these factors were considered part of the cost function.

The proposed formulation was tested on two (2) test systems considering two (2) different scenarios. The two (2) scenarios were selected to illustrate the importance of considering capacitor switching transient on the project investment planning. Considering capacitor switching transient will lead to 41% higher investment cost due to damping reactors installation. However, it will avoid extra 63% in the total avoided loses. In addition, it will avoid capacitors flashover and un-necessary breakers opening which could lead to major operation losses.

The proposed formulation was solved utilizing four (4) optimization techniques. Among these four (4) techniques, two (2) were performed better than the others. These techniques are GA and the proposed BWO. The proposed technique (BWO) performed even better than GA and achieved the highest optimized cost with 16% improvement in the accuracy compared to GA.

7.2 Future Work

With all these factors has been considered and during the problem formulation, two things could be enhanced in the future to get better results:

1) Include harmonics load flow to check the harmonics at each bus. This thesis installed the damping reactor as a harmonics filter to make sure the resonance frequency didn't violate the limits. This was performed after calculating the frequency at each bus individually. Harmonics load flow will check the system harmonics flow even from a bus to a different bus, which is better for more detail harmonics analysis.

2) Integrate Fuzzy Logic Simulation (FLS) with Monte Carlo Simulation (MCS) to have better results and minimize the simulation time.

3) Simulate capacitor-switching transient resonance possibility in different programs such as GAMS to have more accurate failure rate.

APPENDICES

APPENDIX A: Graver's Test System Data

Table A.1 Graver's Load and Injection Data

Bus	Load	
	P_D (p.u.)	Q_D (p.u.)
1	0.240	0.116
2	0.720	0.348
3	0.120	0.058
4	0.480	0.232
5	0.720	0.348

Table A.2 Graver's Line Parameters Data

Line no.	Bus		R (p.u.)	X (p.u.)
	From	To		
1	1	2	0.1000	0.40
2	1	4	0.1500	0.60
3	1	5	0.0500	0.20
4	2	3	0.0500	0.20
5	2	4	0.1000	0.40
6	3	5	0.0500	0.20
7	1	3	0.0950	0.38
8	2	5	0.0775	0.31
9	3	4	0.1475	0.59
10	4	5	0.1575	0.63

APPENDIX B: IEEE-30 Bus Test System Data

Table B.1 IEEE-30 Bus Load and Injection Data

Bus No.	Load		Bus No.	Load	
	P (MW)	Q (MVAr)		P (MW)	Q (MVAr)
1	0.00	0.00	16	3.50	1.80
2	21.7	12.7	17	9.00	5.80
3	2.40	1.20	18	3.20	0.90
4	7.60	1.60	19	9.50	3.40
5	94.2	19.0	20	2.20	0.70
6	0.00	0.00	21	17.5	11.2
7	22.8	10.9	22	0.00	0.00
8	30.0	30.0	23	3.20	1.60
9	0.00	0.00	24	8.70	6.70
10	5.80	2.00	25	0.00	0.00
11	0.00	0.00	26	3.50	2.30
12	11.2	7.50	27	0.00	0.00
13	0.00	0.00	28	0.00	0.00
14	6.20	1.60	29	2.40	0.90
15	8.20	2.50	30	10.6	1.90

Table B.2 IEEE-30 Line Parameters Data

Line No.	From Bus	To Bus	Series Impedance (p.u)		Half Line Charging susceptance (p.u.)	Tap Setting	MVA Rating	Annual Cost (K$/year)
			R	X				
1.	1	2	0.01920	0.05750	0.02640	-	130	216.6125
2.	1	3	0.04520	0.18520	0.02040	-	130	307.2875
3.	2	4	0.05700	0.17370	0.01840	-	65	509.9500
4.	3	4	0.01320	0.03790	0.00420	-	130	700.0000
5.	2	5	0.04720	0.19830	0.02090	-	130	721.5250
6.	2	6	0.05810	0.17630	0.01870	-	65	168.1750
7.	4	6	0.01190	0.04140	0.00450	-	90	474.3000
8.	5	7	0.04600	0.11600	0.01020	-	70	62.0000
9.	6	7	0.02670	0.08200	0.00850	-	130	130.2000
10.	6	8	0.01200	0.04200	0.00450	-	32	104.6250
11.	6	9	0.00000	0.20800	0.00000	1.0155	65	306.9000
12.	6	10	0.00000	0.55600	0.00000	0.9629	32	20.9250
13.	9	11	0.00000	0.20800	0.00000	-	65	83.7000
14.	9	10	0.00000	0.11000	0.00000	-	65	927.6750
15.	4	12	0.00000	0.25600	0.00000	1.0129	65	554.1250
16.	12	13	0.00000	0.14000	0.00000	-	65	15.1125
17.	12	14	0.12310	0.25590	0.00000	-	32	30.2250
18.	12	15	0.06620	0.13040	0.00000	-	32	97.6500
19.	12	16	0.09450	0.19870	0.00000	-	32	179.0250
20.	14	15	0.22100	0.19970	0.00000	-	16	124.7750
21.	16	17	0.08240	0.19320	0.00000	-	16	146.4750
22.	15	18	0.10700	0.21850	0.00000	-	16	80.6000
23.	18	19	0.06390	0.12920	0.00000	-	16	235.6000
24.	19	20	0.03400	0.06800	0.00000	-	32	186.0000
25.	10	20	0.09360	0.20900	0.00000	-	32	117.8000
26.	10	17	0.03240	0.08450	0.00000	-	32	167.4000
27.	10	21	0.03480	0.07490	0.00000	-	32	160.4250
28.	10	22	0.07270	0.14990	0.00000	-	32	195.3000
29.	21	22	0.01160	0.02360	0.00000	-	32	166.2375
30.	15	23	0.10000	0.20200	0.00000	-	16	100.7500
31.	22	24	0.11500	0.17900	0.00000	-	16	40.3000
32.	23	24	0.13200	0.27000	0.00000	-	16	65.1000
33.	24	25	0.18850	0.32920	0.00000	-	16	210.8000
34.	25	26	0.25440	0.38000	0.00000	-	16	204.6000
35.	25	27	0.10930	0.20870	0.00000	-	16	83.7000
36.	28	27	0.00000	0.36900	0.00000	0.9581	65	223.2000
37.	27	29	0.21980	0.41530	0.00000	-	16	160.4250
38.	27	30	0.32020	0.60270	0.00000	-	16	90.6750
39.	29	30	0.23990	0.45330	0.00000	-	16	216.6125
40.	8	28	0.06360	0.20000	0.02140	-	32	54.2500
41.	6	28	0.01690	0.05990	0.00650	-	32	210.8000

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LIST OF PUBLICATIONS

As a result of this work, three (3) papers has been developed and submitted or in the way of submission for publication and they are as follows:

A. A. Almuhanna and M. A. Abido, "Optimal Placement of Power Factor Correction Capactiors Considering Transient Switching Events," to *The IEEE Transactions on Power Systems*, Volume: XX, Issue: XX, 20XX.

B. A. Alnujaimi, A. Almuhanna, A. Alothman and M. Almuhaini, "Optimal Planning of Power Factor Correction Capacitors Placement Considering Transient Switching Events," to *The Journal of Power and Technology*, Volume: XX, Issue: XX, 2018.

C. A. Almuhanna and M. A. Abido, "Reliability Impact for Optimal Placement of Power Factor Correction Capacitors Considering Transient Switching Events," *Not yet Submitted*.

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Academic Background :Joined KFUPM back in 2015 as a part-time Master Degree student. Obtained a Bachelor of Science (B.S.) degree in Electrical Engineering from King Fahd University of Petroleum & Minerals (KFUM), Dhahran, Saudi Arabia in May 2012. The main interest and the studies focuses was on power system studies with smart grid to find solutions in order to maximize the intergration of renewable energies with the grid.

Work Experience :Joined Saudi Aramco, Jeddah Refiner – Engineering Division (JED) in July 2012 as a Technical Support and Design Engineer. Transferred to Ras Tanura Refiner – Engineering Department (RED) due to manpower shortage in October 2012. In 2018, assigned as operation foreman on Power System Unit for three months. Then, moved to Maintenance Planning and Engineering Unit as supervisor and handled the same work up to now. The main work focuses on troubleshooting of electrical failures and finding solutions for optimized operation which led to obtaining the PE certification in electrical power system speciality.