COMPENSATION OF TRANSMISSION GRIDS BY USING OPTIMAL ALLOCATION OF FACTS DEVICES

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Dedication

I dedicate this thesis to my Parents, whose constant and steadfast support have been the foundation of my achievements. I also express my heartfelt appreciation to my teachers for their support, guidance and mentorship.

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All praise and gratitude are due to Allah Almighty, the Most Beneficent and Benevolent, who understands the mysteries and secrets of the universe. I also extend my deepest respect and salutations to The Holy Prophet (S.A.W), whose blessings inspire our aspirations and whose teachings have illuminated humanity in times of despair and darkness.

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ABSTRACT

The increasing complexity and demand on modern power systems necessitate the efficient management of transmission grids to ensure reliability, optimal power flow and maximum power transfer capability. The goal of this research is to enhance power system network performance by means of Flexible Alternating Current Transmission System (FACTS) devices, specifically the Unified Power Flow Controller (UPFC). UPFCs are installed at optimum locations to minimize the Multiple Objective Index comprising of the individual objectives of Active Power Loss (APL), Reactive Power Loss (RPL) and voltage profile. This thesis introduces a novel advanced optimization technique i.e., Sea Horse Optimizer (SHO) to find the optimum locations and ratings for UPFC installation. Initially, Newton-Raphson method is used without the UPFCs to compute APL, RPL and average Per Unit (p.u) voltage. SHO algorithm is then applied to determine the optimal locations and appropriate sizing for UPFC. The parameters—APL, RPL, and p.u voltage are then recalculated with the UPFC in place. The results demonstrate significant improvements in these parameters with the application of the SHO algorithm, showing superior performance as compared to the Artificial Bee Colony (ABC) optimization technique. The computational findings reveal that the SHO algorithm more accurately identifies optimal UPFC locations and sizing as compared to the ABC optimization algorithm, thereby substantially reducing power losses and improving the voltage profile of the transmission system.

KEYWORDS Unified Power Flow Controller (UPFC), Flexible Alternating Current Transmission System (FACTS), Sea Horse Optimizer (SHO), Active Power Loss (APL), Reactive Power Loss (RPL)

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LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
APL	Active Power Loss
FACTS	Flexible Alternating Current Transmission System
GE	Genetic Algorithm
LB	Lower Bound
MOI	Multiple Objective Index
NTDC	National Transmission and Despatch Company
PU	Per Unit
RPL	Reactive Power Loss
SVC	Static Var Compensator
SHO	Sea Horse Optimizer
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
UB	Upper Bound
UPFC	Unified Power Flow Controller

CHAPTER 1

INTRODUCTION

1.1. Background

The increasing integration of renewable energy sources and proliferation of power electronics in the power system networks are leading to more frequent power quality events, which pose significant risks to the stability and reliability to the grid system. Apart from the integration of renewables, the efficient management of transmission networks has also become a significant concern due to the rising complexity of modern power systems caused by rapid industrialization and urbanization. This emphasizes the critical importance of voltage regulation, improved power system stability, and the mitigation of power quality disturbances in ensuring the reliable operation of the power system networks. Power systems need to be built and operated with an emphasis on optimal power flow, stability, and reliability as the demand for electricity is continuously increasing. However, because of the such problems; caused by varying power requirements, transmission congestion, and the requirement to keep voltage profiles within safe limits are becoming exceedingly difficult to manage. The inherent shortcomings of conventional transmission lines can result in large power losses, voltage instability and inefficient power transmission, make these problems even worse to manage [1-5].

In response to these challenges, Flexible Alternating Current Transmission System (FACTS) devices has surfaced as a viable approach to improve power networks' performance. FACTS technology was first discovered in 1994 [6] wherein it was demonstrated that FACTS devices have the capability to regulate the parameters of transmission lines that can directly impact the performance and operation of AC power transmission systems.

Several kinds of FACTS devices and their advantages for power transmission lines are comprehensively discussed in [7]. These devices comprise of the Static Synchronous Compensator (STATCOM), Static VAR Compensators (SVC), Fixed Series Compensation (FSC), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Reactor (TCR), Thyristor Controlled Series Capacitor (TCSC) and Unified Power Flow Controller (UPFC) [8]. These FACTS devices enhance transmission network performance by optimizing the utilization of existing transmission assets thereby increasing power transfer capability.

To meet the increased load demand, there are two options; either to construct the new transmission lines or use the existing infrastructure at its optimum limits by reducing losses and enhance power transfer capability with the use of FACTS devices. Building new transmission lines require huge capital investment, long time for construction and it also impacts the environment as transmission line often passes through ecologically sensitive areas. In contrast, FACTS devices can be deployed quickly, requires less capital expenditure and can be integrated into existing substations or transmission corridors to increase power flow by using the same transmission infrastructure.

Faults and disturbances in the electric system can lead to severe power quality issues, which affects the performance of transmission network [9]. Common disturbances include power loss, voltage instability, overloading or underloading of transmission lines, and overall power system instability. As the load demand continues to rise, the construction of new lines or reconductoring of existing ones becomes necessary; however, these solutions require substantial capital investment, time and resources. To address this growing demand, FACTS devices are employed to increase transmission system performance and maximize the power transfer capability economically by reducing active and reactive power losses. Amongst all FACTS devices, UPFC stands out because it can change magnitude of voltage, impedance, and phase angle all at once. This gives it complete control over power flow in the transmission network. The UPFC is particularly effective at lowering active and reactive power losses, boosting voltage profiles, and improving the power system's overall stability because of its capacity to dynamically modify power flows.

However, these devices must be installed at optimal locations to prevent any adverse effects. Improper compensation can lead to power quality issues and voltage instability in other interconnected lines and buses. The challenge lies in finding the appropriate locations and ratings of these devices, due to the intrinsic non-linearity of the power system [10].

Over time, numerous algorithms have been developed and implemented to find the ideal locations of UPFCs. This includes the Differential Evolution (DE) algorithm, Gravitational Search Algorithm, Bacterial Foraging Algorithm, Genetic algorithm (GA), Particle Swarm Optimization (PSO) algorithm, Cat Swarm Optimization (CSO) algorithm, Spider community optimization algorithm and the Hybrid Group Search Optimization algorithm [11-16] and many others. All of these algorithms have been utilized to determine the best location for FACTS devices installation, with the goal of increasing power system efficiency, performance and stability. Another popular algorithm which has been used to find the best installation points for the various FACTS devices is Gravitational Search Algorithm [17]. Artificial Bee Colony Algorithm (ABC) [18] is also been employed to know about the location of FACTS in power system by taking into consideration various parameters such as power transfer capability, preventing blackouts and improving the power system reliability and stability.

Recently, a novel metaheuristic algorithm method called the Sea-Horse Optimizer (SHO) has been devised [19]. This method is inspired by the natural behaviors of sea horses, specifically their predation, movement and breeding patterns. The SHO algorithm replicates the life cycle of sea-horses in the sea, including its movement, hunting for prey and reproduction activities. In this research, the novel SHO algorithm is used on the NTDC 11 bus transmission network, IEEE 14-bus and IEEE 30-bus test systems to identify the optimal placement and sizing of UPFCs for improving transmission system performance and minimizing power losses. The outcomes are compared with those achieved using the Artificial Bee Colony (ABC) algorithm to illustrate the effectiveness of SHO.

The study starts by calculating the initial power active/reactive losses (APL and RPL) and voltage profiles without the use of UPFCs using the Newton-Raphson load flow analysis method. The best places and configurations for the UPFCs are then determined using the SHO algorithm, and the system's performance is recalculated after the UPFCs are installed. With an emphasis on lowering APL, RPL and boosting voltage stability, the findings are examined to evaluate the power system performance. The results of this study add to our understanding that how the advanced optimization technique can be used to improve the performance of modern power system transmission networks.

1.2. Motivation

The power system is susceptible to various faults, which contribute towards power losses and voltage instability. A significant factor is the fluctuating patterns of generation and load [20]. System stability can be enhanced through the use of reactive power sources. Initially, series and shunt capacitors were deployed to supply reactive power and improve system performance. But, with advancements in power electronics, FACTS devices have been developed and are now extensively being utilized to address these issues, with ongoing research into their efficacy. FACTS devices are extensively used in the power systems to increase the maximum power transfer ability and decrease the Total Harmonic Distortion (THD) [21]. Nonetheless, the placement of FACTS devices is most critical factor to be addressed. Various optimization techniques have been used in the literature to determine the optimal locations for these devices [22-27].

The motivation for this research thesis is to create and implement an optimization algorithm that can reliably and efficiently identify the ideal sites and configurations for UPFC installations. In order to outperform current techniques, such as ABC algorithm, the Sea Horse Optimizer (SHO) algorithm was introduced in this research. It provides better performance in lowering power losses and improving voltage profiles. SHO algorithm is used to determine the optimum placement and rating of UPFCs. Simulations are conducted on the IEEE 14-, IEEE 30-bus test systems, and the NTDC 11-bus transmission system. The study evaluates voltage violations and power losses with and without UPFC installation across different bus systems. Additionally, the results are compared with those obtained using the Artificial Bee Colony optimization algorithm to demonstrate the effectiveness of the SHO approach.

1.3. Problem Statement

The power system is vulnerable to faults including voltage violations, transmission line overloading or underloading, power losses and reduced efficiency. These disturbances can impact power flow, particularly in transmission lines between generators and buses. They also pose risks to system stability and efficiency. Therefore, maintaining voltage within stipulated limits is crucial. To achieve this, FACTS devices must be installed on transmission lines. However, optimal placement of these devices is essential to prevent adverse effects. Improperly placed FACTS devices can create issues for other connected buses and transmission lines. This research study focuses on using the Sea Horse Optimizer to determine the cogent locations and parameter settings for installing UPFCs in the power system.

1.4. Research Objectives

Key objectives of this thesis are as follows.

- To implement Sea Horse Optimizer on IEEE 14, IEEE 30 and NTDCs 11 bus transmission system to find the optimal locations and parameter settings for the installation of UPFC to reduce the active and reactive power loss, while maintaining the voltage profile within permissible limits.
- To study the combined effect of MOI comprising of the individual objectives of APL, RPL and average voltage.
- To investigate the efficacy of SHO method by comparing the results with ABC optimization technique.

1.5. Thesis Contribution

To achieve the stated objectives, the research thesis makes the following novel contributions:

- This research introduces the novel SHO algorithm for determining optimal placement and sizing of UPFC. A comprehensive comparison is conducted with the ABC algorithm to show the effectiveness and accuracy of the SHO.
- The major contribution is to minimize the APL and RPL by using the SHO technique by placing UPFC at best positions to reduce the overall power loss.
- Average voltage is also improved by bringing it closer to the 1.0 p.u. value for better voltage regulation.
- This approach is applied to the IEEE 14-bus and 30-bus power systems, as well as NTDC 11 bus transmission system.
- An analysis is performed to determine the series and shunt voltage values

post-UPFC installation, to identify the optimal sizing.

1.6. Thesis Organization

Thesis document is structured as follows:

Literature review discussion has been made in detail in Chapter 2, wherein the background in the context of FACTS devices and various proposed optimization algorithms for their optimum positioning and sizing along with their mathematical modellings is discussed. UPFC technical discussion and the main contribution of research is also detailed in the said discussion. In Chapter 3, the detailed methodology of Sea Horse Optimizer (SHO) technique and the steps involved are explained explicitly in detail. Proposed technique that how the SHO method is being used to know about the optimal placements and parameters of UPFC has also been discussed. Chapter 4 presents simulations and results, including a comparison of the SHO results with the ABC algorithm. At the last, conclusion of the thesis is presented in the Chapter 5 wherein the results of the research have been summarized and future recommendations and limitations of this research is also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1. Different Types of FACTS Devices

Numerous researchers have focused on various FACTS devices within power systems to address issue of voltage regulation, elimination of overloading conditions, reduction of power system losses and enhancement of power efficiency. The literature on power system optimization is extensively being explored, particularly in the context of enhancing transmission network performance through the use of Flexible Alternating Current Transmission System (FACTS) devices. Different kinds of FACTS devices are used in the power system for different kinds of the applications. All of these devices have some limitations, thus it's important to utilize them appropriately and specifically for the intended purpose. Among these devices, UPFC has garnered significant consideration due to its ability to manage multiple power flow parameters simultaneously.

In paper [28], the comparison of various FACTS devices has been made w.r.t active and reactive power and the author has verified the results after comparing many FACTS devices that the UPFCs are superior in performance as compared to the other FACTS device like SVC, TCSC and STATCOM. Because on transmission lines, UPFC has the ability for the flexible control over the flows of both active and reactive power in the system.

American Electric Power installed the first UPFC in history at the Inez grid station [29]. It is possible to install the UPFC at any location in the system but it will react and function differently at every installation point, so it is imperative to find the best placement for the UPFC installation [30] so that it works with full capability and provide optimal support to power system in reduced production device cost for the said

FACTS device [31-34].

2.2. Various Proposed Algorithms in Literature for Optimal Positioning of FACTS devices

Various optimization techniques, including classical methods and heuristic algorithms have been developed and implemented by the power system researchers to determine the best position for the FACTS devices in order to enhance performance of transmission system. In paper [35], the author used the heuristic Genetic Algorithm (GA) to find the optimal positioning and ratings of TCSC, SVC and UPFC but paper is silent on the quantity of these devices. UPFCs were used to reduce the line contingencies by using the Artificial Algae Algorithm (AAA) but their relationship with other devices was not discussed [36]. The optimal practicable TCSC placement and dimensions are determined by applying the non-dominated sorted genetic algorithm (NSGA-II), which increases the transmission system's loading capacity. But its impacts in existing reactive power sources is not discussed in paper [37]. PV curves were used to find the weak buses and optimal placement of UPFCs in Java-Bali 500 kV Power System of Indonesia, but this paper didn’t discuss anything about the ratings of the FACTS devices [38]. In paper [39], power quality has been improved by using the fuzzy based UPFCs. In this paper, UPFC is perceived with PI and FLC (Fuzzy Logic Controller) to mitigate the issue of power quality. However, optimum locations and ratings hasn’t been proposed. Real power flow performance index sensitivity method is used to determine the optimal TCSC locations in order to maximize the transmission system's power transfer capacity in [40]. But, sizing and possibility of applying single or multiple FACTS devices has not been touched. Salp Swarm Optimization (SSO) algorithm has been used in paper [41] to discover the best placements of UPFC.

UPFCs were proposed in [42] to lessen voltage swells and sags and to enhance power quality. In the paper [43], the author tried to determine the optimum power flow in the power network at the lowest cost fuel by using the Particle Swarm Optimization (PSO) technique to improve the power system stability through the appropriate placement of SVC and UPFC. An attempt was made to use UPFC installations to raise the Total Transfer Capability (TTC) in article [44]. In the publication [45], UPFC and the model predictive control approach were covered for power system stabilization. The authors of this paper confirmed that the said approach leads to the effective dampening of the power system oscillations.

FACTS devices effectiveness is evaluated by using the bus voltage stability index and the line voltage stability index, which are crucial in determining their optimal placement on the transmission line. For this purpose, two algorithms, the Gravitational Search Algorithm and the Bacterial Foraging Algorithm, were proposed. Study concludes that the Bacterial Foraging Algorithm demonstrates superior performance [46]. Another advanced algorithm is Particle Swarm Optimization (PSO), which can effectively interact with various other FACTS devices. A review of this method is provided, aiding in the selection of specific FACTS devices based on different scenarios and objectives [47]. To optimize the placement and ratings of the FACTS devices, the author has suggested using the Autonomous Groups Particle Swarm Optimization (AGPSO) technique. This algorithm is compared with other conventional techniques, showing higher rate of convergence and low active power loss [48-49].

Reliability can be achieved by interacting the Distributed Generation with the FACTS devices. Daily increases in load demand require the deployment of Distributed Generation (DG) units at different locations in order to successfully fulfil this increasing load demand. In this work, the best places for Distributed Generation (DG) and FACTS devices at maximum loading are determined analytically via Optimal Power Flow (OPF) method in MATLAB [50].

Another significant determinant of optimization algorithmic efficiency is its ability to minimize total cost by identifying the best location. The author tested it under abnormal conditions, such as a generator outage, line loss or overload. The outcome demonstrates that proper SVC and TCSC positioning can reduce the likelihood of voltage collapse and device cost [51]. This paper proposes self-adaptive firefly algorithm (SAFA). This technique was applied to decrease real power loss, raise voltage stability and enhance voltage profile [52]. This paper focuses on the two bio-inspired algorithms. These algorithms are applied on two buses IEEE 118 and UPSEB 75. UPFC can control both the series and shunt current injections. Optimal allocation and quantity of UPFC is an extremely important factor to consider because UPFC are really expensive since they are the electronic converter-based devices [53]. The Non-dominated Sorting Genetic Algorithm (NSGA) was used by the author in order to find the best set of solutions for the positioning and capacity of UPFCs. It has been tested on the IEEE 14-bus system to confirm the suggested method's efficacy.

Differential Evolution Invasive Weed Optimization (DEIWO) optimization technique is implemented on 14-bus IEEE system to determine best position for FACTS devices. For true parameter optimization, it is a simple metaheuristic approach [54]. DEIWO is a successful method for addressing a wide range of multi-dimensional, linear and nonlinear optimization problems. It was inspired by the organic process of weed colonization and dispersal [55].

System Security and Optimal power flow are the key factors to be catered in the power transmission system. The Jaya Algorithm-enabled Flower Pollination Algorithm (JA-FPA) was used to implement the multi-objective model which combines individual objectives like the Power Loss Index (PLI), severity, Voltage Stability Index (VSI), Line Collapse Proximity Indexes (LCPI) and TCSC cost to determine the optimal location and capacity of the TCSC FACTS device. The implemented technique demonstrated superior performance as compared to the JA, PSO, GWO, DA, WOA, FPA, PSO + GSA and PSO algorithms [56]. Appropriate location for TCSC for the improvement of the voltage profile of the network and to reduce the power losses has been proposed via Genetic algorithm [57] with objective functions of voltage deviation cost and the installation price of the TCSCs. After performing the simulations on MATLAB, author validated that active power loss reduced from 5.16 to 5.08 MW. Adaptive moth swarm optimization technique was applied in the paper [58]. This technique uses search based bacterial foraging algorithm. The best position of single as well as dual TCSC is executed by using this optimization technique [59-60].

To optimize the real power flow, a meta-heuristic method called Tuna Swarm Optimization was presented, which incorporates wind power generation with FACTS devices. The wind generation model used the Weibull probability density function to get the best values for the choice variables. By applying this technique, the voltage profile was improved and the generating cost and power loss were dropped [61]. The Marine Predator Algorithm method's "high and low-velocity ratios" are used to improve the classic Tuna Swarm and further boost the optimizer's performance [62]. To determine the optimal sites for FACTS devices, the Enhanced Tuna Swarm Optimization approach is proposed. Hunter Prey optimization (HPO) is another algorithm which mimics the behavior of wild predator animals, for instance; leopards, gazelles, lions, wolves and stags. Enhanced HPO method improves the exploration and exploitation stages. For this, an adaptive process for exploitation stage and a random mutation process for exploration stage is used, which balances the transition between the two stages. OPF problem is solved with enhanced HPO, which incorporates FACTS devices and wind power [63].

Selection of appropriate parameter settings and suitable location was studied by using two different FACTS devices i.e., TCSC and SVC. Grasshopper optimizations (GOA) and Mothflame (MFO) algorithms are applied on 14 bus and 30 bus IEEE systems. Best results in terms of loss reduction are achieved by integrating the Thyristor-Controlled Series Capacitor (TCSC) unit, while most favorable outcomes for system stability are obtained by installing the SVC unit [64].

For the reduction of the power system congestion, author implemented a control strategy for FACTS devices to control reactive power by using an evolutionary optimization method. The approach was validated on 57-bus and 118-bus IEEE transmission networks. They utilized the Symbiotic Organism Search (SOS) algorithm to explore the best placements of FACTS devices under varying loading situations. The results demonstrated a minimization in total system loss from 0.2799 to 0.2171 Mega Watts and from 1.3286 to 1.0455 Mega Watts in the cases of 57 and 118 transmission bus networks respectively [65]. When transmission lines aren't able to transfer enough electricity to fulfil load demand, this state is known as congestion of the power system. Congestion management is basically avoiding congestion. Two different methods to avoid congestion of power system is the re-dispatch or the use of FACTS devices [66]. To mitigate effects of congestion, numerous researchers has employed FACTS devices and tried to find their optimal placement in power system networks to improve its performance [67-71].

2.3. Unified Power Flow Controller (UPFC)

UPFC is one of the most versatile and effective devices within the family of FACTS controllers. Unlike other FACTS devices, it has the ability to provide the dynamic control that can regulate the active, reactive power and bus voltage either independently or in tandem. UPFC is made up of two Voltage Source Converters (VSCs) that are connected back-to-back, namely the Static Synchronous Series Compensator (SSSC) and the Static Synchronous Compensator (STATCOM), which share a common capacitor and are DC link connected. UPFC can concurrently provide fast acting active and reactive power without any external connected source. The three factors that affect flow on transmission lines are line reactance, the voltage's magnitude, and phase angle; all can be controlled by UPFC. SSSC within the UPFC is used for the active power control. Active power required for the line is taken from the line itself through STATCOM. While, STATCOM is used for the reactive power controlling [72-75].

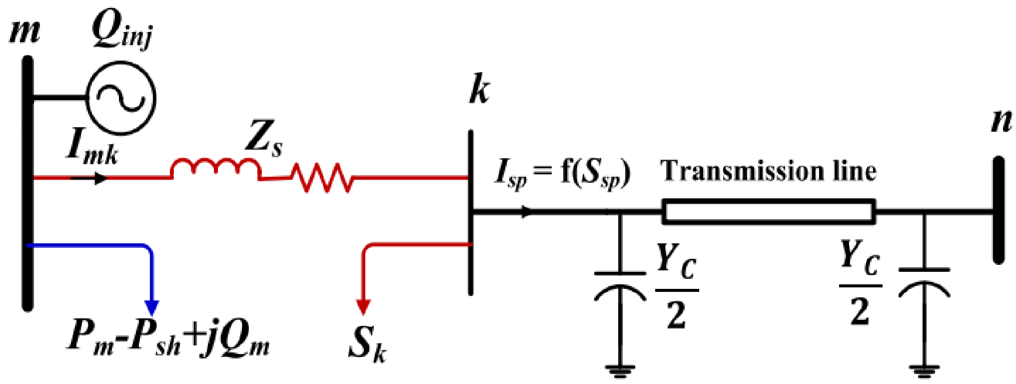


Figure 2. 1 UPFC Control Diagram

The best locations for UPFCs to maximize power transfer and minimize active and reactive power losses in transmission lines are critical to their efficacy in controlling active and reactive power. The bus that is most impacted is typically where the UPFC is placed. But as the lines load up, voltage instability becomes a significant problem, making it difficult to determine where the UPFCs should be placed in order to raise average voltage and lower power losses [76].

2.4. Main Contribution

Since UPFC is delicate and very expensive FACTS device hence it should be placed at optimum locations in order to extract the best performance and to improve the efficacy of transmission system. In this thesis, an attempt has been made to find the series and shunt voltages in order to extract the optimum ratings for UPFC along with the best positions. In this research, novel algorithm named the Sea Horse Optimizer (SHO) has been used to get the requisite outcomes. This algorithm has three crucial phases: moving, predation, and breeding. Local and global search methods are considered for the social behaviors of growth and predation. Simulation results of SHO have also been compared with the ABC technique to show its usefulness. The technique has been confirmed on the IEEE 14 and 30 bus system and also on National Transmission and Despatch Company (NTDC) 11 bus transmission system network.

CHAPTER 3

METHODOLOGY

3.1. Optimization Using Sea Horse Optimization (SHO) Method

Sea Horse Optimization is relatively new gradient free method, which is inspired by breeding, movement and predation characteristics of seahorses. This technique, like other nature-inspired algorithms, uses the unique traits of seahorses to find solutions to complex problems. This technique mimics behavior of seahorses, such as their reproductive strategies, movements and predation behaviors to guide the search to solve optimal solutions for global optimization problems [77].

Seahorses are also referred to as the hippocampus, are the prominent and most beloved creatures in the ocean world. Researchers are always discovering latest the facts and natures about them. For thousands of years, these animals have been significant in superstitions, medicine, fairy tales, and economics. Recent years have brought new knowledge about this creature to the attention of certain experts [78]. Seahorses has been present on earth for the 40 million years and some species of them are still present on Earth. These days, their survival is in jeopardy, and the World Wildlife Fund organization has categorised them as endangered species [79].

It's one of the bio-inspired algorithms that are drawn from the natural world to resolve the real-life complex problems and challenges. SHO's performance is compared with six cutting-edge metaheuristic algorithms on 23 popular functions and the CEC-2014 benchmark functions. The efficacy of SHO is also tested on five engineering challenges from the actual world. The outcomes of the results show that SHO is a highly effective optimizer with positive adaptability for handling optimization problems [80]. Seahorse Optimization algorithm (SHO) is particularly designed based on the unique behavior and characteristics of seahorses.

The modified SHO is more robust and has the ability to move through the search space so that the solution can be obtained more optimally and convergence can be achieved. It uses the innovative strategy of the SHO to move towards the exploitation phase more than the exploration phase to know the more optimum answer to resolve the more complex optimization problems.

3.2. Steps Involved in Sea Horse Optimization (SHO) Algorithm

Detailed step-by-step breakdown of how the Seahorse Optimizer typically works is given as under:

3.2.1. Initialization

Like other metaheuristic optimization techniques, SHO also starts from the initialization of population size to explain the global optimization problems. In this step, the initial solutions are generated. Solutions are often represented as individuals in a population size. Overall population of sea horses can be written as [80]:

$$Seahorses = \begin{bmatrix} x_1^1 \ldots\ldots\ldots\ldots\ldots\ldots.. x_1^{Dim} \\ \ldots\ldots \\ \ldots\ldots \\ \ldots\ldots \\ x_{pop}^1 \ \ldots\ldots\ldots\ldots\ldots. x_{pop}^{Dim} \end{bmatrix} \quad \textbf{(1)}$$

Here, population size is represented by pop and variable's dimension is symbolized by the variable Dim. Every solution is randomly produced between the LB & UB. The expression of the i^{th} individual X_i expression in search space is [LB, UB]

$$X_i = \{[X_i^1 \ldots\ldots\ldots, x_i^{Dim}] \quad \textbf{(2)}$$

$$x_i^j = rand \times (UB^j - LB^j) + LB^j \quad \textbf{(3)}$$

rand denotes the any random number between 0 and 1. x_i^j is i^{th} individual and j^{th} represents the dimension. So, x_i^j is the i^{th} individual in the j^{th} dimension, i is a positive number from 1 to population size and j is any number in range of [1, Dim]. UB^j & LB^j are the upper bound and lower bound of the j^{th} variable of the under-consideration problem to be optimized.

3.2.2. Fitness Evaluation

In this step, assessment is made that how well each solution performs. A predetermined goal function is used to create the fitness of each individual candidate solution in the population size. Objective function measures how well each solution performs in solving the problem.

For instance, consider that the under-review optimization problem is a minimum function, then individual with the minimum fitness function which is represented as X_{elite} will be obtained by the following Equation [80].

$$X_{elite} = argmin\big(F(x_i)\big) \quad \textbf{(4)}$$

where f (...) is the fitness function of any under consideration optimization problem which is to be solved.

3.2.3. Movement Behavior

The movement behavior of SHO can be categorized into Spiral and Brownian movements. When it comes to the first behavior, sea horses' movement patterns correspond to the normal distribution randn (0,1). In case of spiral motion, sea horses move towards the best position X_{elite} in random space in order to widen its local search for exploration and exploitation of algorithm.

$$X_{new}^{1}(t+1) = X_i(t) + Levy(\lambda)\,\big(X_{elite}(t) - X_i(t)\big) \times x \times y \times z + X_{elite}(t) \quad \textbf{(5)}$$

Where;

$l = \rho \times \cos(\theta)$,

$m = \rho \times \sin(\theta)$

$n = \rho \times \theta$

It represents the components of l, m, n coordinate dimensions showing the twisting motion of the sea horses. These coordinates assist to update the locations of search agents. ρ denotes measurement of the stems determined by constants of spiral that are u and v. θ is randomly chosen value between 0 to 2π. λ is any random integer between [0, 2]

Lévy flight is a function to find the sea horses step size. Lévy flight distribution is represented by Levy (z) and is taken from [81]:

$$Levy\ (z) = s \times \frac{w \times \sigma}{|k|^{1/\lambda}} \quad \textbf{(6)}$$

s is a fixed number of 0.01, w and k are any numbers between 0 to 1. σ can be found by the equation:

$$\sigma = \left[\frac{\tau\,(1+\lambda)\times sin\left(\frac{\pi\lambda}{2}\right)}{\tau\left(\frac{1+\lambda}{2}\right)\times\lambda\times 2^{\left(\frac{\lambda-1}{2}\right)}}\right] \quad \textbf{(7)}$$

A sea horse imitates the motion of another sea horse by moving with the waves during Brownian movements. It can be expressed via equations as follows:

$$X_{new}^{1}(t+1) = X_i(t) + rand \times l \times \beta_t \times (X_i(t) - \beta_t \times X_{elite}) \quad \textbf{(8)}$$

l represents the constant co-efficient. βt is random number of Brownian motion walk coefficient and can be obtained by using

$$\beta_t = \frac{1}{\sqrt{2\pi}} exp\left(-\frac{x^2}{2}\right) \quad \textbf{(9)}$$

3.2.4. Predation Behavior

Two possible outcomes in case of predation are Pass or Fail. If pass, there is 90% probability that the prey is captured and 10% probability that it isn't captured. If $r_2 > 0.1$, it means that the prey has been successfully captured and the sea horse is at its best position as he has moved faster than the prey and has captured it. Conversely, if predation is failed, then the sea horse will explore the further search space. Equations for predation can be written as under:

If $r_2 > 0.1$:

$$X_{new}^{2}(t+1) = \alpha \times \left(X_{elite} - rand \times X_{new}^{1}(t)\right) + (1-\alpha) \times X_{elite}) \quad \textbf{(10)}$$

If $r_2 \leq 0.1$:

$$X_{new}^{2}(t+1) = (1-\alpha) \times (X_{new}^{1}(t) - rand \times X_{elite}) + \alpha \times X_{new}^{1}(t) \quad \textbf{(11)}$$

$$\alpha = \left(1 - \frac{t}{T}\right)^{\frac{2t}{T}} \quad \textbf{(12)}$$

Here, α is the sea horse step size that decreases linearly when sea horses reach close to the prey. Maximum number of iterations are represented by T.

3.2.5. Breeding Behavior

Breeding behavior of sea horses is implemented when the movement and predation behaviors have been concluded. It is pertinent to mention that the sea horses are the unique creatures in which male sea horses produces the offspring as female sea horse lays eggs in the brood pouch of her male partner. Half population is categorized as males and half as females. Males and females randomly mate and for ease, it is presumed that sea horses breed only 1 child. The equation for the offspring is:

$$fathers = x_{sort}^2\left(1:\frac{pop}{2}\right) \quad \textbf{(13)}$$

$$mothers = x_{sort}^2\left(\frac{pop}{2}+1:pop\right) \quad \textbf{(14)}$$

$$X_i^{offspring} = r_3 X_i^{father} + (1-r_3)X_i^{mother} \quad \textbf{(15)}$$

3.2.6. Iterations

The algorithm cycles through the movement, predation and breeding steps over many sets of iterations with each cycle aims to improve the solutions by exploring new configurations, improving in on promising ones and combining good solutions to generate newer ones until an ending criterion is met (i.e., convergence to solution or a predefined number of iterations have been performed).

3.2.7. Termination

The algorithm terminates when the stopping requirement is satisfied. The optimal option discovered throughout the optimization process is chosen as final result.

3.3. Pseudo Code of SHO

Step 1: Start

Step 2: Initialize Population: Generate initial solutions.

Step 3: Evaluate Fitness:
Evaluate how well each solution performs and determine best sea horse.

Step 4: Determine the upper and lower boundaries

Step 5: After initializing all the parameters, position of the sea horses is updated by using eq (5).

Step 6: In this step, position of the seahorses is updated by using expression (8).

Step 7: In this step, position of the seahorses is adjusted again but this time by using the predation behaviour by using above expressions (10) and (11).

Step 8: In this step, the variables which are out of set boundary are discarded after achieving required fitness level.

Step 9: In this step, algorithm moves to the exploitation phase where the populations of mothers and fathers is chosen from the population size mentioned in above expressions (13) and (14)

Step 10: Once the father and mother have been selected, offspring is produced by using mathematical equation (15) and new population is generated.

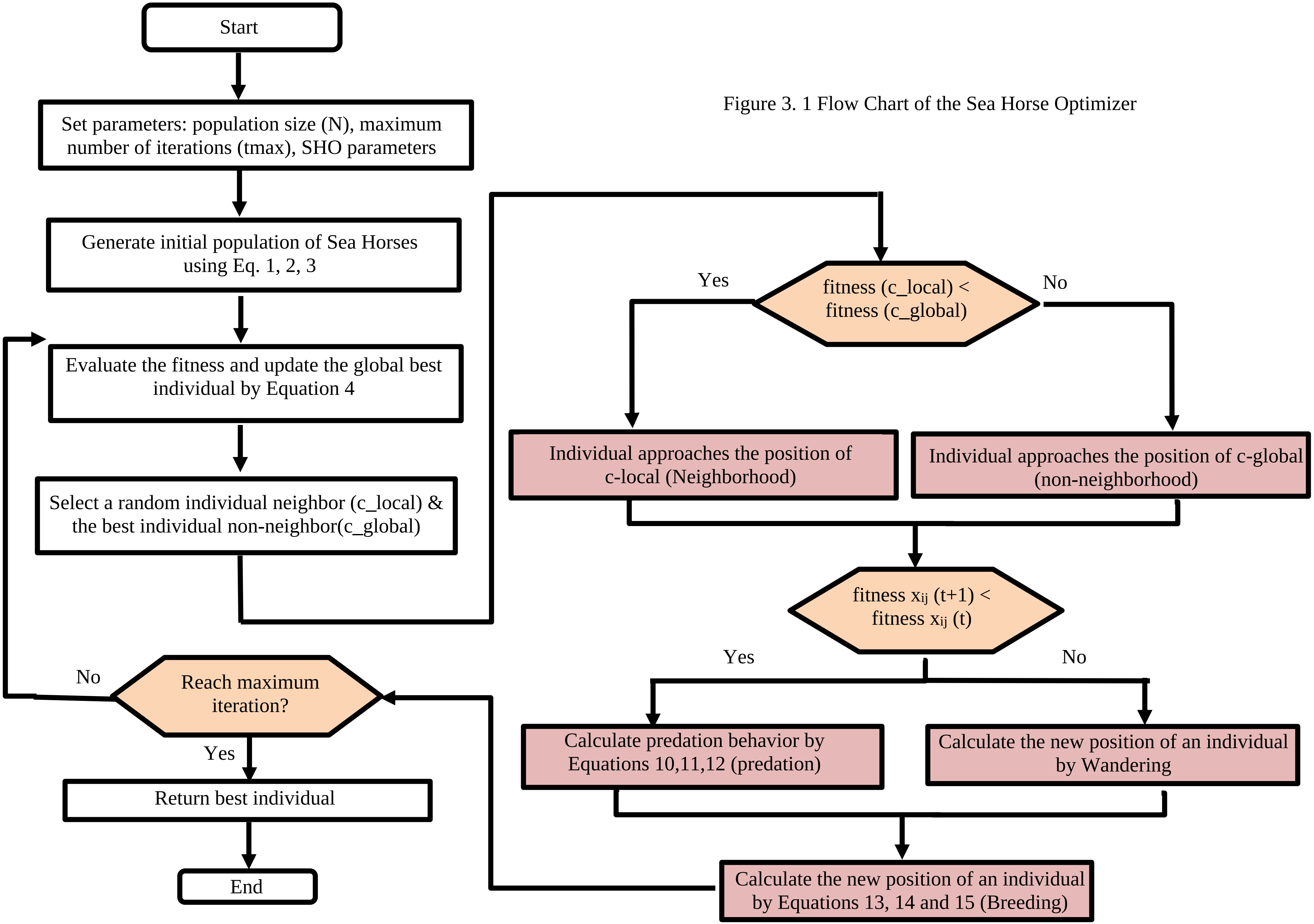
Step 11: The generated population must be in the set upper and lower bounds and the same can be verified by using eq (3).

Step 12: In this step, the fitness of newly created population is verified. If it corresponds to the required outcome of X_{elite}; then the solution is converged and stored in the memory. Conversely, if solution is not within the limit, algorithm moves to the next iteration ($t = t + 1$) and it is performed by using above eq (12) and the top ranked parents in the fitness function are called.

Step 13: When the iterations are completed and best fitness level of the algorithm is achieved, the algorithm is converged and solution is updated to the previous best value.

However, the original SHO has some shortcomings in achieving the right balance between local and global search behaviours especially during the movement phase. Therefore, in this research, modified Sea Horse Optimizer (mSHO) is used as it outperforms the original SHO by introducing various adjustments and refines the balance between the exploration and exploitation phases to improve the convergence rate and avoid local optima. Original SHO provides good baseline performance but it struggles during the movement phase because fixed values are given which restricts its ability to find solution effectively to new positions to find the global optimum. In contrast, mSHO gives better accuracy and overall performance by exploiting the space solution more effectively. Modified SHO has 03 distinct steps which are neighbourhood based local search (c_local), non-neighbourhood based global search (c_global) and wandering around based search strategy. It uses the innovative strategy of the SHO to move towards the exploitation phase more than the exploration phase to know the more optimum answer to resolve the more complex optimization problems [82]. The flow chart for the process of modified Sea Horse Optimization Algorithm is given in Figure 3.1.

Figure 3. 1 Flow Chart of the Sea Horse Optimizer



3.4. Application of SHO to find Optimum locations of UPFC

At start, set of candidate solutions (seahorses) is generated, representing possible locations and settings for the UPFC in the power system. Each candidate solution includes variables for the placement and ratings of the UPFC. Then the Multi Objective Index is defined as the combination of three induvial objectives APL, RPL and average voltage. Equal weights have been used for all three variables to form the MOI. Each candidate solution (seahorse) is assessed based on the fitness function. In this case, power system performance is simulated with the UPFC placed at the candidate locations and objective function is calculated. SHO algorithm balances exploration phase wherein new areas of the solution space are searched and exploitation phase therein the current best solutions are refined further for the improvement of results. Seahorses update their positions based on the best solutions found to ensure diversity in the search behavior. SHO uses many strategies like spiral movements which replicates the same natural movement of seahorses to explore the solution space, aiming to find a better configuration for UPFC placement. The algorithm continues to run when stopping criterion is met and that is achieved when the maximum number of set iterations have been carried out by updating and evaluating solutions or convergence to a certain level of performance improvement is achieved. The flow chart of how the SHO is working in this research thesis is provided in the Figure 3.2.

Initially, Load flow analysis is implemented on IEEE 14 and 30 bus system as well as NTDC 11 bus system in MATPOWER via Newton-Raphson method to investigate the standard load flows and power flows [83]. The objectives of study are to minimize the APL and RPL while increasing the system V_{avg} at the same time to bring it closer to the standard 1.0 p.u. value to avoid voltage instability and regulate the system voltage to avoid any negative consequences to the interconnected grid networks. These parameters are calculated firstly so that once the UPFC are installed, the comparison of the results may be made before and after the use of UPFC.

Then, SHO technique is applied on said test bus systems to optimize and know about the most appropriate locations for the installation of UPFC. After the connection of these UPFC devices at optimum positions, again the parameters for APL, RPL and average voltage are calculated. The ultimate goal is to decrease the active and reactive power loss and improve the voltage profile. Best parameter settings of the UPFC i.e., series voltage (V_{se}) and shunt voltage (V_{sh}) values has also been calculated via Sea Horse Optimizer to know about the best parameters for the said FACTS devices.

3.5. Multiple Objective Index

The individual objectives of this study are amalgamated to form the cumulative Multiple Objective Index (MOI). MOI in this case is a weighted sum of APL, RPL and average voltage profile. It is given as follows [84]:

$$MOI = w1 \times APL + w2 \times RPL + w3 \times \left(1 - V_{avg}\right) \quad \textbf{(16)}$$

$w1, w2$ & $w3$ are the weights which is used with the objective parameters of APL, RPL and V_{avg}. Equal Weights have been used in this research and these are enlisted in the Table 3.1

Sr. No	**Parameter**	**Weight**
1.	APL	0.333
2.	RPL	0.333
3.	V_{avg}	0.333

Table 3. 1 Weight Indices

Based on the APL, RPL, and V_{avg} parameters, MOI has been computed. Once FACTS devices are positioned at suitable sites to improve grid performance, the parameters APL and RPL must be decreased. Whereas, average voltage is required to be maintained near to 1.0 p. u value to have better voltage profile and avoid voltage instability. Any deviations from this required value depicts poor voltage regulation and voltage instability. As APL and RPL after the placement of UPFC should be reduced so the MOI has been modeled as the overall minimum function and to cater the situation of average voltage, the fraction for the V_{avg} is reversed so that MOI commutatively becomes the minimum fitness function.

$$MOI = \frac{APL_{after}}{APL_{before}} + \frac{RPL_{after}}{RPL_{before}} + \frac{V_{avg(after)}}{V_{avg(before)}} \quad \textbf{(17)}$$

3.6. Data Entry Modelling

The proposed optimization method is tested on the test cases of IEEE 14 and 30 bus system. In order to build the case for 11 bus NTDC network, Torrit software tool is used. This tool assists electrical engineers to perform the tasks like power flow analysis, economic dispatch, unit commitment and contingency analysis [85]. Using this tool, we can create the graphical power networks and it produces the mfile which can be run in MATALB to perform various simulations. The simulations have been performed in MATLAB 2018b. It helps to build case files of MATPOWER which are then run in the MATLAB to perform load flow analysis.

To build a new case with Torrit, first choose the New Project tab from the File menu. This comprises of four options; Generator, Load, Bus Bar, and Transmission Line Connector. Busses of the power system networks should be added in a sequence according to their numbers. But transmission lines should not necessarily be built in a sequential fashion. In order to enter Generator, Bus, and Transmission line paraments, user must double click on the icon and provide the necessary parameter of the particular model. In this research, portion of the NTDC transmission network was considered for testing the efficacy of SHO algorithm in finding the best solutions. 11 bus network of the NTDC was envisaged and built by using the MATPOWER Case Building with Torrit software. After building the case, all the requisite values were entered in the Torrit and the file was run. The software produced the mfile of the said network, which was imported in the MATLAB for performing the simulations.

Flowchart of the approach being used in this research for the implementation of NTDC network is depicted in Figure 3.2

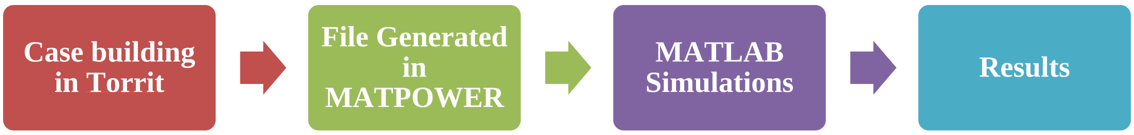


Figure 3. 2 Flow Chart of the approach

CHAPTER 4

SIMULATION, RESULTS & DISCUSSION

In this research, Sea Horse Optimization algorithm is executed in MATLAB. SHO, a novel swarm-based gradient-free metaheuristic optimization algorithm is based by mimicking the movement, reproduction and predation behaviors of sea horses. Local and global search strategies are applied for predation and movement behaviors respectively to improve the performance of SHO. In this thesis, modified SHO shortly written as mSHO is used because of its better ability to converge more on the global solutions rather than the local. Modified SHO is better able to find the more accurate locations and ratings for the UPFC as compared to simple SHO. This Algorithm has been applied on two case scenarios of IEEE test bus systems i.e., IEEE-14 and IEEE-30 and on NTDC 11-bus Transmission system. SHO algorithm results have been compared with ABC optimization method to demonstrate its effectiveness and better optimization results. For all test case scenarios, the number of UPFCs, minimum and maximum p.u. voltage range, which are taken into consideration in this thesis are kept same. A thorough comparison of the outcomes with the ABC algorithm is then made to show the effectiveness of recommended method.

4.1. Case Scenario: 1 (IEEE 14 bus test network)

IEEE has developed many standard case networks that are being used by the power system engineers to perform the research after performing the simulations on these networks, one of those is the 14-bus System. This network is obtained from the portion of American Electric Power system and used as standard test case transmission system. It comprises of the five (05) generators, twenty (20) transmission lines and eleven (11) connected loads [86].

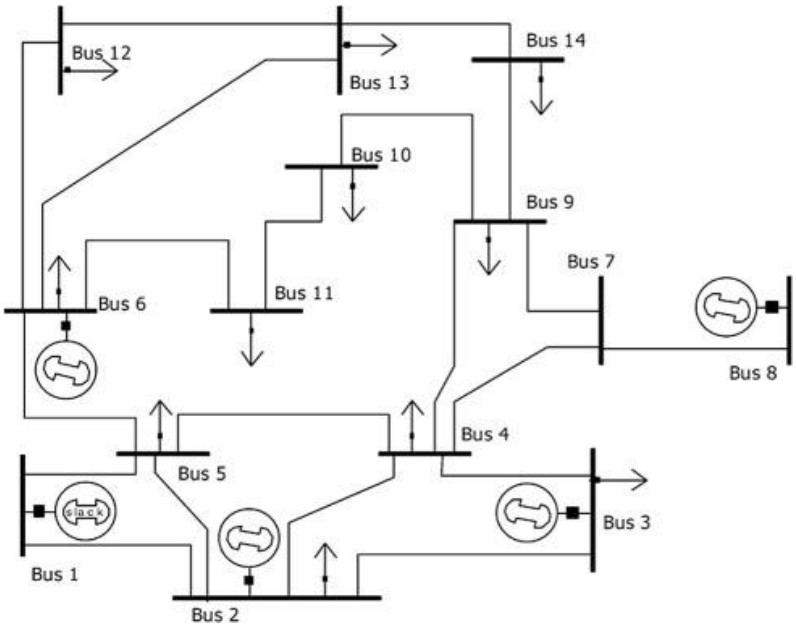


Figure 4. 1 IEEE 14 bus network

i. Without UPFCs:

In the first step, standard Newton Raphson (NR) load flow analysis is implemented to find the APL, RPL and average voltage. NR Power flow method produces P_{LOSS} of 13,393.27 kW, Q_{LOSS} of 54,538.31 kVar, voltage profile of 1.0484 and V_{min} of 1.01 at bus 3 without the introduction of UPFCs, which is the base case situation. These values will serve as a basis for later comparisons, to investigate the improvement that are incurred in the requisite parameters when the UPFC devices are installed at optimum positions.

Parameter	**APL “kW”**	**RPL “kVar”**	**Average Voltage “p.u”**	**Minimum Voltage**	**At Bus**
Value	13,393.27	54,538.31	1.048473	1.01	3

Table 4. 1 IEEE 14 bus network: parameters without UPFC

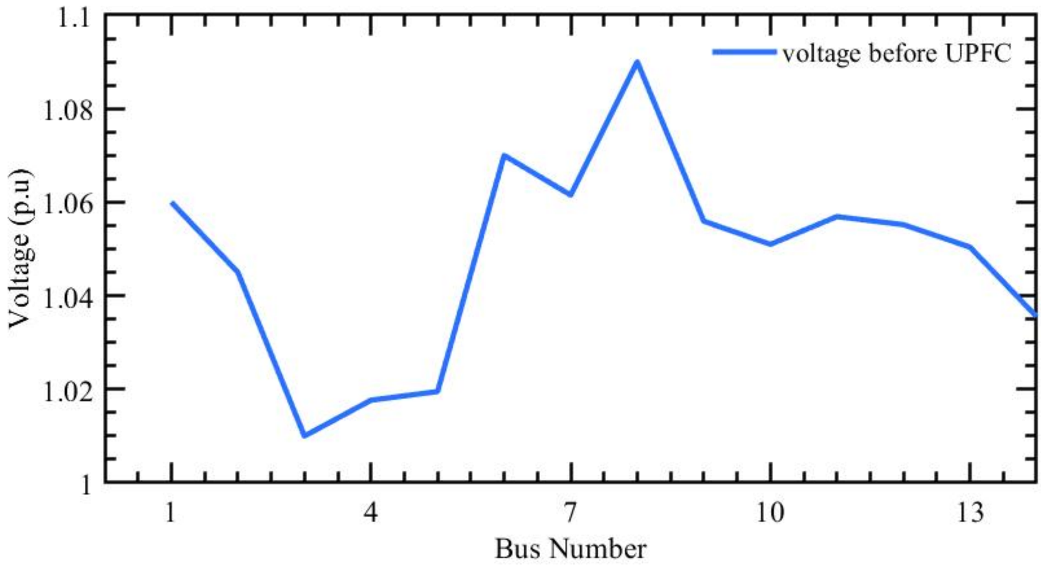


Figure 4. 2 IEEE 14 bus network: Voltage Profile without UPFC

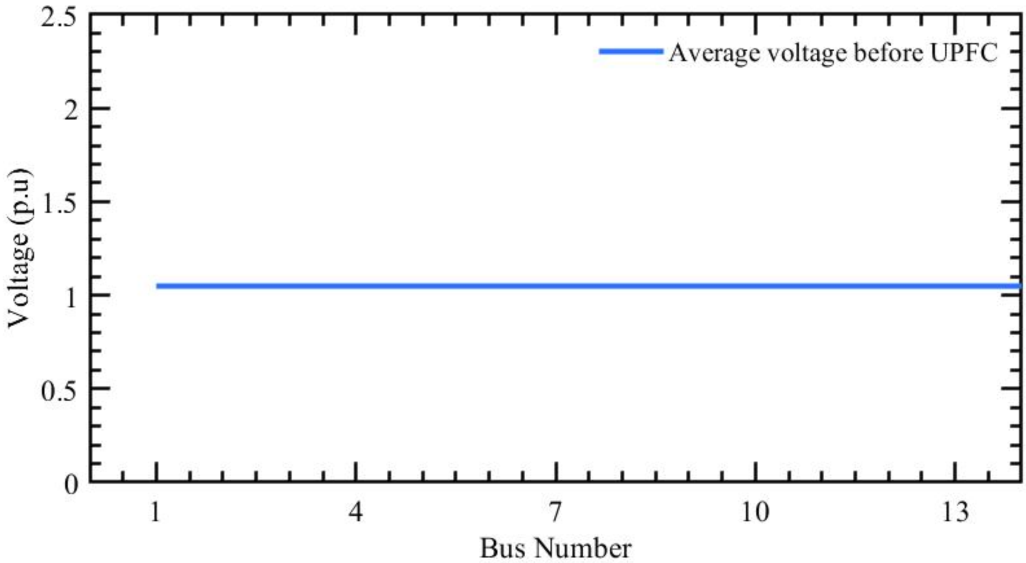


Figure 4. 3 IEEE 14 bus network: Average p.u Voltage without UPFC

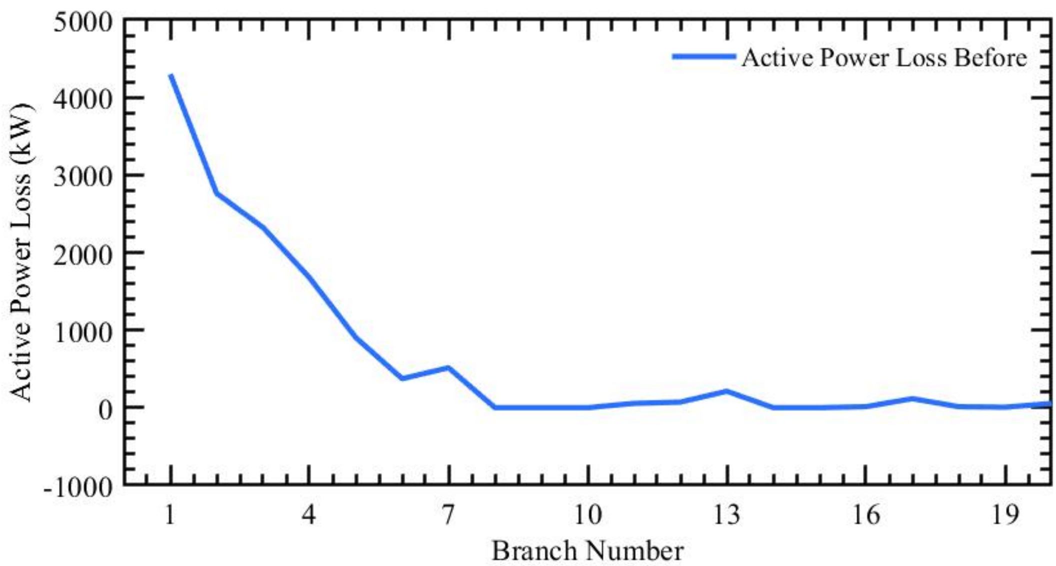


Figure 4. 4 IEEE 14 bus network: Active Power Loss with and without UPFC

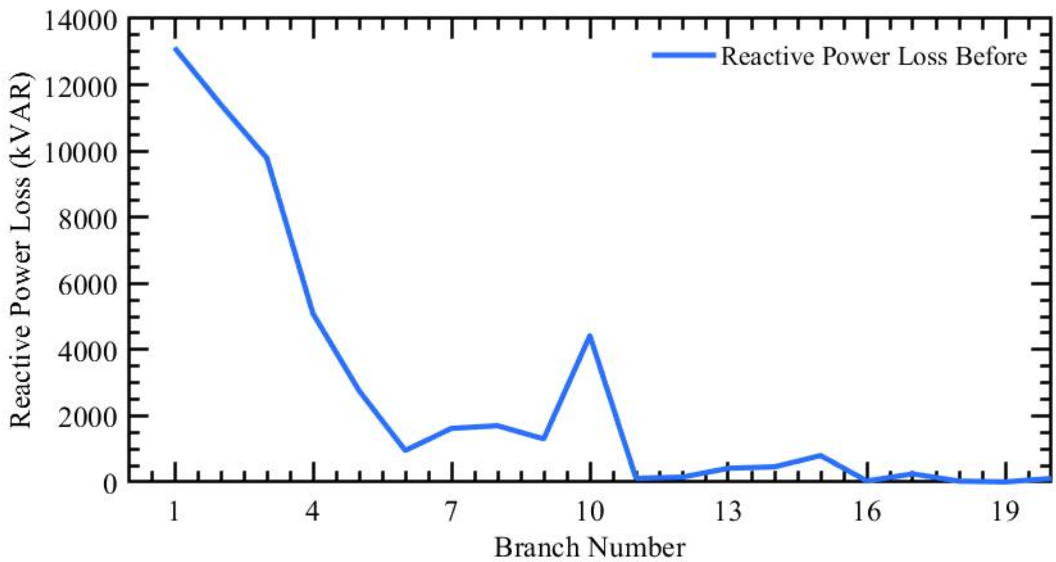


Figure 4. 5 IEEE 14 bus network: Reactive Power Loss without UPFC

ii. Optimization of UPFCs with SHO:

SHO is used in the second stage to determine the best ratings and locations for UPFC. Three (03) Nos. UPFCs have been taken in this study. 100% of the line loading is regarded as the typical limit and the standard voltage limits used to measure voltage variations are 0.9 to 1.1 p.u. Bus voltage angles are initialized in the range of -90 to 90 degrees.

After running the simulations for the set number of population size and fixed number of iterations, SHO algorithm identified the 3 ideal locations i.e., between busses 3-4; 2-3; 1-5 for the placement of UPFCs to reduce the active/reactive power losses and improvement of the voltage profile. Results show significant reduction in the individual objectives of APL, RPL and V_{avg}. P_{LOSS} was reduced from 13,393.27 kW to 7224.15 kW, Q_{LOSS} was reduced from 54,538.30 to 31982.54 kVar and average voltage was slightly increased from 1.0484 to 1.0525 p.u. Multiple Objective Index value obtained from implementation of SHO is 0.3574.

Sr. No	**Parameter**	**Without UPFC**	**With UPFC**
1.	**MOI**	-	0.3574
2.	P_{LOSS} **"kW"**	13393.27	7224.15
3.	Q_{LOSS} **"kVar"**	54538.30	31982.54
4.	V_{avg} **"p.u"**	1.0484	1.0525
5.	**UPFC Locations**	-	3-4; 2-3; 1-5
6.	**Min Voltage/ Bus No**		1.01/3
7.	V_{se}	-	0.2999 0.1048 0.0386
8.	V_{sh}	-	1.0395 1.0554 1.0524

Table 4. 2 IEEE 14 bus network: parameters comparison with and without UPFC

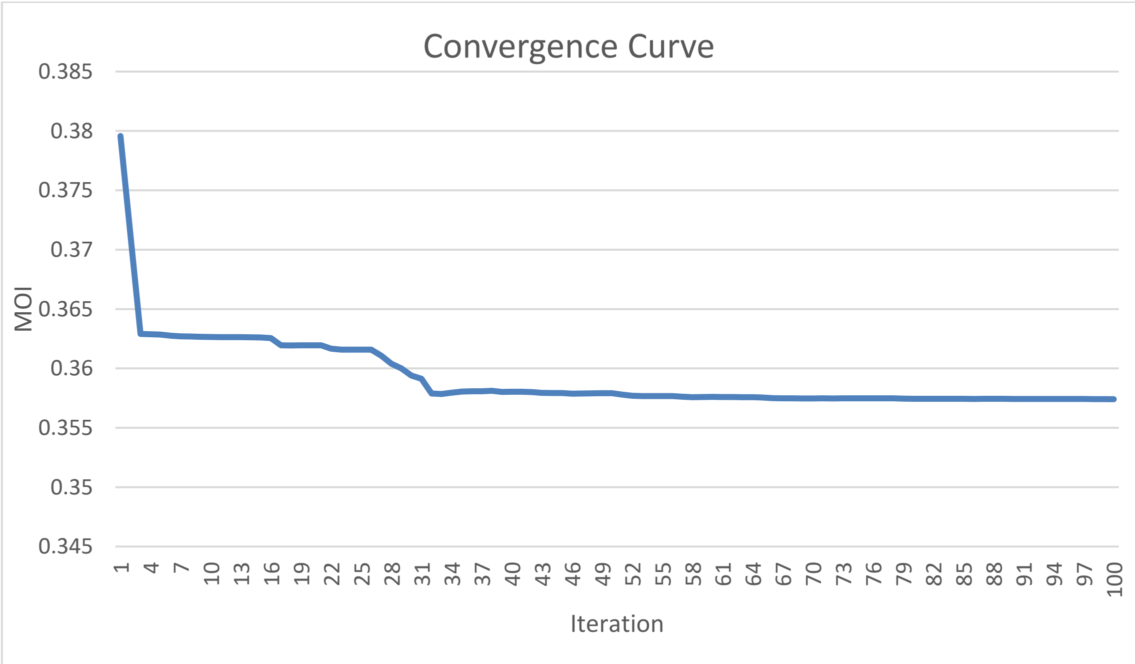


Figure 4. 6 IEEE 14 bus network: SHO Convergence Curve

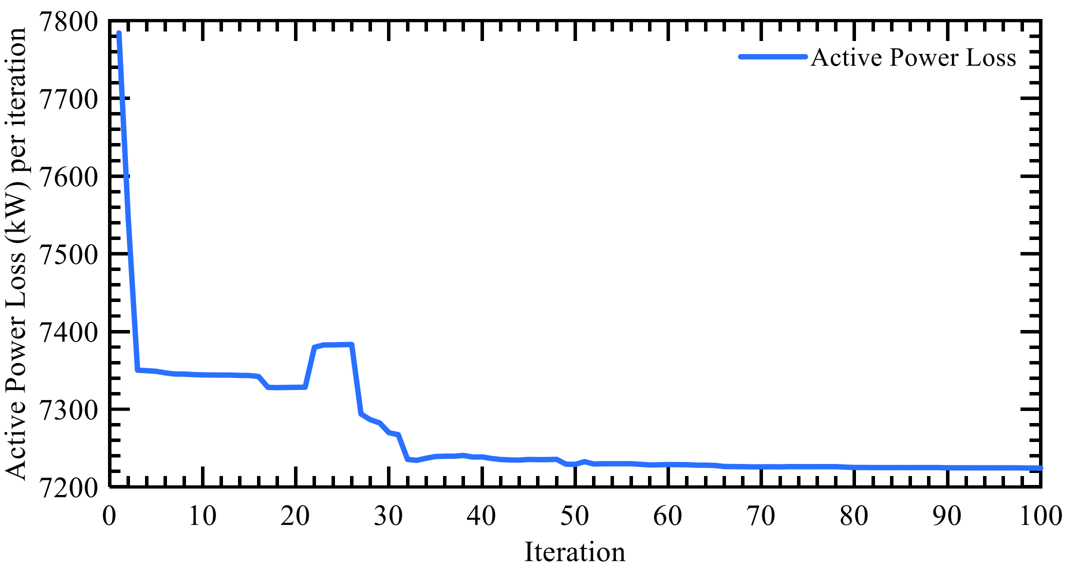


Figure 4. 7 IEEE 14 bus network: Active Power Loss per iteration (SHO)

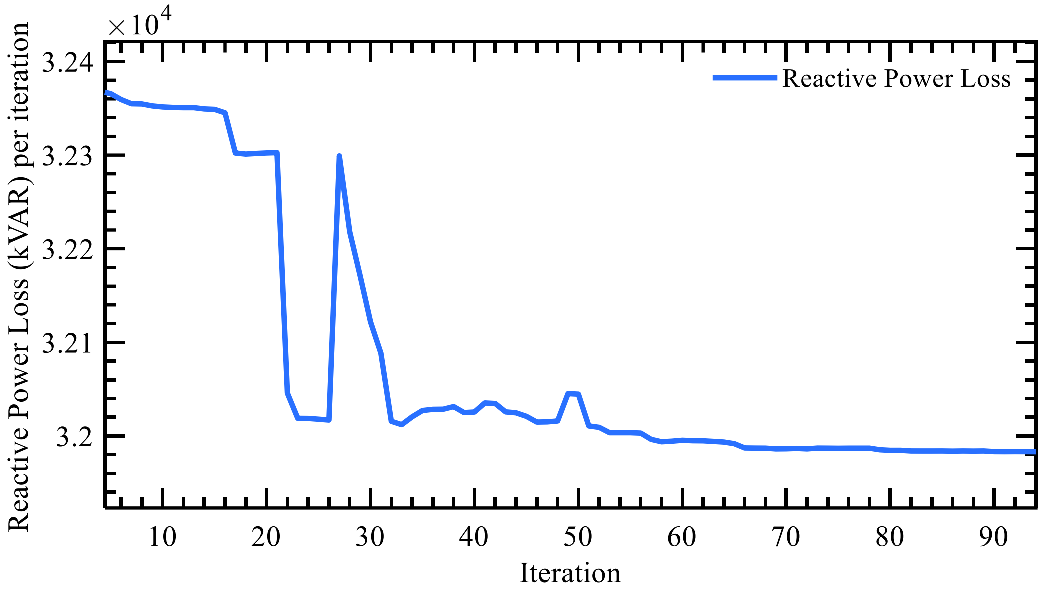


Figure 4. 8 IEEE 14 bus network: Reactive Power Loss per iteration (SHO)

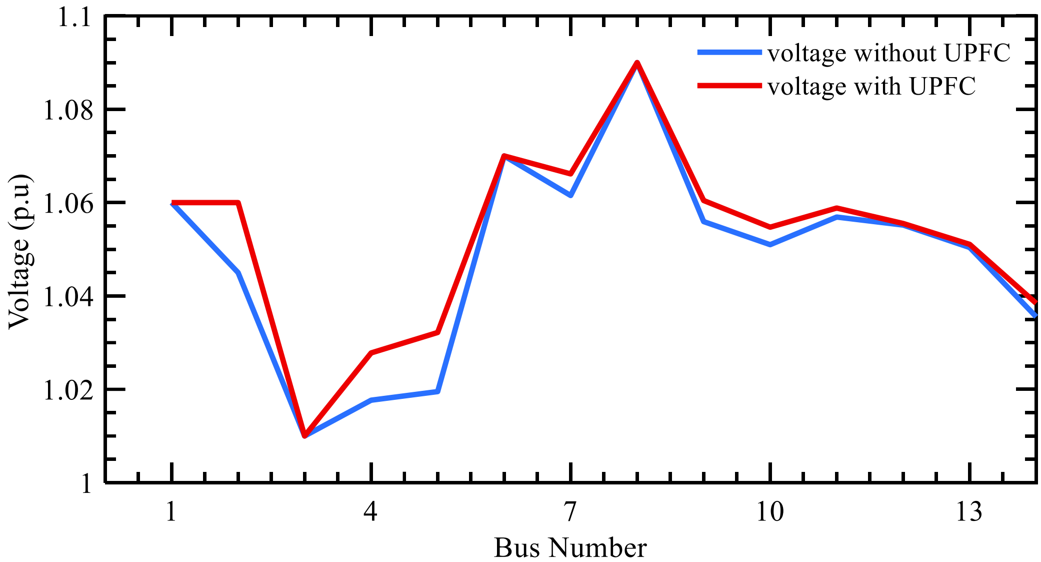


Figure 4. 9 IEEE 14 bus network: Comparison of Voltage on each bus with and without UPFC (SHO)

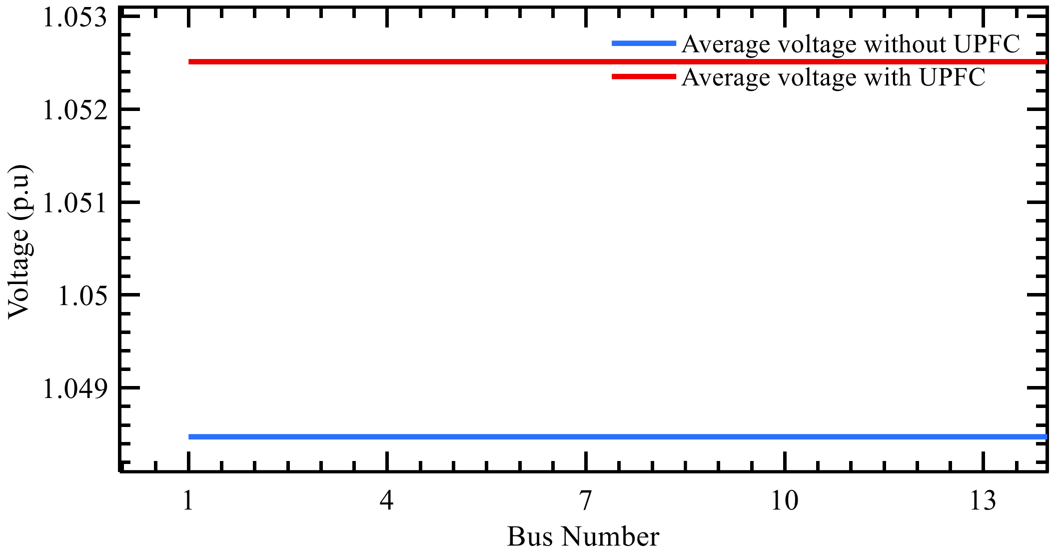


Figure 4. 10 IEEE 14 bus network: Comparison of Average Voltage (SHO)

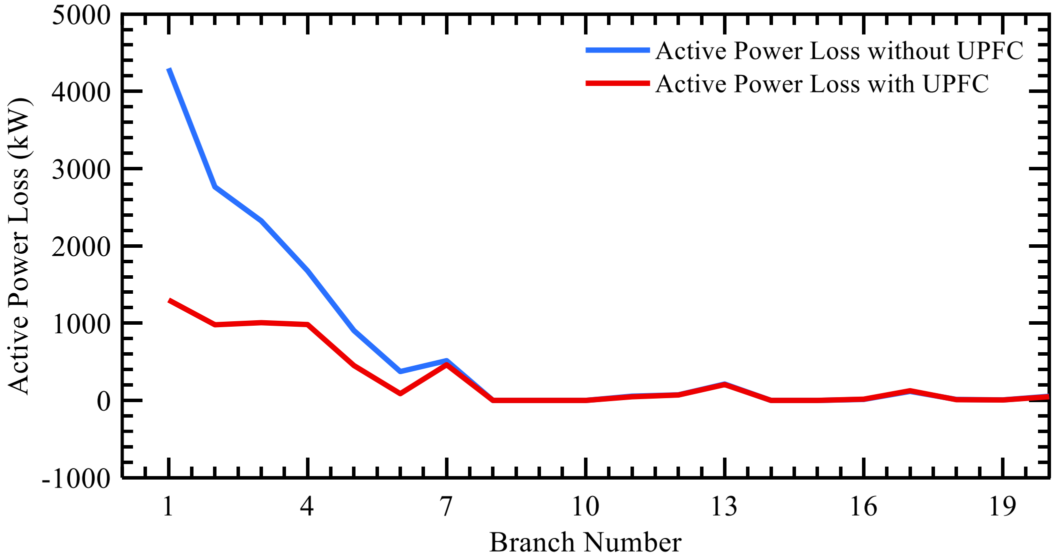


Figure 4. 11 IEEE 14 bus network: Comparison of Active power loss with and without UPFC (SHO)

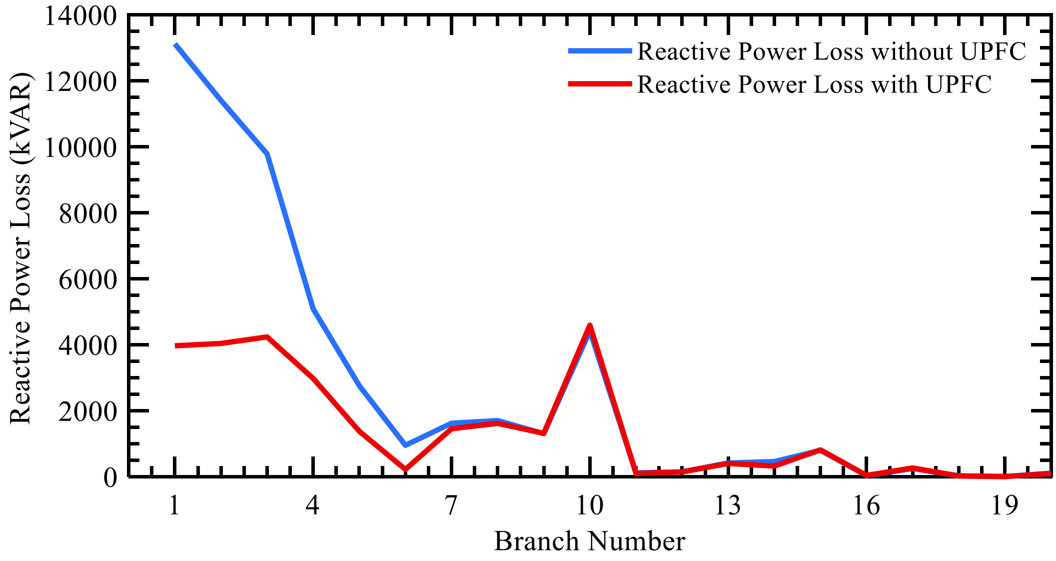


Figure 4. 12 IEEE 14 bus network: Comparison of Reactive power loss with and without UPFC (SHO)

iii. Optimization of UPFCs with ABC:

The results received from the implementation of the SHO is compared with the ABC optimization technique to demonstrate its effectiveness. The same input parameters were used for comparison of the results with SHO. Bus locations identified by ABC technique was on branches 3-4; 2-3 and 1-5. P_{LOSS} was reduced from 13,393.27 kW to 7465.45 kW, Q_{LOSS} was reduced from 54,538.30 to 32470.82 kVar and average voltage increased from 1.0484 to 1.0596 p.u. MOI obtained from the implementation of ABC optimization technique is 0.3640, which is 0.66% more than the results obtained from the SHO algorithm.

Sr. No	Parameter	Without UPFC	After UPFC With ABC	After UPFC With SHO	Improvement in Results
1.	Population Size	-	300	300	-
2.	Iterations	-	100	100	-
3.	MOI	-	0.3640	0.3574	0.0066
4.	P_{LOSS} "kW"	13393.27	7465.45	7224.15	241.30
5.	% age	-	44.25%	46.06%	1.81%

	Improvement				
6.	Q_{LOSS} **"kVar"**	54538.30	32470.82	31982.54	488.28
7.	**% age Improvement**	-	40.46%	41.35%	0.89%
8.	**V_{avg} "p.u"**	1.0484	1.0596	1.0525	-0.0071
9.	**UPFC Locations**	-	3-4; 2-3; 1-5	3-4; 2-3; 1-5	-
10.	**Min Voltage/ Bus No**	1.01/3	1.0404/5	1.01/3	-
11.	**V_{se}**	-	0.2999 0.3000 0.3000	0.2999 0.1048 0.0386	0 0.1952 0.2614
12.	**V_{sh}**	-	1.0360 1.0490 1.0638	1.0395 1.0554 1.0524	-0.0035 -0.0064 0.0114

Table 4. 3 IEEE 14 bus network: Comparative Analysis of SHO and ABC Algorithms

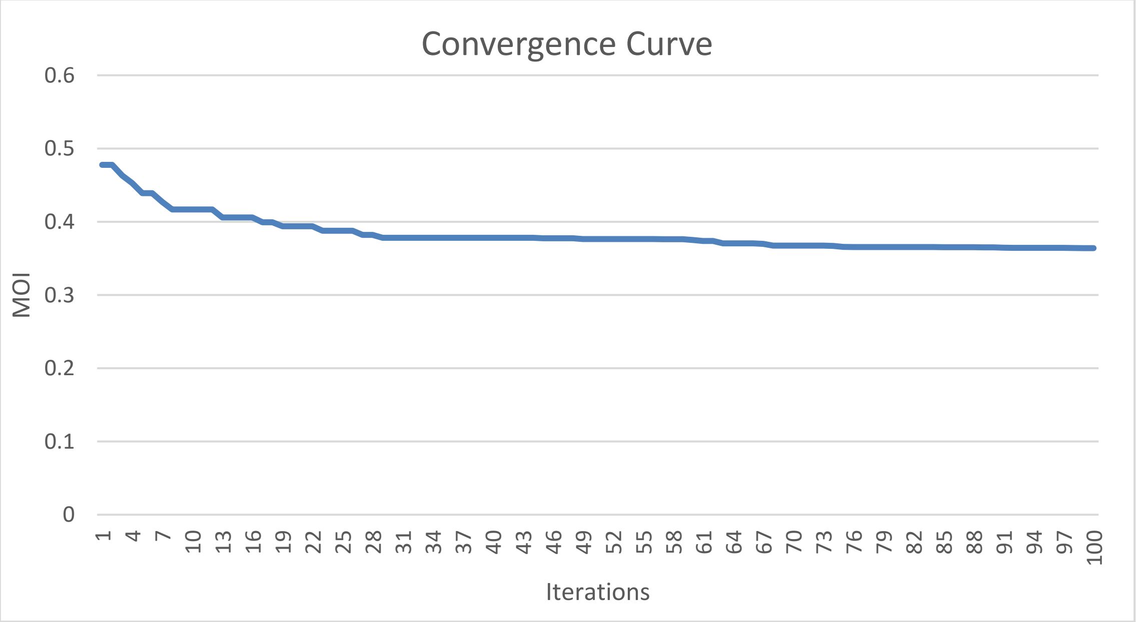


Figure 4. 13 IEEE 14 bus network: ABC Convergence Curve

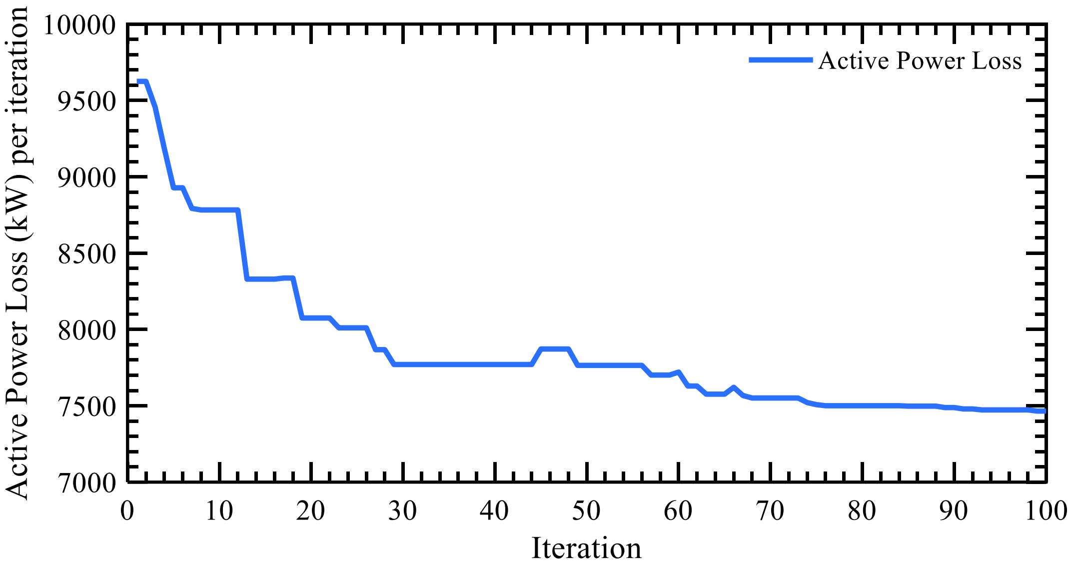


Figure 4. 14 IEEE 14 bus network: Active Power Loss per iteration (ABC)

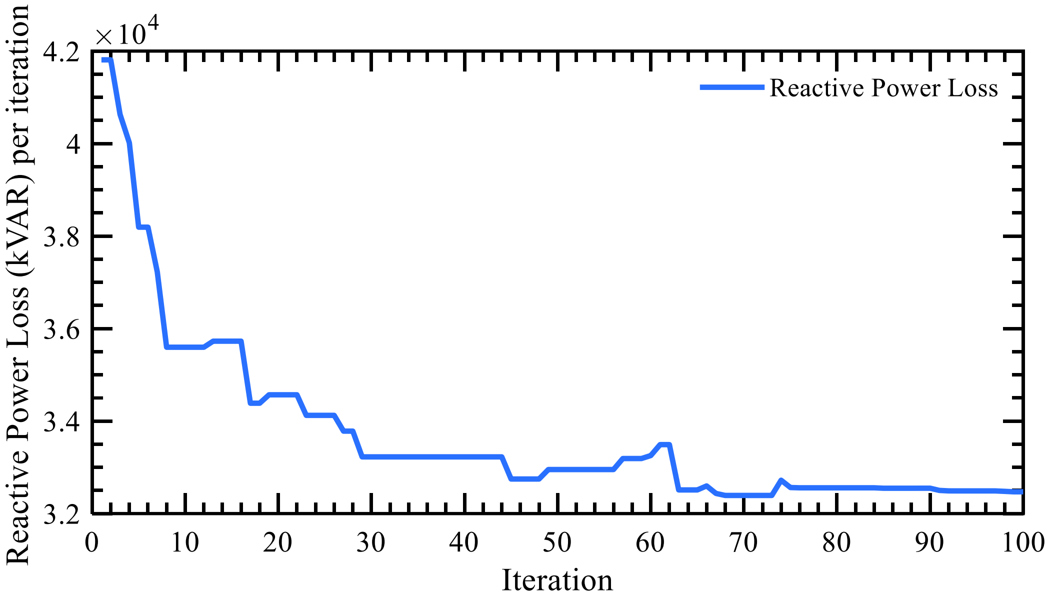


Figure 4. 15 IEEE 14 bus network: Reactive Power Loss per iteration (ABC)

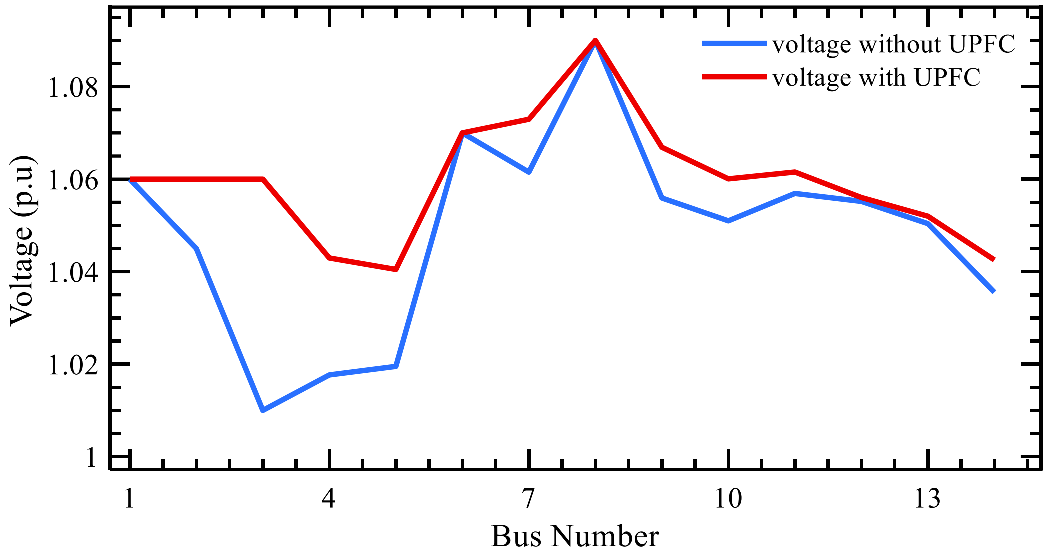


Figure 4. 16 IEEE 14 bus network: Comparison of Voltage on each bus with and without UPFC (ABC)

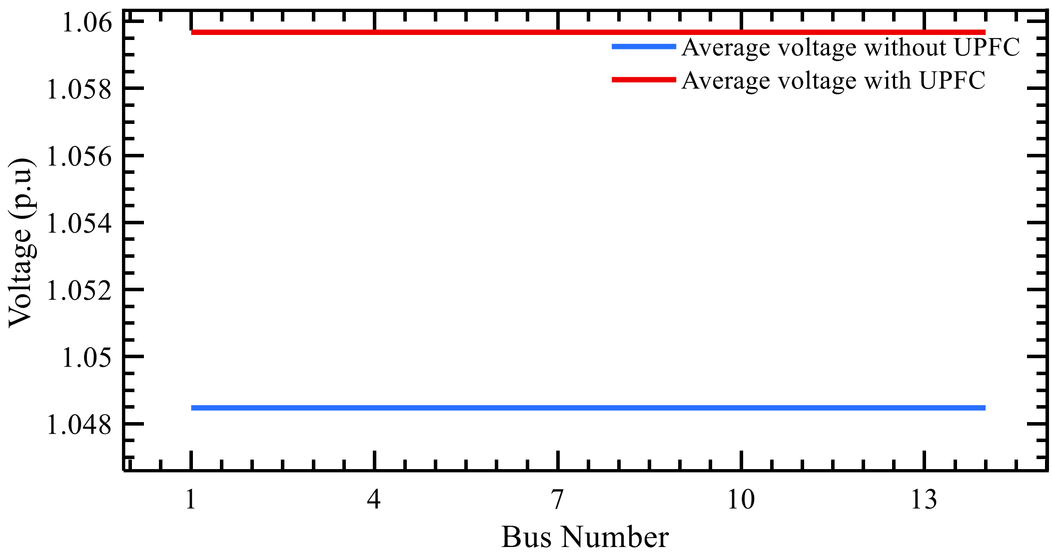


Figure 4. 17 IEEE 14 bus network Comparison of Average Voltage (ABC)

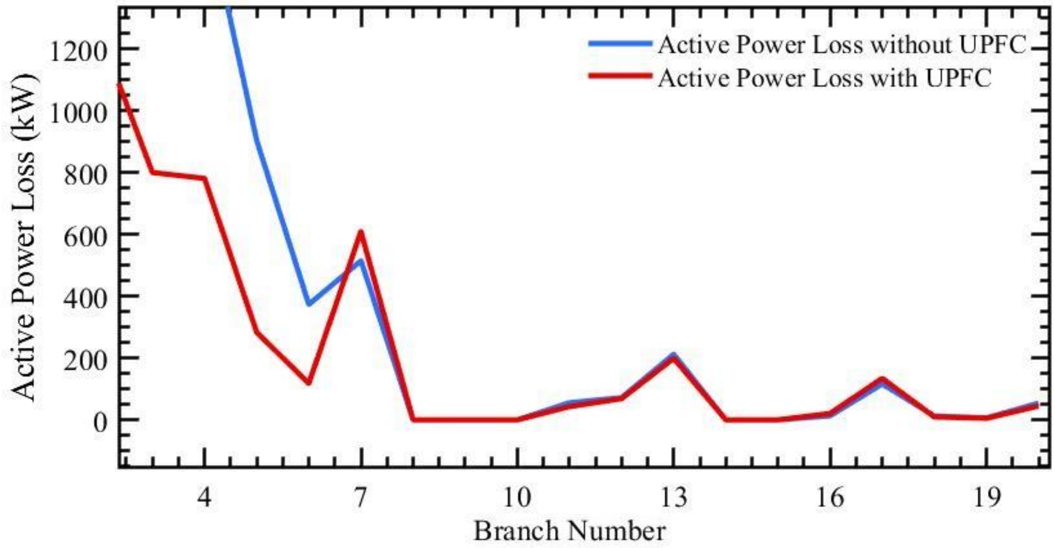


Figure 4. 18 IEEE 14 bus network: Comparison of Active power loss with and without UPFC (ABC)

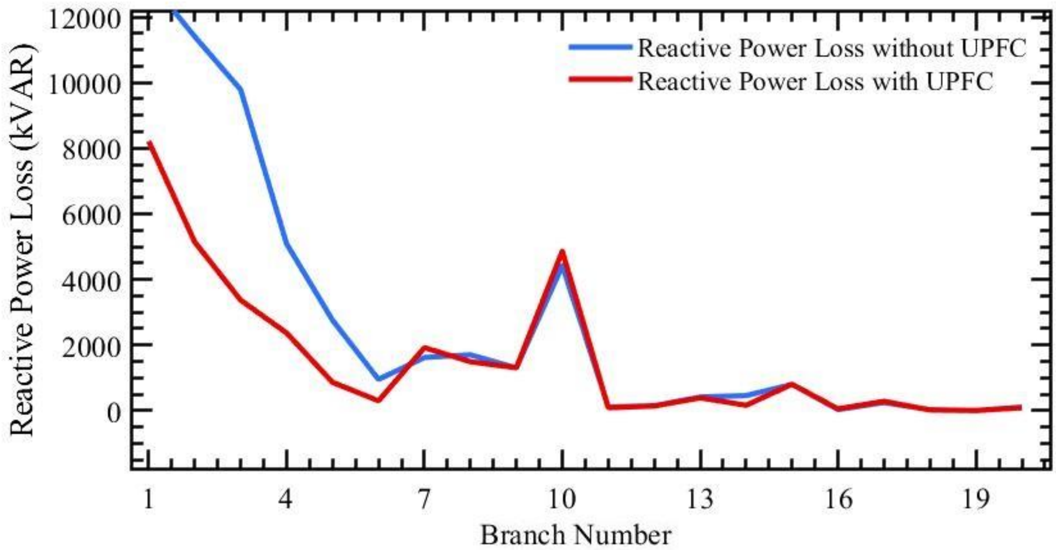


Figure 4. 19 IEEE 14 bus network: Comparison of Reactive power loss with and without UPFC (ABC)

4.2. Case Scenario: 2 (IEEE 30 bus test network)

This is one of the many standard test case transmission network of the IEEE which are taken from the portion of American Electric Power system. This method is used for the investigation of the power systems by the power system engineers. It consists of Thirty (30) buses, Six (06) generators and forty-one (41) branches.

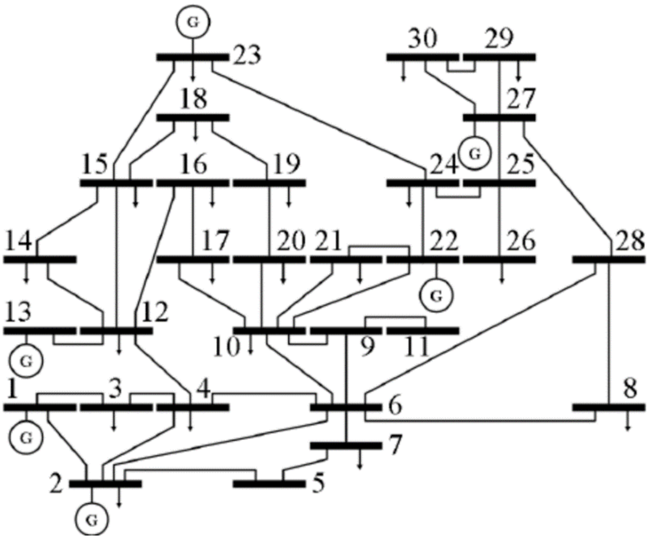


Figure 4. 20 IEEE 30 bus system network

i. Without UPFCs:

In the first step, standard Newton Raphson load flow analysis is implemented to find the APL, RPL and average voltage. P_{LOSS} of 2443.80 kW, Q_{LOSS} of 8989.94 kVar, average voltage of 0.9819 and V_{min} of 0.9606 at bus 8 is recorded without the insertion of UPFCs, which is the basic case situation These values will serve as a basis for later comparisons of the results, when the FACTS devices are installed at optimum positions.

Parameter	**APL "kW"**	**RPL "kVar"**	**Average Voltage "p.u"**	**Minimum Voltage**	**At Bus**
Value	2443.80	8989.94	0.9819	0.9606	8

Table 4. 4 IEEE 30 bus network: parameters without UPFC

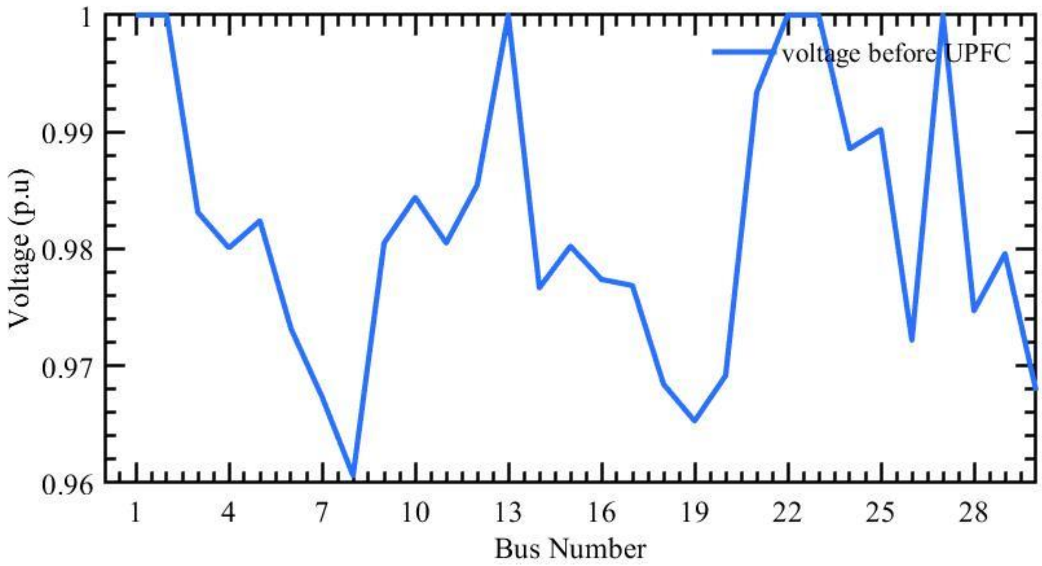


Figure 4. 21 IEEE 30 bus network: Voltage Profile without UPFC

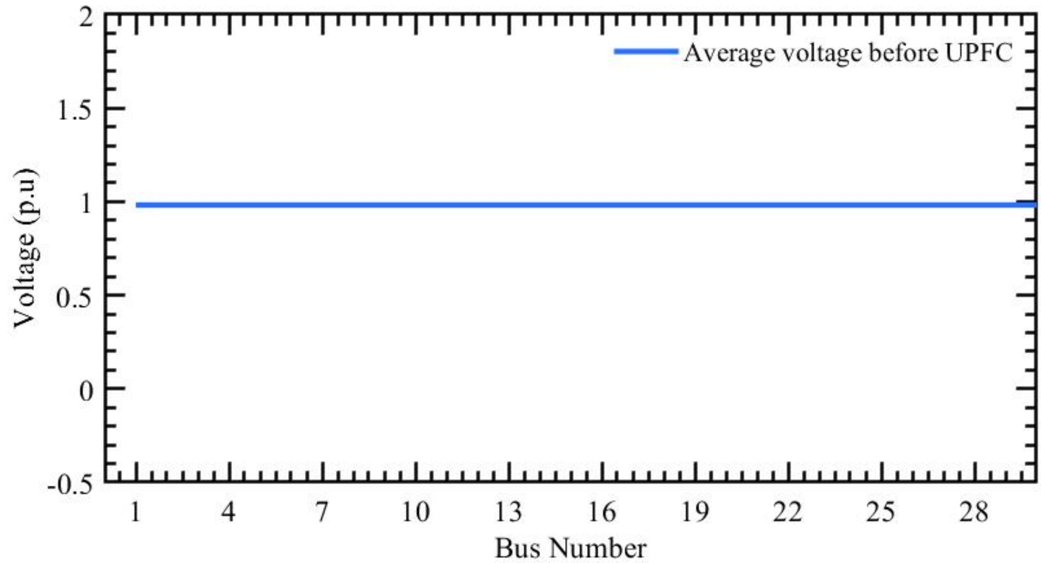


Figure 4. 22 IEEE 30 bus network: Average p.u Voltage without UPFC

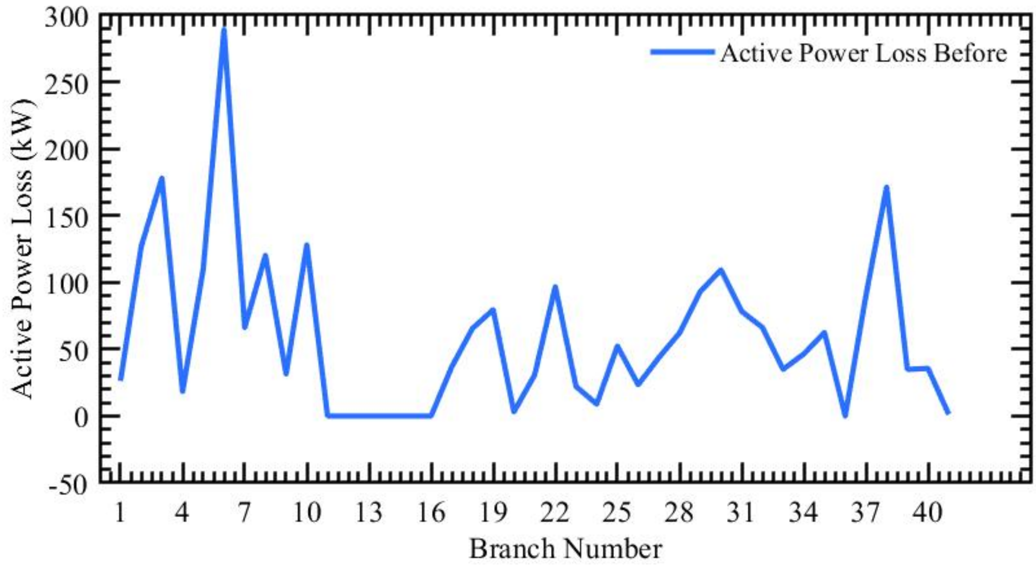


Figure 4. 23 IEEE 30 bus network: Active Power Loss without UPFC

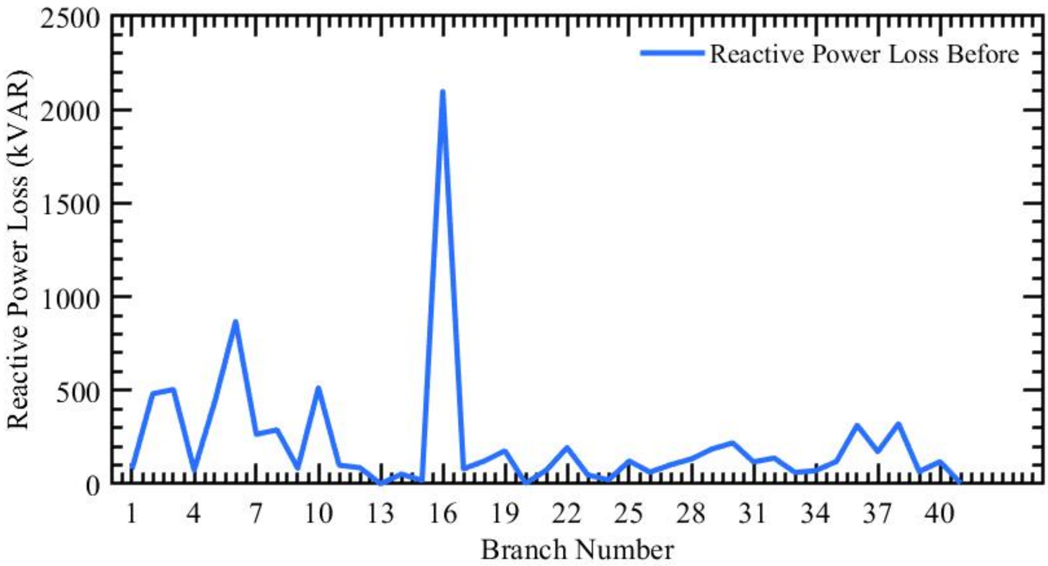


Figure 4. 24 IEEE 30 bus network: Reactive Power Loss without UPFC

ii. Optimization of UPFCs with SHO:

SHO is used in the second stage to determine the best ratings and placements for UPFC. Three (03) Nos. UPFCs have been taken in this study. 100% of the line loading is regarded as the typical limit and the standard voltage limits used to measure voltage variations are 0.9 to 1.1 p.u. Bus voltage angles are initialized in the range of -180 to 180 degrees.

SHO algorithm identified the 3 ideal bus locations i.e., on branches 9-10, 2-6 and 12-13 for the placement of UPFCs to improve the voltage profile and reduce the power losses. Results show substantial reduction in the individual objectives of APL, RPL and V_{avg}. P_{LOSS} was reduced from 2443.80 kW to 1516.75 kW, Q_{LOSS} was reduced from 8989.94 to 5402.46 kVar and average voltage was increased from 0.9819 to 0.9918 p.u. After the placement of UPFCs at optimal branches, minimum voltage of 0.9678 was observed at bus 30, that was within the prescribed limits. Multi Objective Index value obtained from implementation of SHO is 0.4095. The detailed results of the parameters obtained are given in the Table 4.5.

Sr. No	Parameter	Without UPFC	With UPFC
1.	**MOI**	-	0.4095
2.	P_{LOSS} **"kW"**	2443.80	1516.75
3.	Q_{LOSS} **"kVar"**	8989.94	5402.46
4.	V_{avg} **"p.u"**	0.9819	0.9918
5.	**UPFC Locations**	-	9-10; 2-6; 12-13
6.	**Min Voltage/Bus No.**	0.9606/8	0.9678/30
7.	V_{se}	-	0.2999 0.0320 0.2998
8.	V_{sh}	-	0.9914 0.9999 0.9968

Table 4. 5 IEEE 30 bus network: parameters comparison with and without UPFC

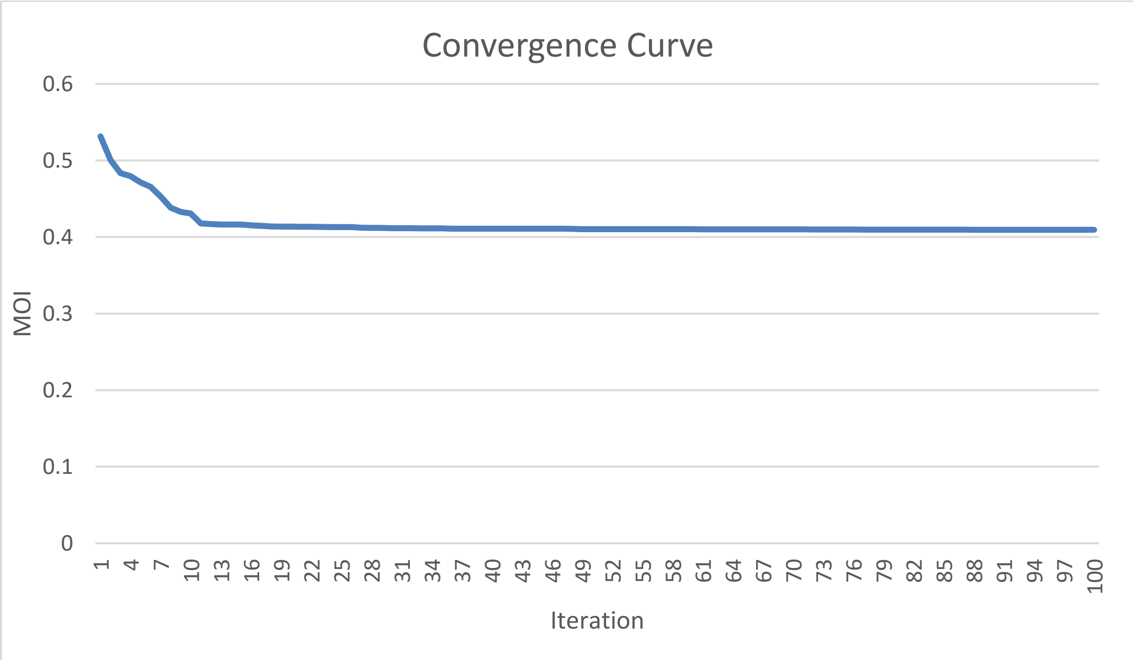


Figure 4. 25 IEEE 30 bus network: SHO Convergence Curve

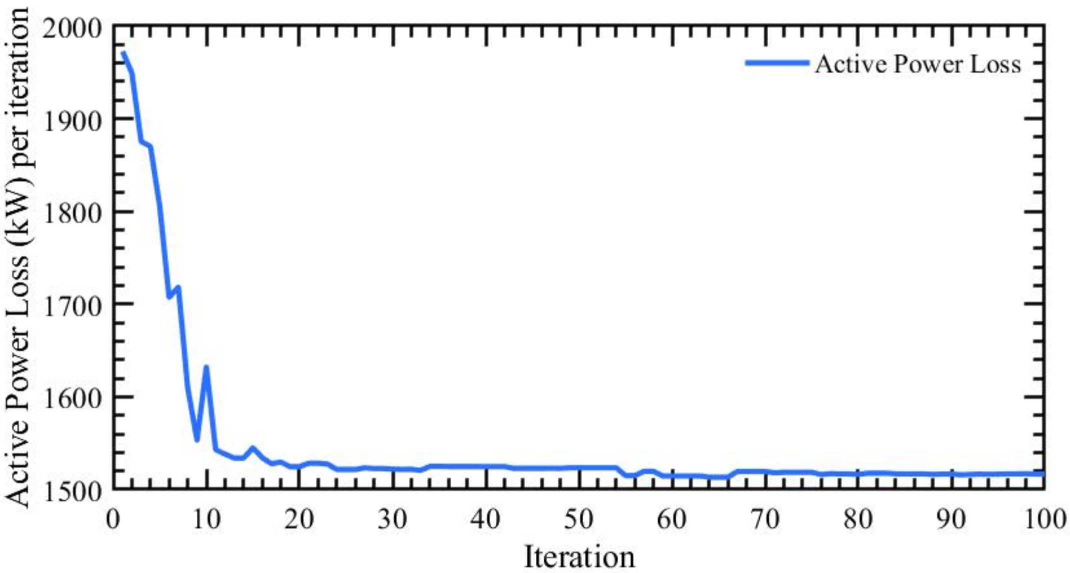


Figure 4. 26 IEEE 30 bus system network: Active Power Loss per iteration (SHO)

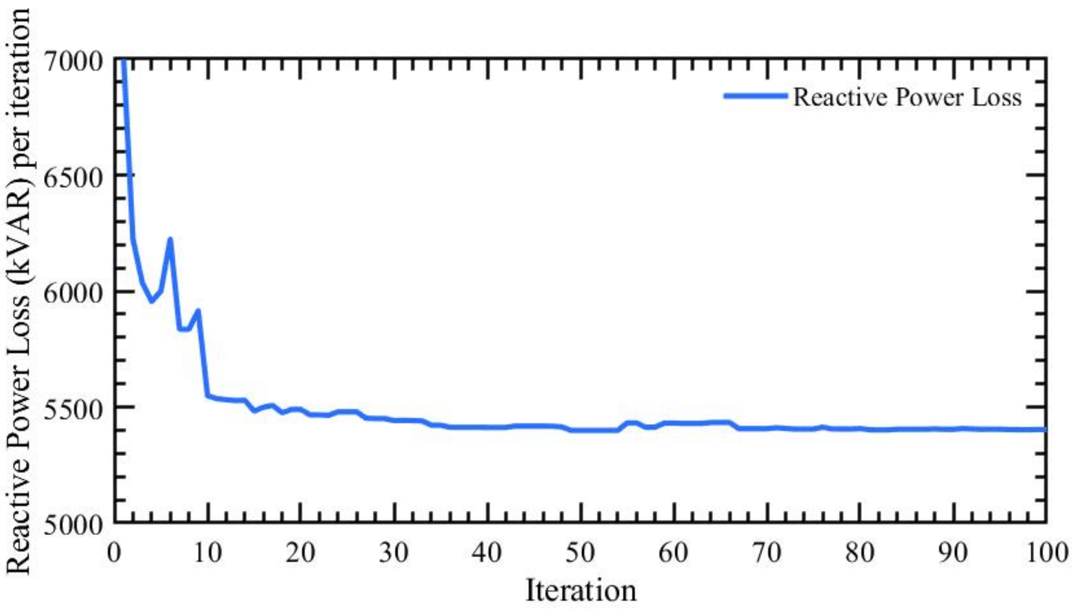


Figure 4. 27 IEEE 30 bus system network: Reactive Power Loss per iteration (SHO)

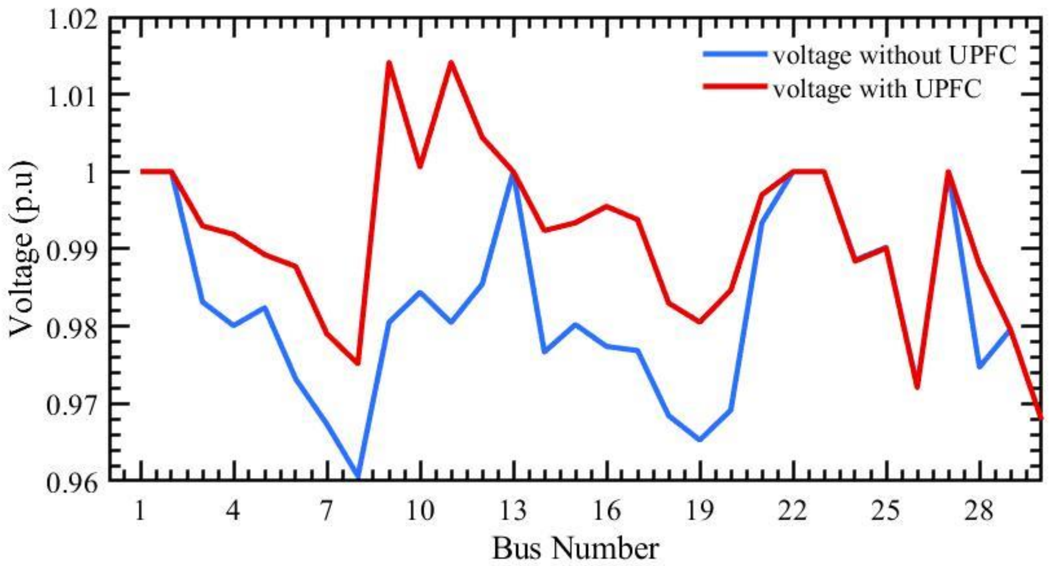


Figure 4. 288 IEEE 30 bus network: Comparison of Voltage on each bus with and without UPFC (SHO)

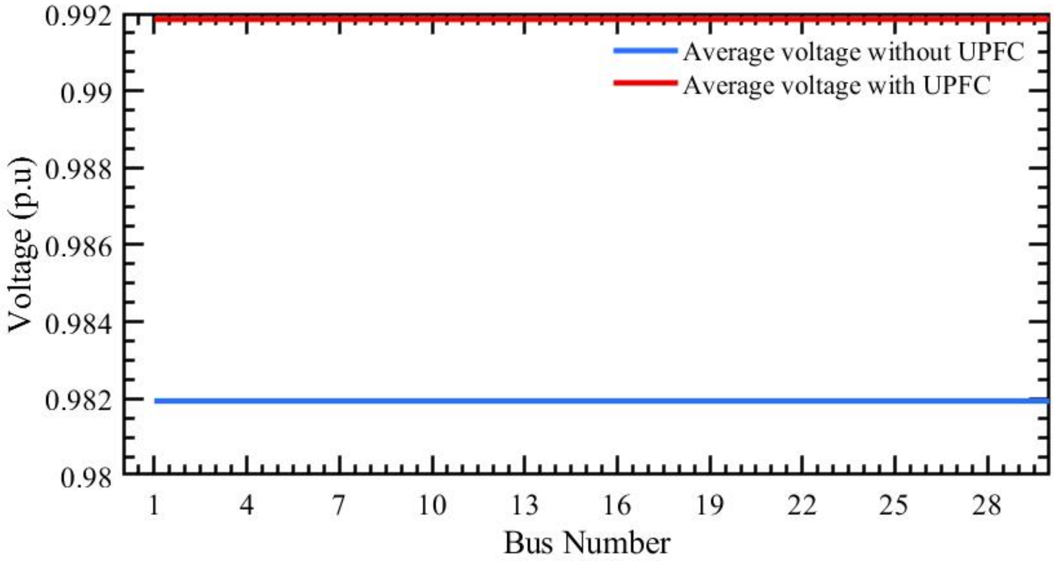


Figure 4. 29 IEEE 30 bus network: Comparison of Average Voltage (SHO)

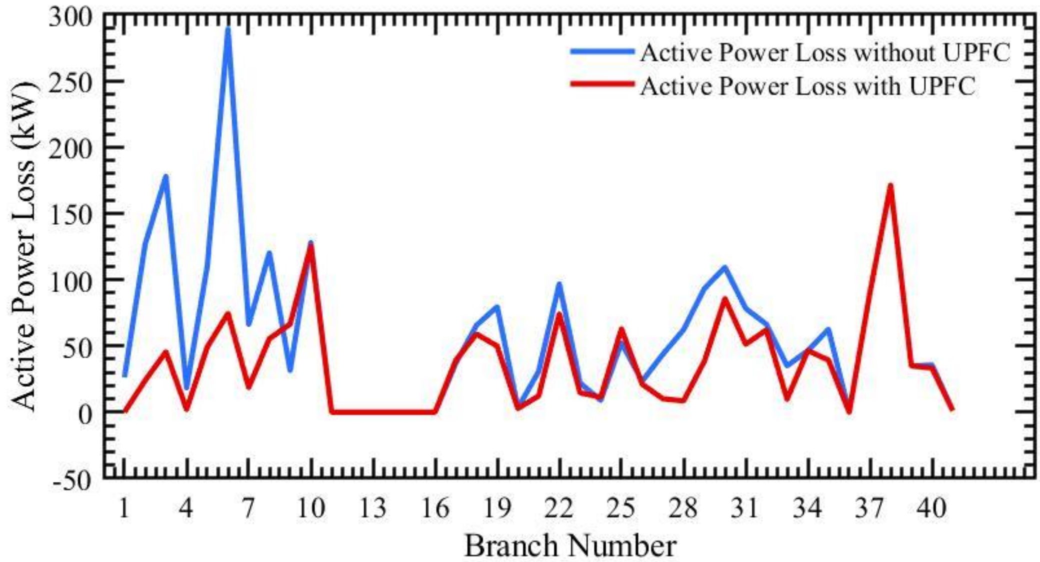


Figure 4. 30 IEEE 30 bus network: Comparison of Active power loss with and without UPFC (SHO)

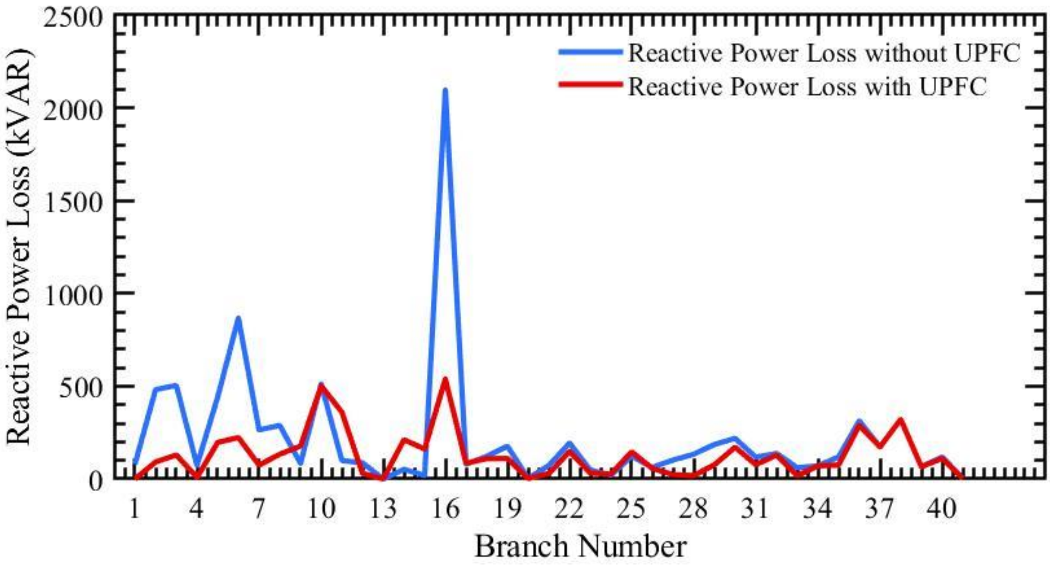


Figure 4. 31 IEEE 30 bus network: Comparison of Reactive power loss with and without UPFC (SHO)

iii. Optimization of UPFCs with ABC:

The results obtained from the use of the SHO were also compared with the ABC optimization technique to demonstrate the effectiveness. The same input parameters were used for better comparison of the results with SHO. Bus locations identified by ABC technique was between bus 10-17, 2-6, 12-13. P_{LOSS} was reduced from 2443.80 kW to 1715.89 kW, Q_{LOSS} was reduced from 8989.94 to 6071.74 kVar and average voltage was slightly increased from 0.9819 to 0.9930 p.u. MOI obtained from the implementation of SHO is 0.4610. The minimum voltage obtained was 0.9678 at bus 30, which is the same as was obtained in case of application of SHO algorithm.

Sr. No	Parameter	Without UPFC	After UPFC With ABC	After UPFC With SHO	Improvement in Results
1.	Population Size	-	100	100	-
2.	Iterations	-	100	100	-
3.	MOI	-	0.4610	0.4095	0.0515
4.	P_{LOSS} “kW”	2443.80	1715.89	1516.75	199.14

5.	**% age Improvement**	-	29.78%	37.93%	8.15%
6.	Q_{LOSS} **"kVar"**	8989.94	6071.74	5402.46	669.28
7.	**% age Improvement**	-	32.46%	39.90%	7.44%
8.	**V_{avg} "p.u"**	0.9819	0.9930	0.9918	0.0012
9.	**UPFC Locations**	-	10-17; 2-6; 12-13	9-10; 2-6; 12-13	-
10.	**Min Voltage/ Bus No**	0.9606/8	0.9678/30	0.9678/30	-
11.	**V_{se}**	-	0.3000 0.0450 0.3000	0.2999 0.0320 0.2998	0.0001 0.0130 0.0002
12.	**V_{sh}**	-	1.0164 1.0231 1.0098	0.9914 0.9999 0.9968	0.0250 0.0232 0.0130

Table 4. 6 IEEE 30 bus network: Comparative Analysis of SHO and ABC Algorithms

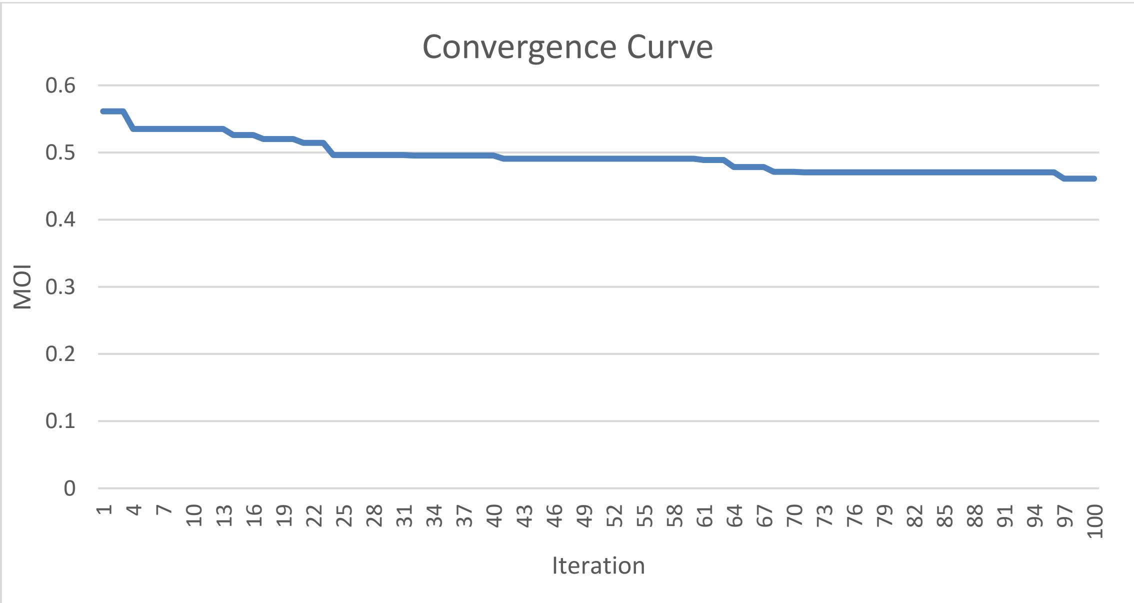


Figure 4. 32 IEEE 30 bus network: ABC Convergence Curve

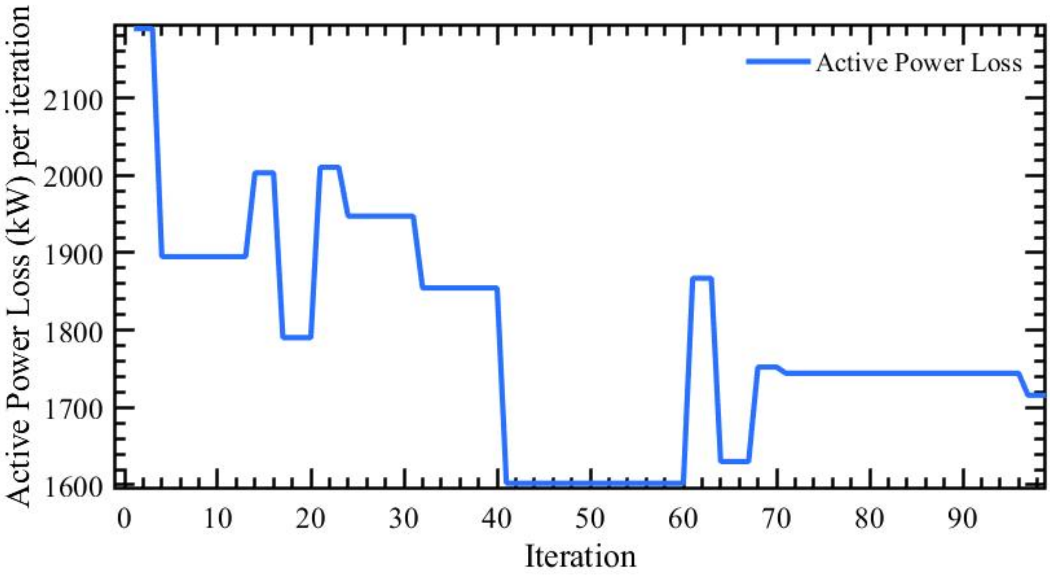


Figure 4. 33 IEEE 30 bus system network: Active Power Loss per iteration (ABC)

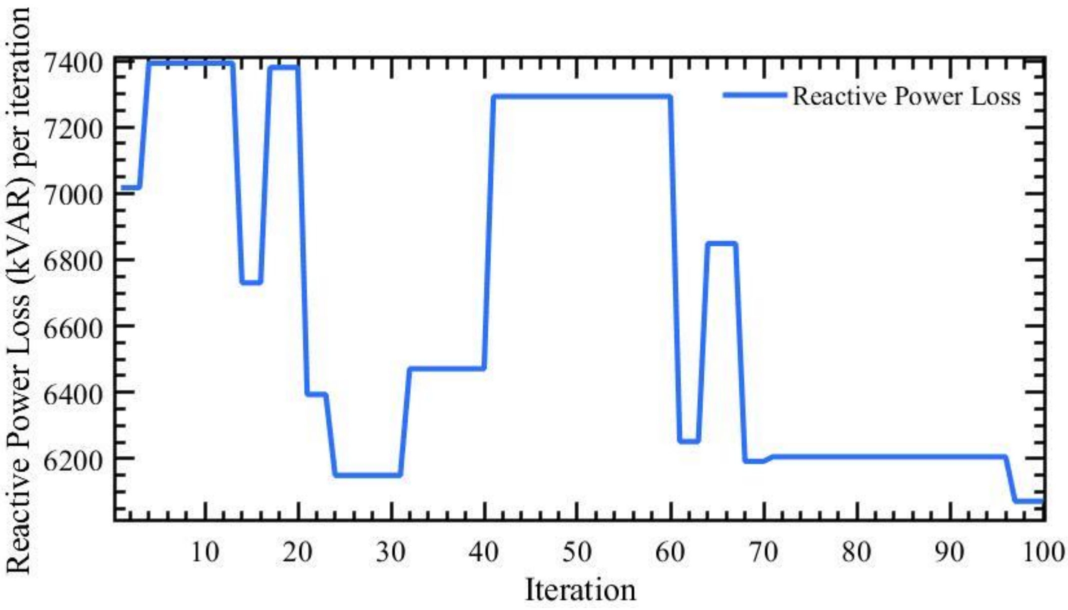


Figure 4. 34 IEEE 30 bus system network: Reactive Power Loss per iteration (ABC)

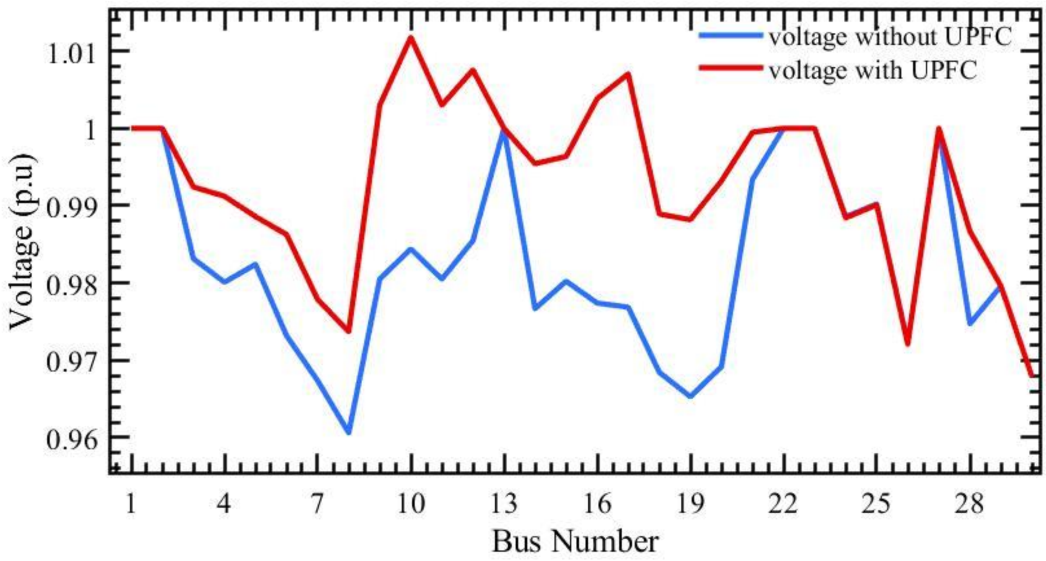


Figure 4. 35 IEEE 30 bus network: Comparison of Voltage on each bus with and without UPFC (ABC)

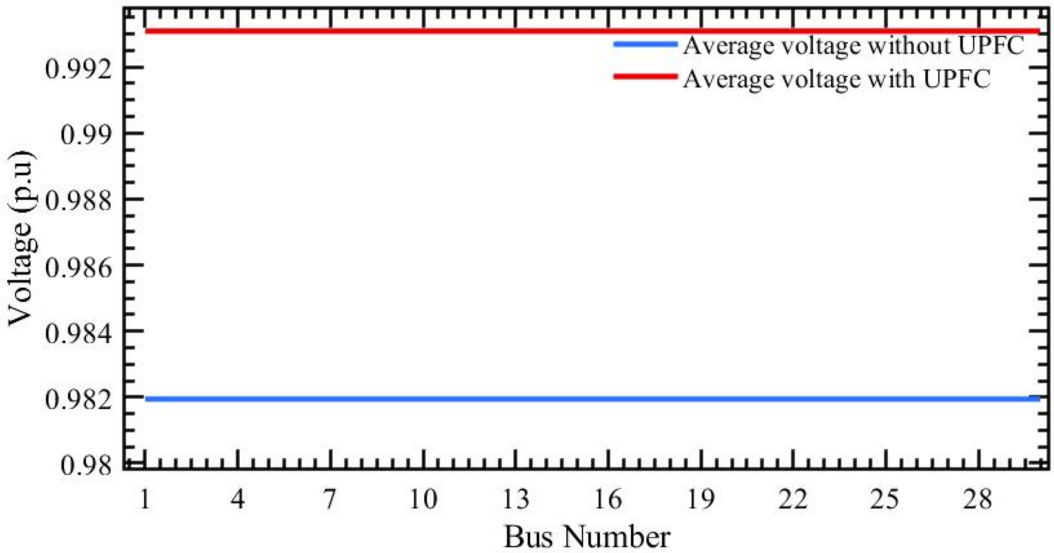


Figure 4. 36 IEEE 30 bus network: Comparison of Average Voltage (ABC)

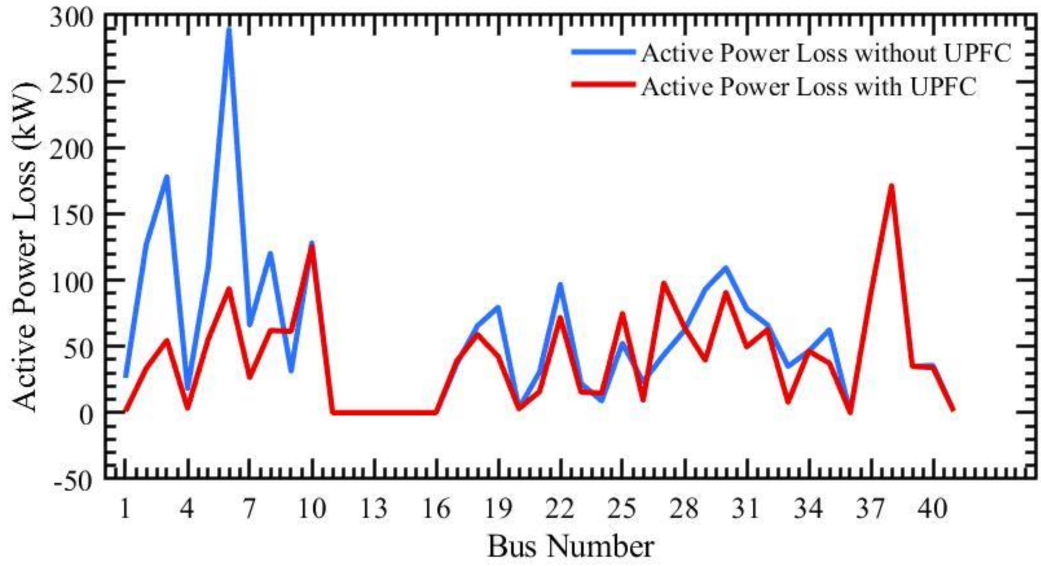


Figure 4. 37 IEEE 30 bus network: Comparison of Active power loss with and without UPFC (ABC)

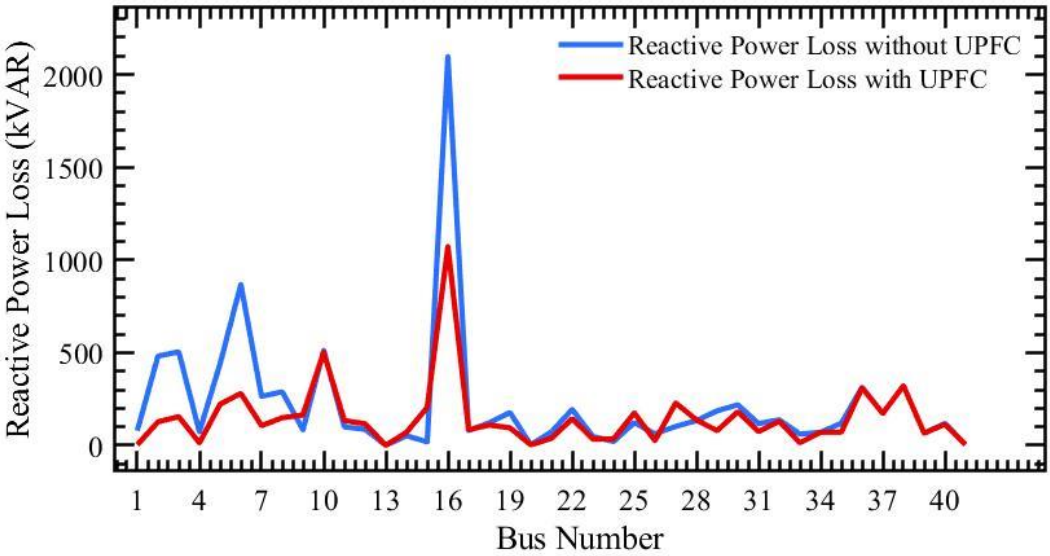


Figure 4. 38 IEEE 30 bus network: Comparison of Reactive power loss with and without UPFC (ABC)

4.3. Case Scenario: 3 (NTDC 11 Bus System)

This scenario has been developed from the portion of power system transmission network of National Transmission and Despatch Company. This system comprises of the 10 branches and 11 buses which are bifurcated into two (02) Nos. 765 kV buses, four (04) 500 kV buses and five (05) 220 kV buses. The system is connected with 1 generator capable or producing active and reactive power of 360 MW and 150 MVAR respectively.

The network is built on the MATPOWER case building with Torrit. The figure of the network drawn on the torrit is given as under. After putting the values for all the parameters, the software tool produced the mfile which was run on the MATLAB for carrying out the simulations.

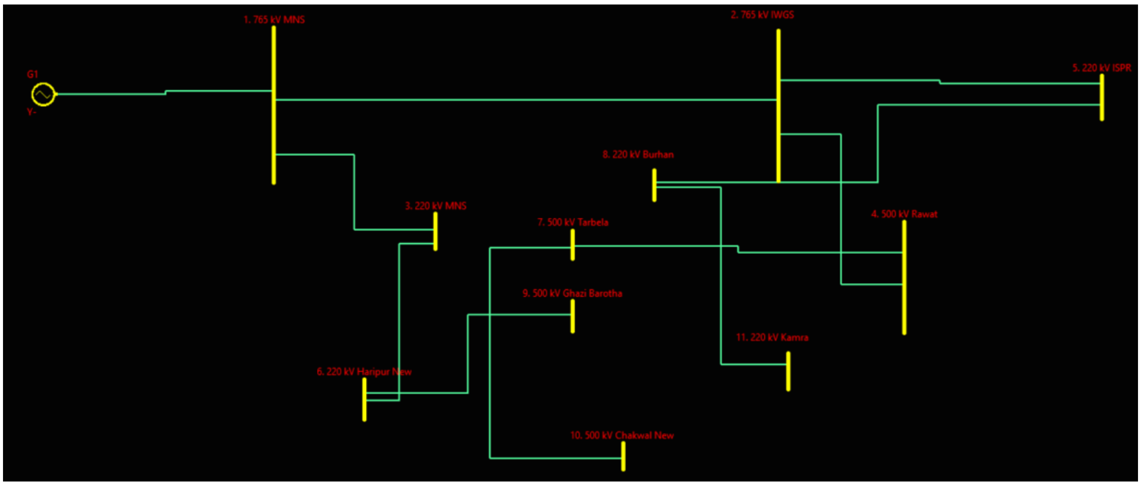


Figure 4. 39 NTDC 11 bus transmission system network

i. Without UPFCs:

Newton Raphson method of load flow analysis is deployed to compute the APL, RPL and average voltage. P_{LOSS} of 13,851.82 kW, Q_{LOSS} of 182,159.3 kVar, voltage profile of 0.8757 and V_{min} of 0.8011 at bus 10 is recorded without the insertion of UPFCs, which serves as the base case situation These values will serve as a base for later comparisons of the results, when the FACTS devices are installed at optimum positions.

Parameter	APL “kW”	RPL “kVar”	Average Voltage “p.u”	Minimum Voltage	At Bus
Value	13851.82	182159.3	0.8757	0.8011	10

Table 4. 7 NTDC 11 bus system: network parameters without UPFC

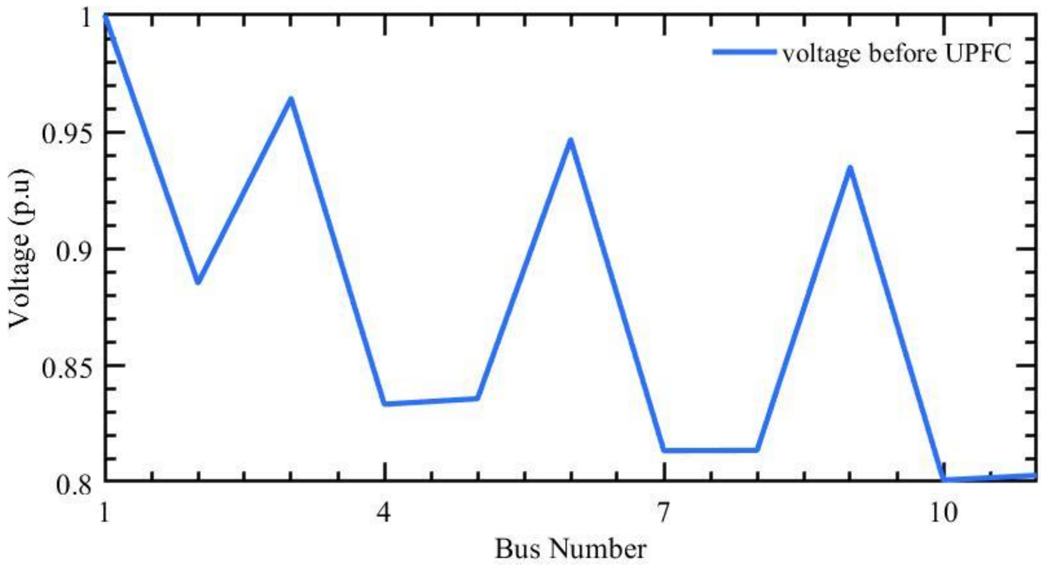


Figure 4. 40 NTDC 11 bus system: Voltage Profile without UPFC

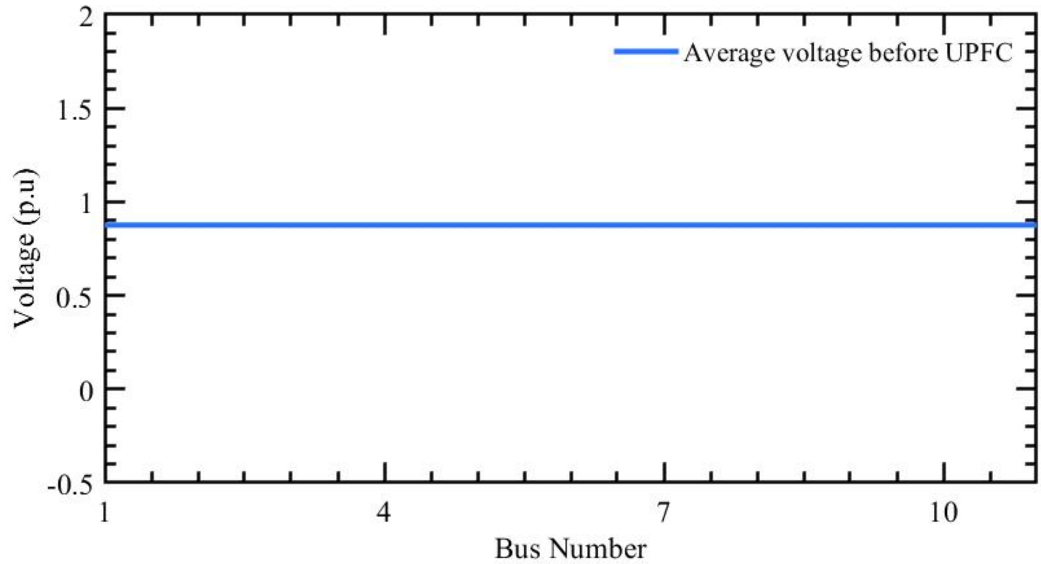


Figure 4. 41 NTDC 11 bus system: p.u Voltage without UPFC

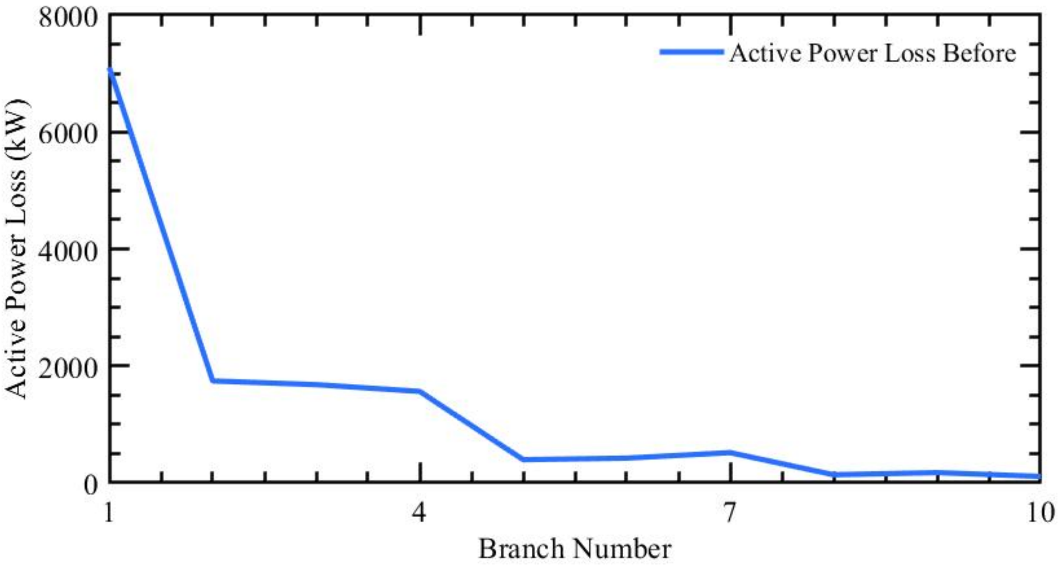


Figure 4. 42 NTDC 11 bus system: Active Power Loss without UPFC

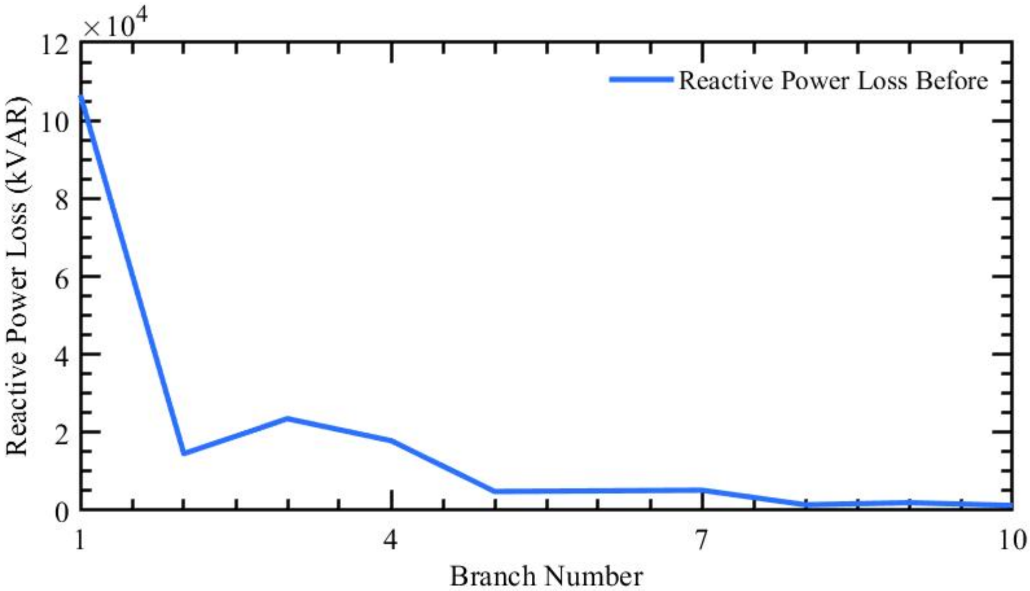


Figure 4. 43 NTDC 11 bus system: Reactive Power Loss without UPFC

ii. Optimization of UPFCs with SHO:

After taking the results from the NR method, in the next phase, SHO is implemented to determine the optimal placements & ratings for UPFC. In this research, 3 Nos. UPFCs have been considered. 100% of the line loading is regarded as the typical limit. The voltage limits used to measure voltage variations are 0.9 to 1.1 p.u. Minimum and maximum initial value of Series and shunt resistance, reactance and impedance are considered as 1 and 100 respectively.

SHO algorithm identified the 3 ideal bus locations i.e., between busses 1-3; 2-4 and 1-2 for the placement of UPFCs to reduce APL, RPL and improvement of the voltage profile. Results show significant reduction in the individual objectives of APL, RPL and V_{avg}. P_{LOSS} was reduced from 13,851.82 kW to 4,441.03 kW, Q_{LOSS} was reduced from 182,159.34 to 51,372.75 kVar and average voltage was increased from 0.8757 to 0.9878 p.u. MOI obtained from implementation of SHO is 0.2047.

Sr. No	**Parameter**	**Without UPFC**	**With UPFC**
1.	**MOI**	-	0.2047
2.	P_{LOSS} **“kW”**	13851.82	4441.03
3.	Q_{LOSS} **“kVar”**	182159.34	51372.75
4.	V_{avg} **“p.u”**	0.8757	0.9878
5.	**UPFC Locations**	-	1-3; 2-4; 1-2
6.	**Min. Voltage/ Bus No**	0.8011/10	0.9539/9
7.	V_{se}	-	0.1225 0.2999 0.0345
8.	V_{sh}	-	0.9997 0.9892 0.9994

Table 4. 8 NTDC 11 bus system: parameters comparison with and without UPFC

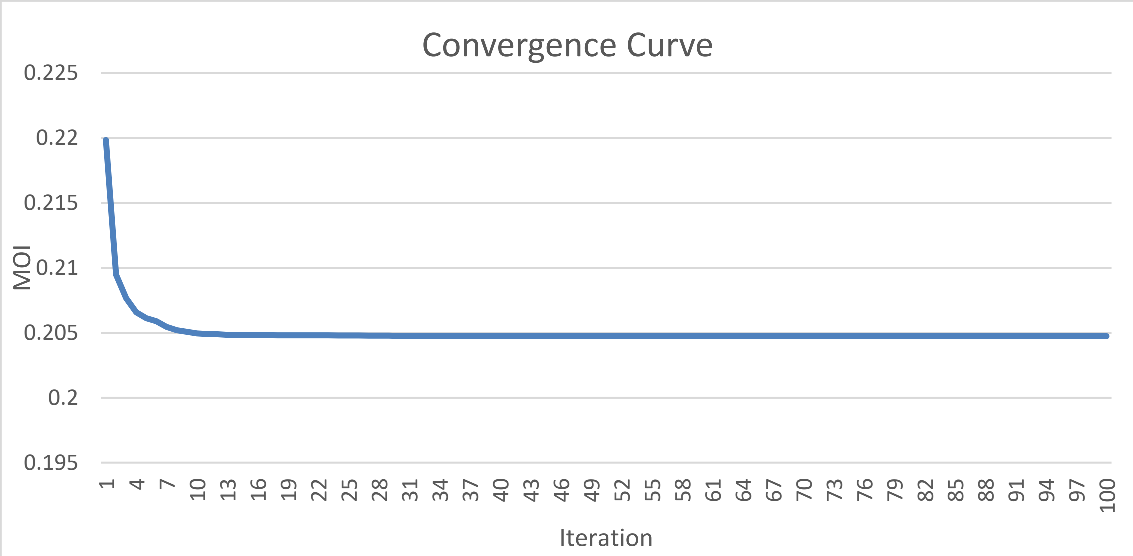


Figure 4. 44 NTDC 11 bus system: SHO Convergence Curve

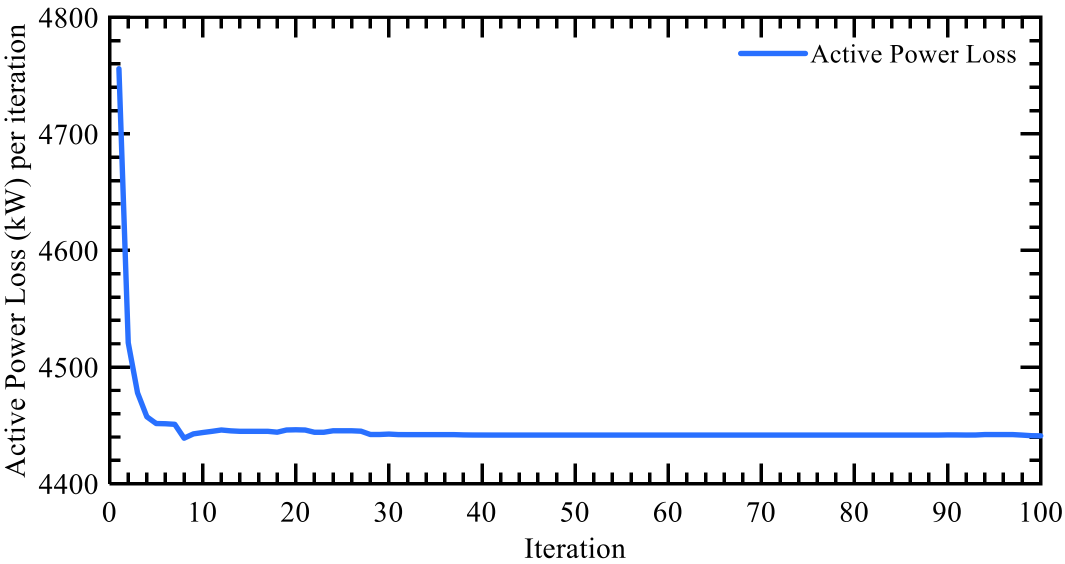


Figure 4. 45 NTDC 11 bus system: Active Power Loss per iteration (SHO)

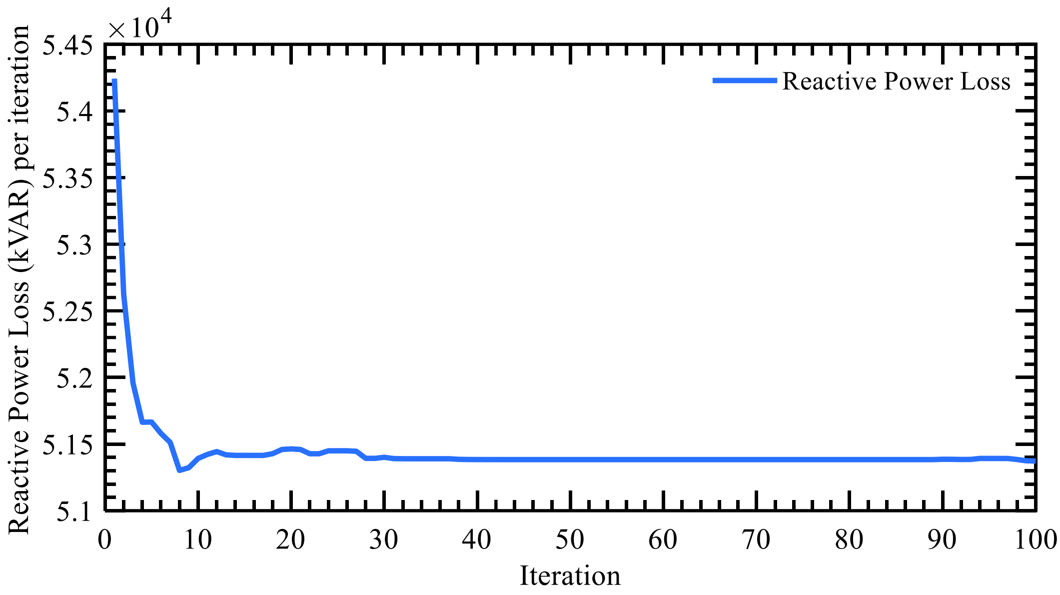


Figure 4. 46 NTDC 11 bus system: Reactive Power Loss per iteration (SHO)

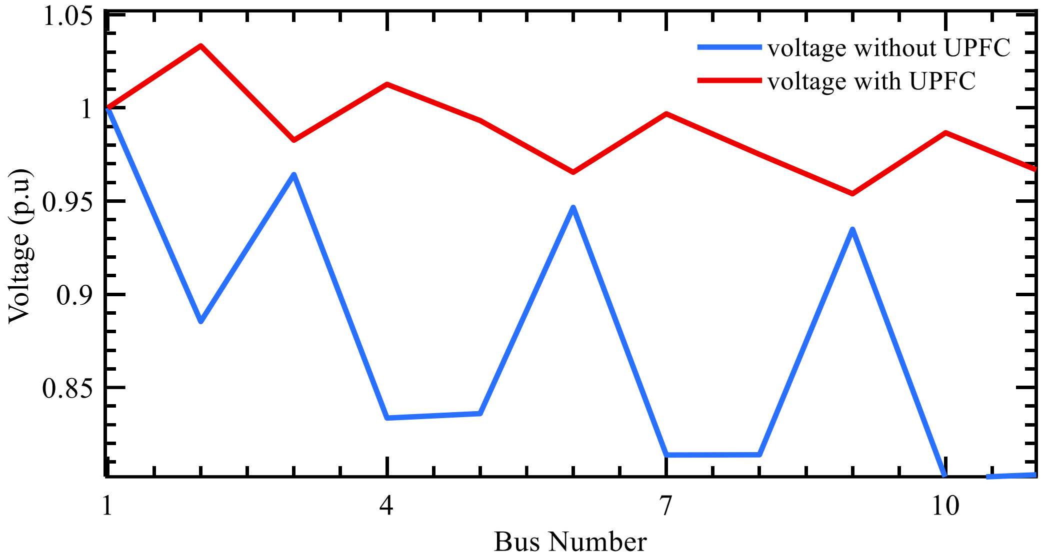


Figure 4. 47 NTDC 11 bus system: Comparison of Voltage on each bus with and without UPFC (SHO)

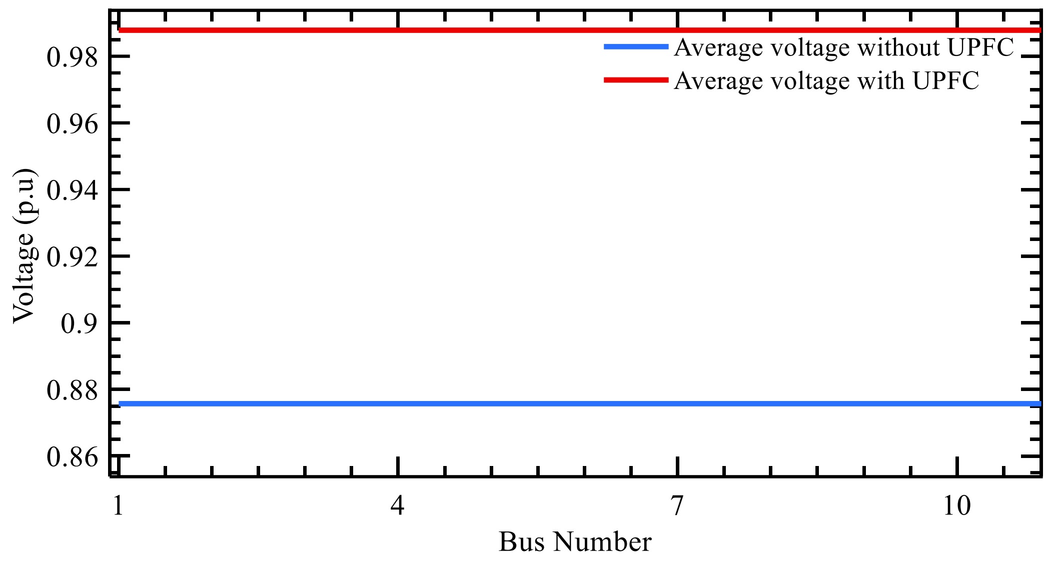


Figure 4. 48 NTDC 11 bus system: Comparison of Average Voltage (SHO)

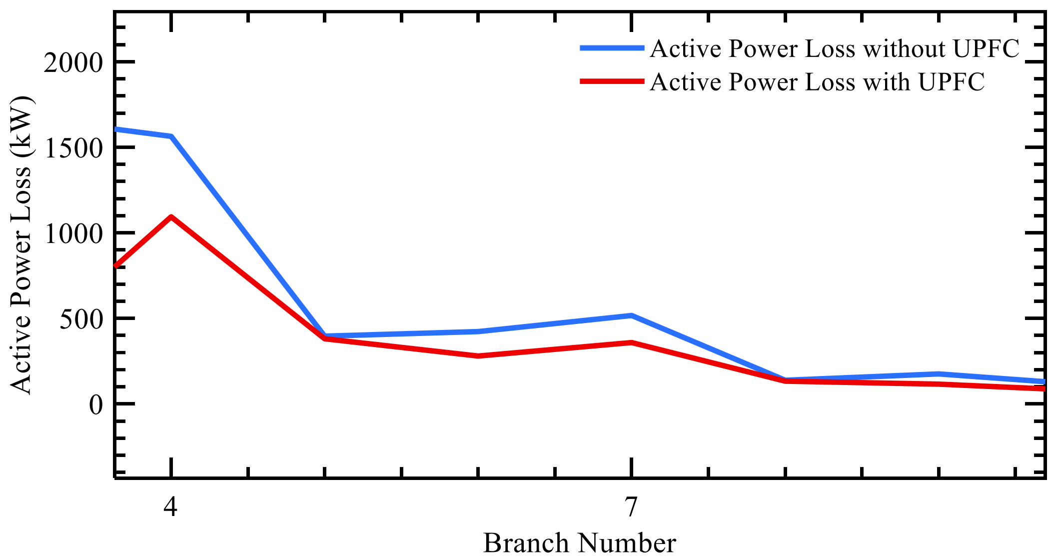


Figure 4. 49 NTDC 11 bus system: Comparison of Active power loss with and without UPFC (SHO)

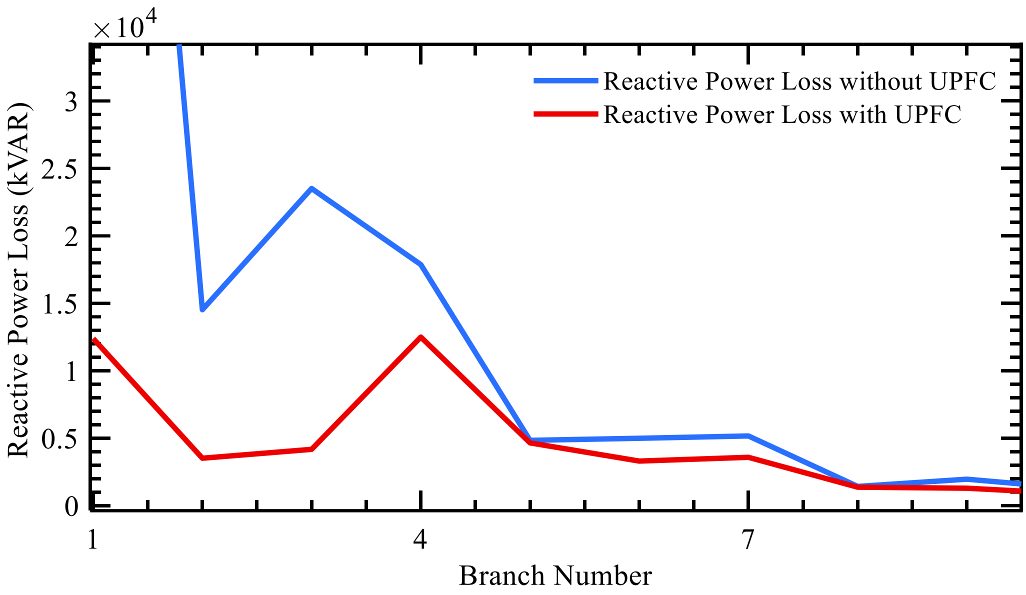


Figure 4. 50 NTDC 11 bus system: Comparison of Reactive power loss with and without UPFC (SHO)

iii. Optimization of UPFCs with ABC:

The results obtained by using the SHO is compared with ABC technique to demonstrate the effectiveness. The same input parameters were used for better comparison of the results with SHO. Bus locations identified by ABC technique was between buses 1-3; 1-2; 2-4, which is same as was identified by the SHO technique. P_{LOSS} was reduced from 13,851.82 kW to 4557.80 kW, Q_{LOSS} was reduced from 182,159.34 to 52,132.19 kVar and average voltage was increased from 0.8757 to 0.9890 p.u. MOI obtained from the implementation of ABC is 0.2085.

Sr. No	Parameter	Without UPFC	After UPFC With ABC	After UPFC With SHO	Improvement in Results
1.	Population Size	-	300	300	-
2.	Iterations	-	100	100	-
3.	MOI	-	0.2085	0.2047	0.0038
4.	P_{LOSS} "kW"	13851.82	4557.80	4441.03	116.77
5.	% age	-	67.09%	67.93%	0.84%

	Improvement				
6.	Q_{LOSS} **"kVar"**	182159.34	52132.19	51372.75	759.44
7.	**% age Improvement**	-	71.38%	71.80%	0.42%
8.	V_{avg} **"p.u"**	0.8757	0.9890	0.9878	0.0012
9.	**UPFC Locations**	-	1-3; 1-2; 2-4	1-3; 2-4; 1-2	-
10.	**Min. Voltage/ Bus No**	0.8011/10	0.9539/9	0.9539/9	-
11.	V_{se}	-	0.0456 0.1902 0.3000	0.1225 0.2999 0.0345	-0.0769 -0.1097 0.2655
12.	V_{sh}	-	0.9997 0.9993 0.9505	0.9997 0.9892 0.9994	0 0.0101 -0.0489

Table 4. 9 NTDC 11 bus System: Comparative Analysis of SHO and ABC Algorithms

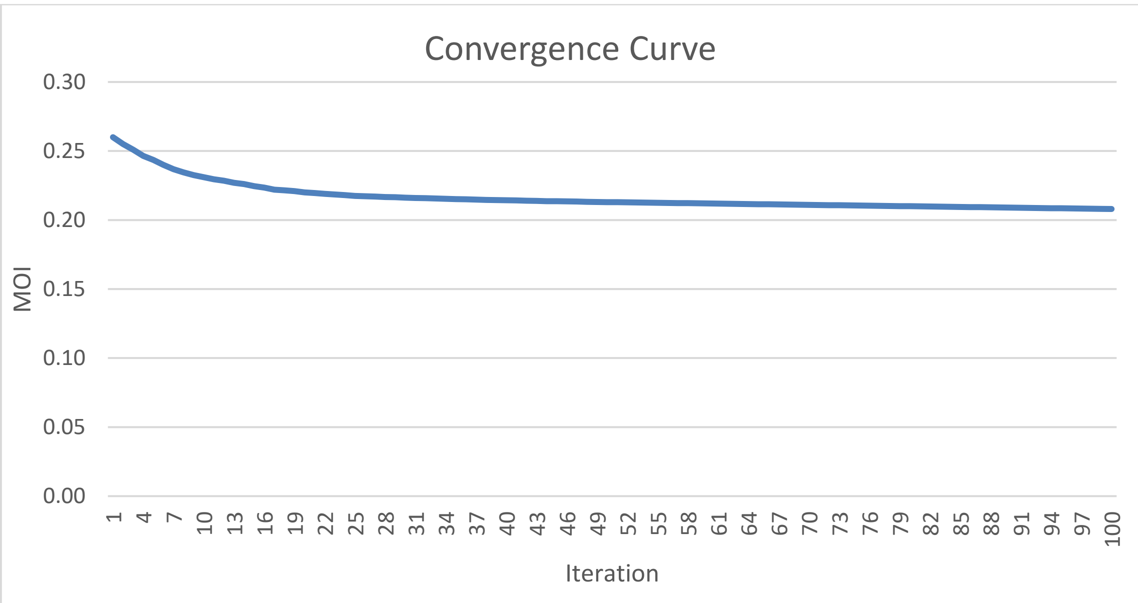


Figure 4. 51 NTDC 11 bus system: ABC Convergence Curve

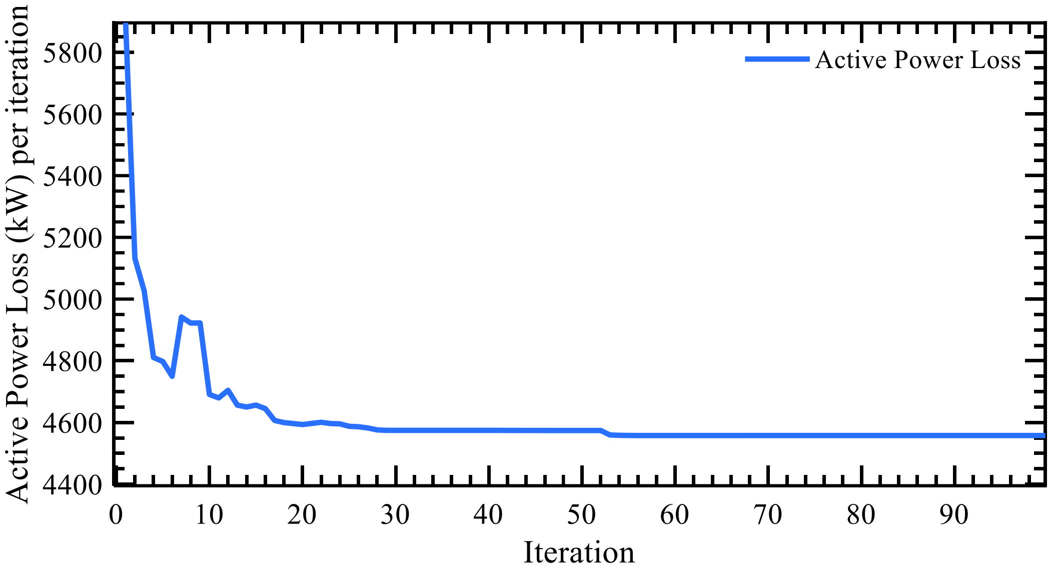


Figure 4. 52 NTDC 11 bus system: Active Power Loss per iteration (ABC)

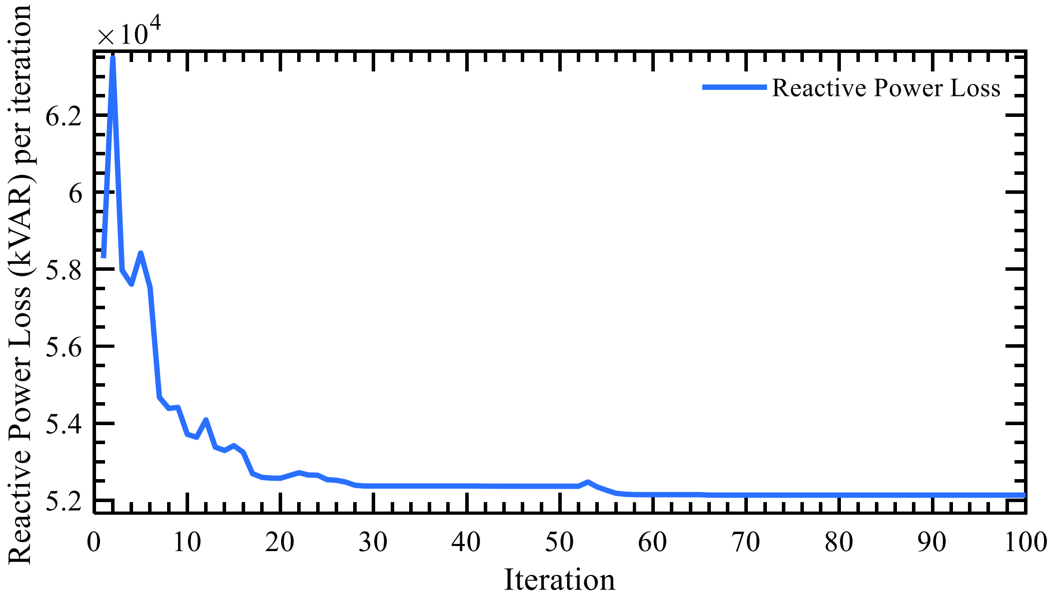


Figure 4. 53 NTDC 11 bus system: Reactive Power Loss per iteration (ABC)

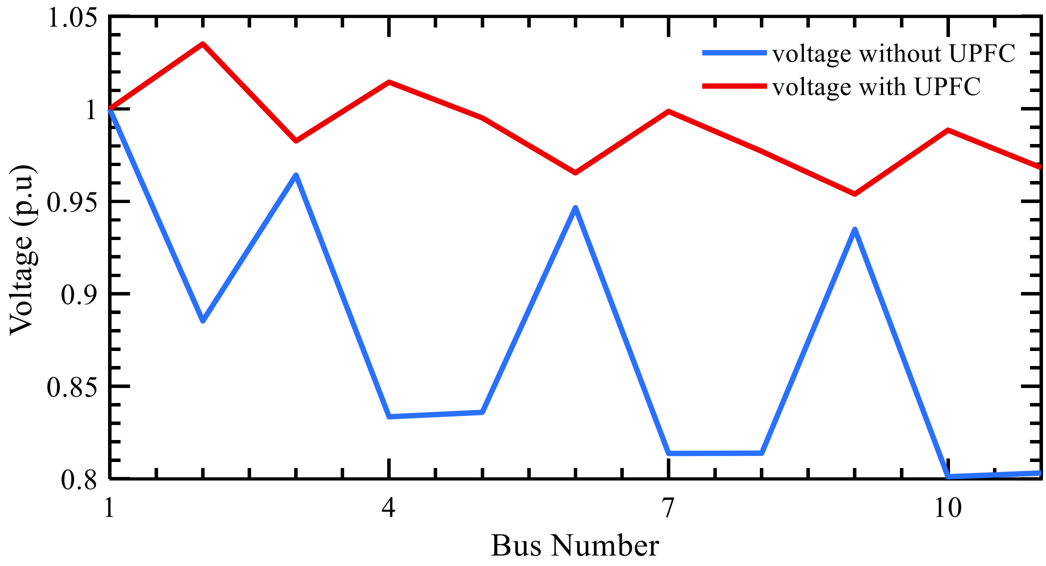


Figure 4. 54 NTDC 11 bus system: Comparison of Voltage on each bus with and without UPFC (ABC)

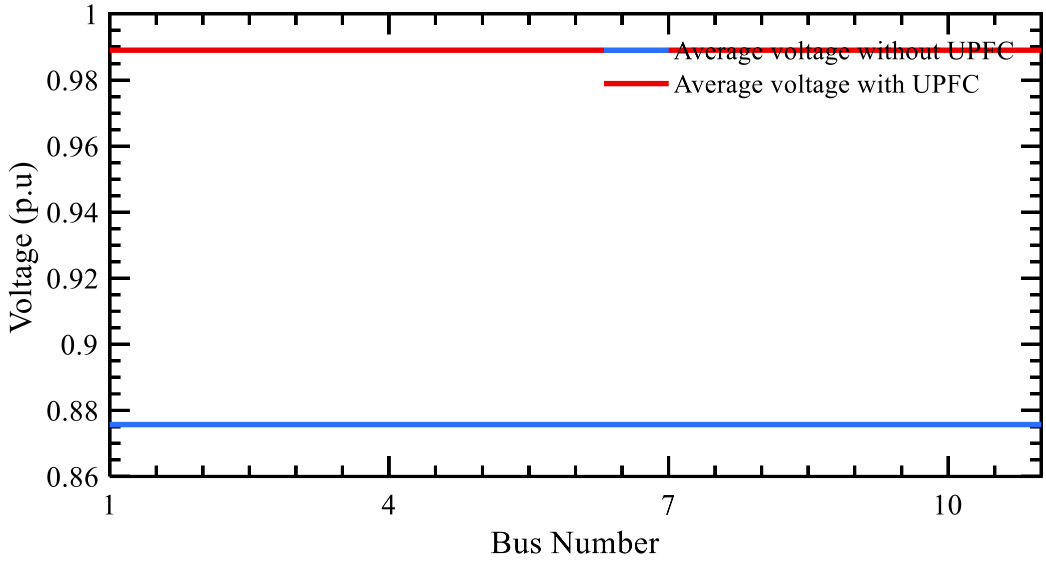


Figure 4. 55 NTDC 11 bus system: Comparison of Average Voltage (ABC)

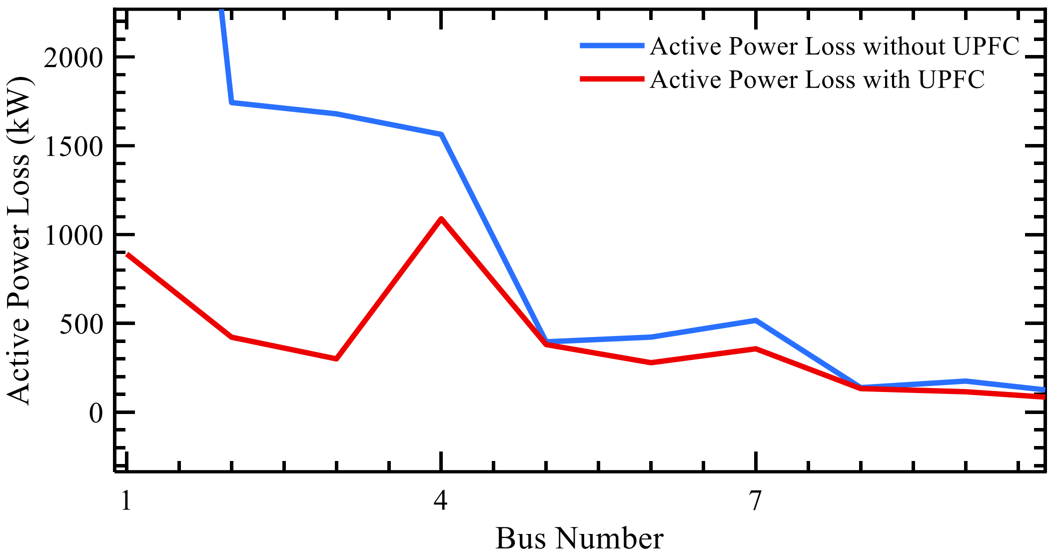


Figure 4. 56 NTDC 11 bus system: Comparison of Active power loss with and without UPFC (ABC)

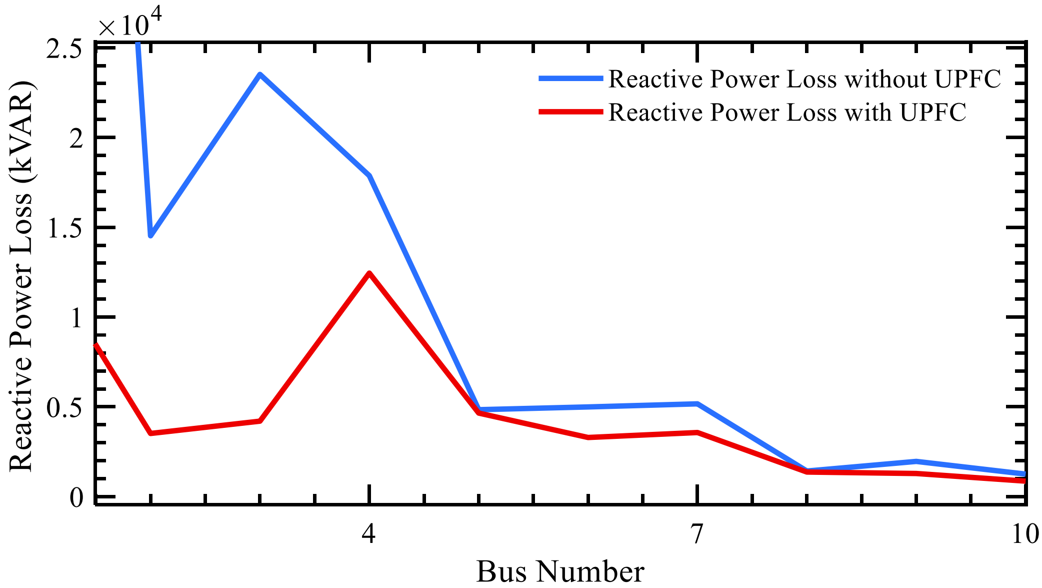


Figure 4. 57 NTDC 11 bus system: Comparison of Reactive power loss with and without UPFC (ABC)

CHAPTER 5

CONCLUSION

5.1. Conclusion

It was investigated in detail in this research that how well the Unified Power Flow Controllers (UPFC) can improve transmission grid compensation. The Sea Horse Optimiser (SHO), a relatively new metaheuristic optimization method is used to identify the ideal locations and parameter settings for UPFC installation. SHO algorithm performance is also rigorously compared with the well-established Artificial Bee Colony (ABC) optimization technique, providing a robust comparative analysis. The simulations have been performed on the NTDC 11 bus system, IEEE 14 and 30 bus systems, providing a comprehensive analysis of the algorithms' efficiency in reducing both APL and RPL and enhancement of the average voltage. mSHO's ability to navigate the solution space more effectively allowed for more accurate identification of locations and parameter settings for UPFC, leading to improved grid compensation. As a result, in every evaluated case scenario, the SHO algorithm resulted in reduced active and reactive power losses. Results show APL and RPL improvement of 46.06% & 41.35% in IEEE 11 bus system, 37.93% & 39.90% in IEEE 30 bus network and 67.93% & 71.80% in NTDC 11 bus transmission system respectively, while maintaining voltage within limits. The findings showed that in every evaluated case, the SHO algorithm performed better than the ABC algorithm, resulting in improved power loss reduction and raising the power system's overall stability and efficiency.

5.2. Limitations

Although, a detailed work has been done in this research thesis and significant advancements and contribution is made in optimizing the placement and sizing of UPFC via using SHO, however it is not without its limitations. One of the primary limitations is that although SHO has performed better in the trial, however its efficacy can vary depending on the circumstances. The number of buses in a network, load circumstances, and system configurations can all affect how well optimization algorithm’s function. The argument that SHO is generally better could be reinforced by a more thorough assessment with other metaheuristic algorithms (such as GA, PSO, Cuckoo Search Algorithm, Harris Hawks Algorithm or others). Testing on IEEE 14 and 30 bus systems and NTDC 11 bus system is performed in this thesis. Even though these are smaller systems, they pale in comparison to the thousands of buses that exist in actual power networks. It is still unknown if the SHO method can scale to much larger and more complicated systems. The practical issues of deploying UPFC, such as the expenses related to installation, operation, and maintenance are not included in the thesis. For practical applications, the economic viability and cost-benefit analysis of placing UPFC employing SHO are essential. The research is mainly concerned with steady-state variables such as average p.u. voltage, APL and RPL. However, transient and dynamic stability analysis of the system after UPFC installation is not addressed. When implementing the solution on real grids, there may be risks associated with ignoring the impact that UPFC have on the system's transient behaviour. Last but not the least, the computational complexity and time required to run the SHO algorithm on larger networks comprising of hundreds and thousands of buses have not been explored, which could be a concern in cases where real-time optimization is needed.

5.3. Future Recommendations

The aim of this thesis was to determine where the UPFC should be installed to minimize the system losses and optimize the average voltage. More research may look into combining UPFC with other FACTS devices, SVC, TCSC and STATCOM etc., which may improve grid efficiency and stability even more. It is possible to research hybrid optimization strategies further, which combine the advantages of the SHO with other metaheuristic methodologies as PSO, GA or others. These hybrid approaches might be able to provide better optimization outcomes and faster rates of convergence. The stability and dependability of the power grid systems are nowadays being threatened by the growing integration of renewables, which are variable and intermittent. In networks with renewable integration, further research might investigate how the SHO algorithm can optimize the FACTS device allocation, reducing the negative consequences of disturbances and improving grid reliability. Future optimization attempts can also take economic variables into account, weighing technical performance against cost considerations to identify more economically feasible options. Moreover, in the future the robustness of SHO should be checked under various contingency scenarios, such as line outages and generator failures. This would help ensure that the optimization results remain effective and reliable under adverse conditions. At the last, this study considered three individual objectives to form the MOI. However, MOI function can also be created by considering other factors like installation cost and voltage deviations.

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