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Enhancement of a Distribution System Performance Based on A Nested Corona Herd Immunity Optimizer

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ABSTRACT

Electrical distribution systems are essential for the delivery of power to end users. Enhancing the performance of these systems is a strategic approach to meet increasing demands on the electrical grid. Recently, many types of power electronics converters are employed for such enhancement of performance. These converters are either used to alter the topology of the system such as Soft Open Points (SOPs) or are connected directly at buses. For an achievable enhancement of distribution system to occur, an optimization problem must be articulated. In this work a Corona Herd Immunity Optimizer (CHIO), which is inspired by the world wide Corona outbreak, is employed to find the optimal apparent power flow, these converters must condition to achieve a desired objective. In this context two CHIOs are used consecutively to achieve minimal active losses through the connection of two back to back converters and maintain voltage profile within limits using a power converter that condition reactive power flow. Results underscore CHIO effectiveness in minimizing power losses and maintaining voltage stability, demonstrating its potential to enhance overall system efficiency. Simulations conducted in MATLAB, on a standard distribution system, evaluated multiple power electronics converter positions, incorporating Distributed Generation, further affirming the robustness of the CHIO approach.

1. INTRODUCTION

Electrical distribution networks are essential components of the power system that deliver electricity from transmission systems to individual consumers, and enhancing the performance of a distribution system is crucial for ensuring the efficient delivery of services from producers to consumers. A well-optimized distribution system reduces costs, minimizes delays, and improves customer satisfaction. Power electronic converters can provide a solution to elevate efficiency and reduce losses, Ultimately, a high-performing distribution system is integral to maintaining the flow of electricity in an increasingly complex and dynamic global economy.

As the demand for electricity increases, so do these losses; also, voltage profile index, where the voltage at different points (buses) in the distribution system can fluctuate due to varying loads. Keeping the voltage within a specified range is crucial for the proper functioning of electrical devices, and load load balances [1]. As demand for electrical energy rises over time, these losses tend to increase, leading to a decline in the voltage profile. These losses tend to increase with geographical distances from the power feeding source and with rising load demands due to the increase in currents passing through various lines of the distribution system. Previous research has explored various methods for strengthening electrical distribution networks to achieve optimal performance and stability. For example, an analytical method was developed to determine the optimal operating points of a back-to-back converter, referred to as Soft Open Points (SOP), using multi-objective particle swarm optimization, and was applied to the IEEE 33-bus system [2]. Dutta et al. [3] addressed the Optimal Reactive Power Dispatch (ORPD) problem using chemical reaction optimization (CRO) with a static series synchronous compensator (SSSC) to minimize power losses in the IEEE 30-bus and IEEE 57-bus systems. Ibrahim and Alwash [4] proposed an optimal DG integration strategy aimed at simultaneously maximizing the Distributed Generation (DG) hosting capacity, minimizing system losses, and improving the voltage stability index (VSI). This optimization process was carried out using the Coronavirus Herd Immunity Optimizer (CHIO). In the studies [5-8], tackled the Optimal Reactive Power Dispatch (ORPD) problem through several conventional methods, such as linear and nonlinear programming, the interior point method, and quadratic programming techniques. Salau et al. [9] applied the Selective Particle Swarm Optimization (SPSO) algorithm to identify the most suitable tie and sectionalizing branches to open or close within the IEEE 33-bus radial distribution system to minimize total real power losses and enhance the system's bus voltages. The applications of Soft Open Points (SOPs) were analyzed and verified in relation to DG accommodation, feeder load balance, and voltage profile improvement [10]. A power converter operated as an SSSC achieves the necessary controllability by introducing an AC voltage with precisely regulated magnitude and phase angle in series with the transmission line [11, 12]. Amin et al. [13] explored the Optimal Reactive Power Dispatch (ORPD) problem with the inclusion of an SSSC in the IEEE 30-bus system to enhance the voltage profile and improve voltage stability using the Grey Wolf Optimizer (GWO) method. Prashant et al. [14] have investigated the optimal sizing and placement of Distribution Static Synchronous Compensator (D-STATCOM) to enhance the performance of distribution networks, focusing on various objective functions such as voltage profile, line power loss, accuracy, sensitivity, total harmonic distortion (THD). Marouani et al. [15] applied a multi-objective evolutionary algorithm (MOEA) to the ORPD problem, incorporating an SSSC in a 6-bus system to reduce real power losses and voltage deviations. Khan et al. [16] focused on optimizing the size and placement of Static Synchronous Series Compensator (SSSC) controllers in power systems. It employs a novel modified Salp Swarm Algorithm (SSA) to achieve these objectives. The study uses a basic SSSC model combined with Optimal Reactive Power Dispatch (ORPD) to minimize power losses, reduce voltage deviations, and improve voltage stability in IEEE 30-bus and IEEE 57-bus systems.

While the aforementioned methods have notably enhanced the performance of the distribution system, a more thorough analysis is needed to further explore the improvements achieved through power electronics converters. Benefits of power electronics converters can be extended to impact key aspects of modern power systems. In this study, the performance of a distribution system is improved through the integration of power electronic devices. This enhancement is achieved by optimizing the operating points of these devices to impact two key aspects of distribution system operation, namely reducing active power losses and improving voltage profiles. Therefore, the CHIO [17] is implemented in this work as two cascaded algorithms. The first minimizes the power losses through the optimizing of the active and reactive power flow of a back-back power electronics converter [18]. The second algorithm, remedies any voltage at any bus that deviates from the tolerated deviation through optimization of reactive power flow for another power converter.

CHIO's primary advantage over other optimization techniques lies in its ease of implementation compared to genetic algorithms or molecular swarm optimization [19]. Additionally, it enhances population diversity by avoiding constraints to specific solutions, making it a robust choice for addressing highly complex optimization problems [19].

The rest of this paper is organized as follows, Section 2, details power electronic devices in distribution system. In Section 3 corona herd immunization is explained. In Section 4, distribution of optimal controlled power of power electronic devices. In Section 5, results and discussions.

2. POWER ELECTRONIC DEVICES IN DISTRIBUTION SYSTEM

A power electronic devices is a technology used in electrical distribution networks to enhance their flexibility, reliability, and efficiency [20]. In high-voltage transmission networks, this technology is often termed as Flexible AC Transmission Systems (FACTS) or custom power devices [20]. These devices can also be utilized within distribution networks to offer compensation, thereby improving system performance in terms of efficiency and precise feeder balancing [21]. At the distribution level, several power electronic devices are employed, including Static Synchronous Compensators (STATCOM), back-to-back (B2B) Voltage Source Converters (VSCs) also known as Soft Open Points (SOPs), multi-terminal (MT) VSCs, Static Synchronous Series Compensators (SSSC), and Unified Power Flow Controllers (UPFC) [20]. Figure 1 provides adepiction of each device's typology.

2.1 Back- back power electronics converter

This is a converter used in electrical distribution networks to enhance their flexibility, reliability, and efficiency. It is essentially a controllable power electronic device that can connect and disconnect sections of the network as needed, facilitating the dynamic management of power flows [10].

The SOPs work on controlling power flow where it can actively manage the direction and magnitude of power flows within the network, allowing for better load balancing and reducing congestion [2], where a general converter is shown in Figure 2. Moreover, by optimizing the flow of electricity, SOPs can help reduce I^2R losses in the distribution network and eventually improving overall efficiency [21].

Soft Open Points (SOPs) are advanced power electronic devices that play a crucial role in modernizing electrical distribution networks. They provide enhanced control over power flows, improve reliability and efficiency, and facilitate the integration of distributed energy resources, making them integral to the development of smart and flexible power systems [21].

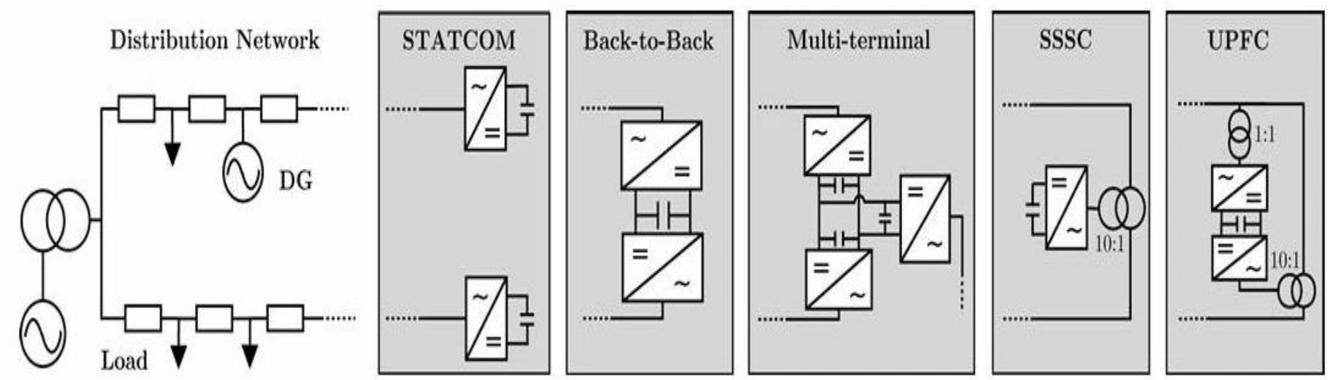


Figure 1. Power electronic devices utilized at the distribution level [20]

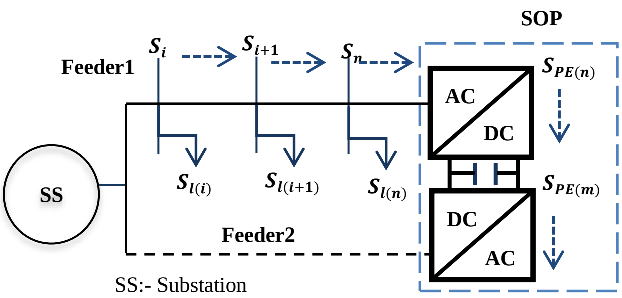


Figure 2. Single line diagram of two power electronic devices in a two-feeder distribution system with a back-to-back converter setup

2.2 Static Synchronous Series Compensator (SSSC)

This convertor is a type of Flexible AC Transmission System (FACTS) device used to control power flow and improve the stability of the power system [20]. A Static Synchronous Series Compensator (SSSC) typically includes a coupling transformer, an inverter, and a capacitor [22]. As shown in Figure 1, the basic Concept of SSSC is based on a Voltage Source Converter (VSC) which generates a controllable AC voltage. It is assumed that the transmission line is series connected to the SSSC through its bus. This voltage is injected in series with the transmission line to control the power flow, could either inject or absorb reactive power to achieve an optimal voltage profile, altering the line impedance and thereby controlling the power flow [23]. The primary function of an SSSC is to generate a compensating voltage that is injected into the transmission line [24]. This compensating voltage is generally in quadrature (90 degrees phase shift) with the line current, allowing it to control the reactive power flow. The SSSC provides dynamic control over the voltage profile of the transmission line [25], improving system stability and hence the better benefit of SSSC it's dynamic voltage control, implemented by controlling the flow of reactive power at the bus which is connected to. Consider Figure 3, where a general converter is shown that produce a controlled apparent power flow.

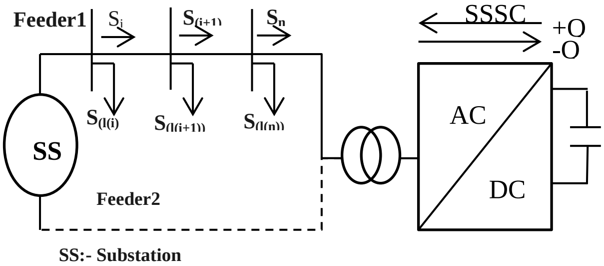


Figure 3. Single line diagram of an SSSC connection in distribution system

2.3 Modeling of power electronic devices in distribution systems

In general, power electronic converters influence the power flow at the connection point, with each device exhibiting unique characteristics. This paper focuses on two types of power electronic devices used in a distribution system: the Soft Open Point (SOP) and the Static Synchronous Series Compensator (SSSC). These devices are modeled to control power flow effectively [26].

In normal state, two adjacent buses, with index, i & $i+1$ the power equilibrium is expressed as,

$$S_{(i+1)} = S_i - S_{l(i+1)} - S_{loss(i,i+1)} \quad (1)$$

where, $S_i, S_{(i+1)}$ is the apparent power flow at bus i & i+1 respectively. $S_{l(i+1)}$ is the load profile at bus, $i+1$ and finally $S_{loss(i,i+1)}$ is the complex representation of active and reactive power losses due to line resistance and reactance between buses i & i+1. These losses are dependent on the current flowing in the branch line and is given by:

$$S_{loss(i,i+1)} = I^2_{(i,i+1)} \times R_{(i,i+1)} + j\, I^2_{(i,i+1)} \times X_{(i,i+1)} \quad (2)$$

If a power electronics device is inserted at bus i+1, that injects an apparent power of, $S_{PE(i+1)}$, then Eq. (1) is modified as:

$$S_{i+1} + S_{PE(i+1)} = S_i - S_{l(i+1)} - S_{loss(i,i+1)} \quad (3)$$

If the power electronics device is a back to back SOP, then the apparent power at buses i & i+1 will be effected by an injector or absorb process. Moreover, both of the apparent power will be affected. A power balance is necessary for the case of an SOP operation and therefore for a lossless converter, this balance is expressed as [2]:

$$S_{PE(i+1)} = S_i - P_{PE(i)} \pm jQ_{PE(i)} \quad (4)$$

$$P_{PE(i)} = -P_{PE(i+1)} \quad (5)$$

If a SSSC is assumed to be connected at buses, there are only reactive powers at buses i & i+1 that will be affected, where the $P_{PE(i+1)} = 0$, $P_{PE(i)} = 0$ this equation is expressed as:

$$S_{PE(i+1)} = \pm jQ_{PE(i+1)} \quad (6)$$

$$S_{PE(i)} = \pm jQ_{PE(i)} \quad (7)$$

The focuses here is on finding the controlled flow from the converter (s) that minimizes two specified cost function; power losses and voltage deviation at a bus. For the first cost function, an SOP is connected at two buses for example, i & i+1, then the real and imaginary parts of $S_{PE(i)}$ & $S_{PE(i+1)}$ must be determined by the optimization process to minimize the sum of active losses. If an SSSC is connected at bus, k (considering that this bus has violated the specified voltage limit) then the optimization is formulated based on finding the imaginary part of, $S_{PE(i+1)}$ corresponding to the minimization of a defined second cost function which is the voltage deviation.

3. CORONA HERD IMMUNIZATION OPTIMIZATION PROCESS

Herd Immunity Algorithm (HIA) optimization is an evolutionary computation technique inspired by the concept of herd immunity in epidemiology [27]. Herd immunity refers to the resistance to the spread of an infectious disease within a population when a sufficiently high proportion of individuals are immune, either through vaccination or previous infections. In optimization, this concept is applied to solve complex problems by simulating the spread of solutions through a population [28], where the population represents a group of potential solutions to the optimization problem and each individual (solution) in the population has certain attributes (parameters) and a fitness value indicating its quality. The immunity be Analogous to the fitness of solutions, where better solutions (higher fitness) have a higher immunity to "infection" (poor solutions) as shown in Figure 4 [26], The goal is to increase the overall fitness of the population by promoting the spread of high-quality solutions.

3.1 The Corona Herd Immunity Algorithm (CHIO)

The population represents a group of potential solutions to the optimization problem. And each individual (solution) in the population has certain attributes (parameters) and a fitness value indicating its quality. The population is categorized into three distinct groups according to the status of individuals [19]:

- Susceptible Persons (status = 0): This category encompasses the majority of the population utilized in the CHIO optimization framework. It includes individuals who are in direct contact with infected persons and are therefore at risk of contracting the virus.
- Infected Persons (status = 1): This is the second-largest group within the population, with its size likely to increase if social distancing measures are not adhered to. It includes individuals who have been confirmed as infected, and who may either recover or succumb to the illness.
- Immune Persons (status = 2): This group begins with no individuals and its size increases as the population evolves. The pandemic eventually concludes when a majority of the population achieves immunity.

Figure 5 illustrates the progression of the virus from individuals with a high likelihood of infection to the attainment of herd immunity through illness and recovery. Additionally, it highlights that a portion of the population may experience a fatal outcome.

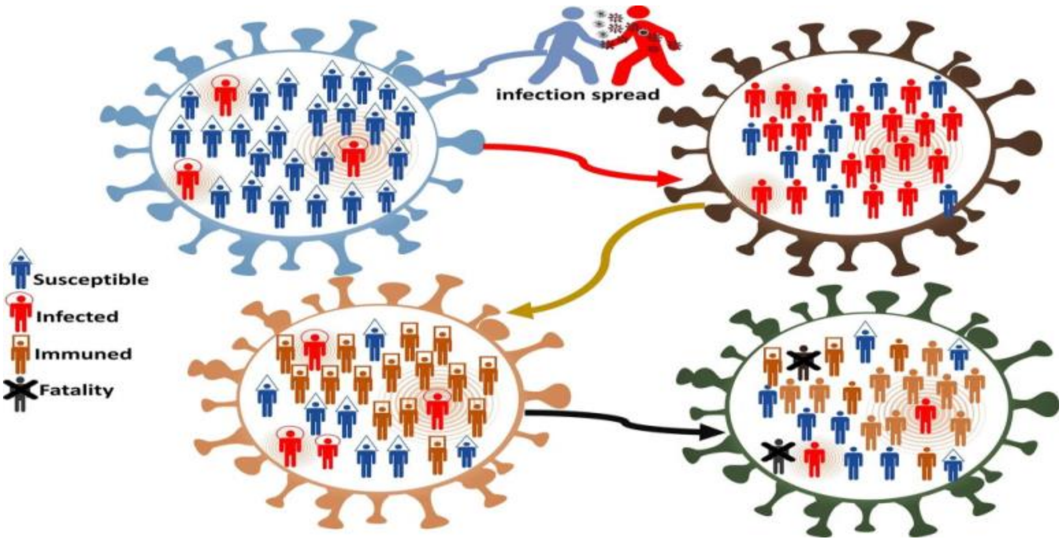


Figure 4. Illustration of herd immunity mechanism [28]

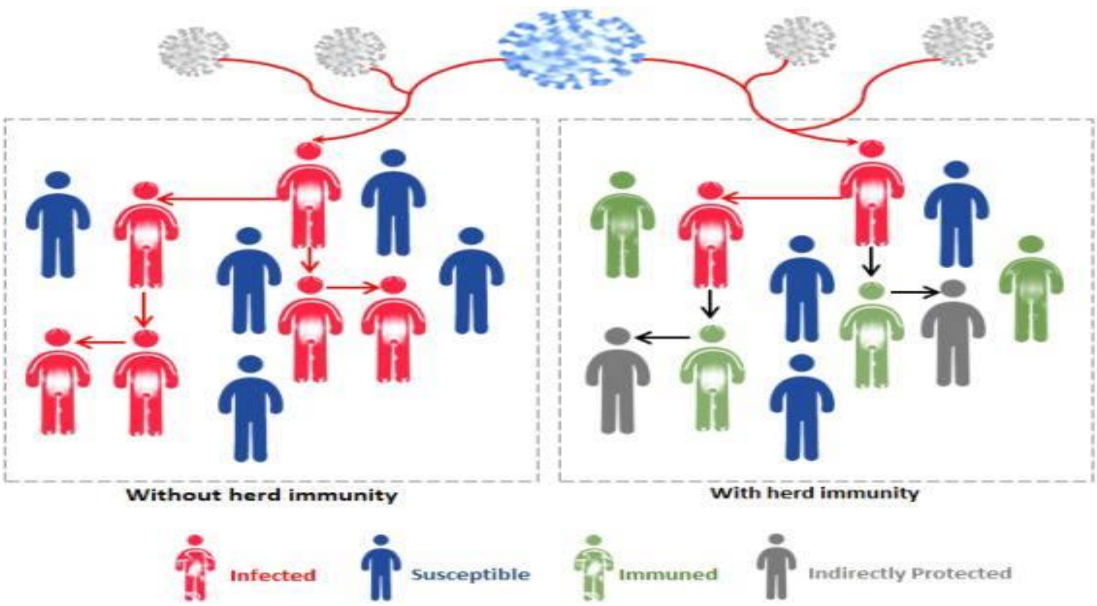


Figure 5. COVID-19 spreading control procedure [29]

3.2 Procedure of corona herd immunity optimization

The general procedure steps of the developed optimization algorithm CHIO is described as mentioned below [19]:

1. Initialize Population: Generate an initial population of individuals (solutions) with random parameters, this indicates the initial origin or source of the virus.
2. Evaluation of Fitness: Compute the fitness of each individual.
3. Infection: Each individual, randomly select an infector based on fitness. Modify the individual's parameters to reflect the infector's attributes.
4. Immunization: Identify and retain the top individuals based on fitness to protect high-quality solutions.
5. Selection: Form a new population by selecting individuals based on their fitness and immunity.
6. Termination Check: Repeat the infection, immunization, and selection steps until the stopping criterion is met.

3.3 The cost function

There are a number of cost functions when minimized, results in an enhanced operation of the distribution system. In general, the primary objective is to minimize the active power loss within the system [30] by using SOP for CHIO1, the secondary objective is to minimize the reactive power loss within the system [30] by using SSSC for CHIO2 (or nested with CHIO1). Achieving the optimal value of this function is crucial for enhancing overall system efficiency. The active losses can be defined from CHIO1:

$$P_{loss(i,i+1)} = Real\ (S_{loss(i,i+1)}) \quad (8)$$

The reactive losses can be defined as:

$$Q_{loss(i,i+1)} = Imajnary\ (S_{loss(i,i+1)}) \quad (9)$$

To account for the overall losses, Eq. (2) is summed for all branches of the system:

$$P_{loss} = \sum_{k=1}^{Nb} Real\ (S_{loss(k)}) \quad (10)$$

where, *Nb* is the total number of branches in the system. For the voltage, the cost function is to reduce the deviation from the nominal 1 per unit value and hence its defined for the k^{th} bus as:

$$\Delta V_k = ABS(1 - \Delta V_k) \quad (11)$$

This objective function serves as a critical parameter in the design and operation of electrical systems, ensuring they operate with maximum efficiency and minimal energy dissipation.

4. DETERMINATION OF OPTIMAL CONTROLLED POWER FLOW FOR CONVERTERS

In this paper, the approach proposed by CHIO in the study [11] is utilized to determine the optimal power flow for the SOP and SSSC devices, if the latter are used. Specifically, the method involves using a back-to-back SOPs device in the initial section CHIO1 and a static synchronous series compensator in the subsequent nested section CHIO2. Consequently, the optimization process is aimed at determining the apparent powers, $S_{PE(i)}$ and $S_{PE(i+1)}$. According to the CHIO method, the variables are categorized as Susceptible, Infected, or Immune, reflecting the real and imaginary components of the apparent power for each converter. Initially, each variable is assigned a status of zero, indicating it is susceptible to potential infection.

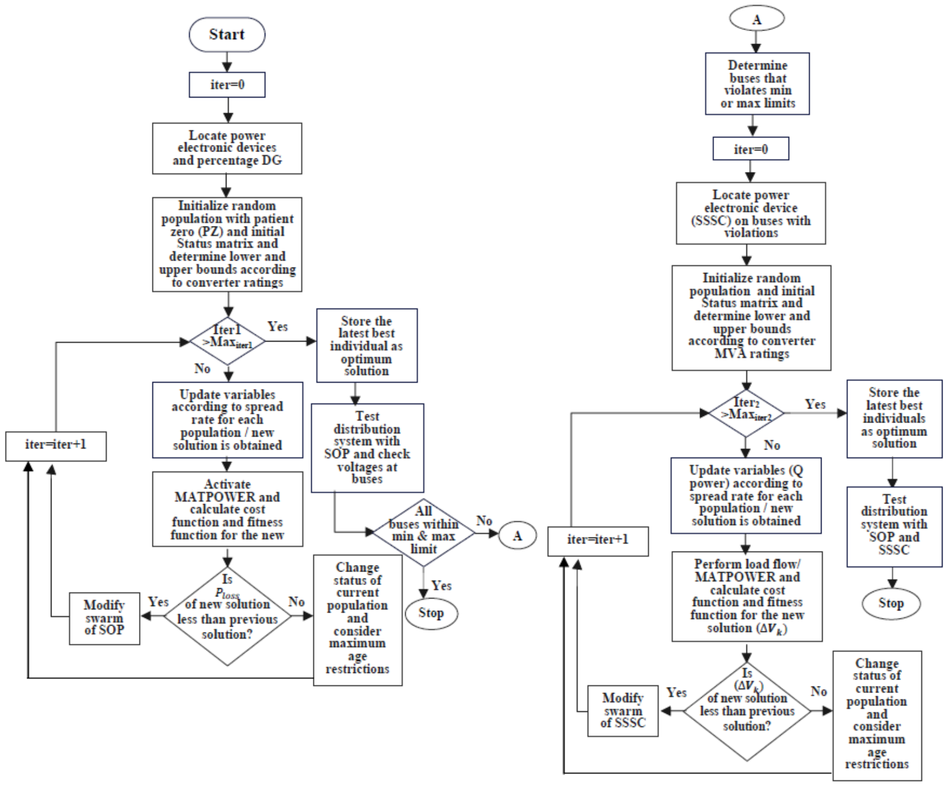


Figure 6. Flow chart of the proposed nested method

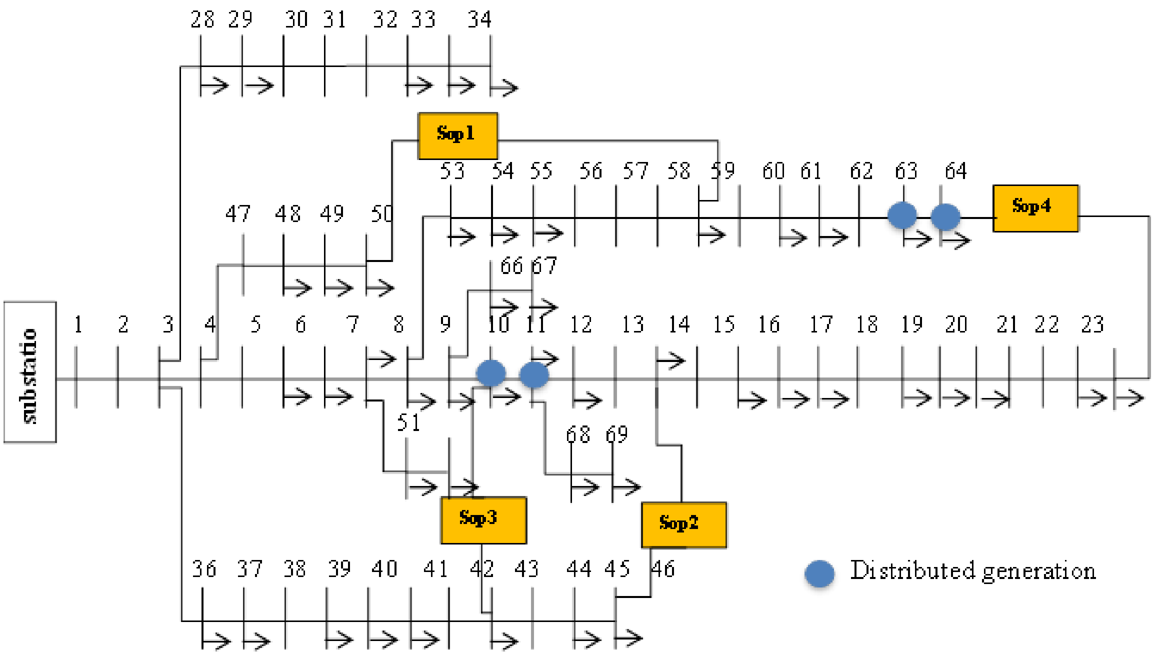


Figure 7. The IEEE 69-bus distribution network includes designated locations for both Soft Open Points (SOPs) and Distributed Generation (DG)

The optimal solution is determined using the herd immunity algorithm when a population reaches a status of (2), indicating that individuals have been infected and subsequently recovered, thereby acquiring herd immunity. This algorithm involves iterative processes where an individual's condition progresses from infected (status = 0) to recovered (status = 1). Cases exceeding the maximum age are deemed fatal. During each iteration, the algorithm selects the lowest value among the recovery states, compares it with the subsequent recovery state, and retains the optimal (lowest) value while disregarding the others.

This lowest value represents the optimal solution for electrical power losses or minimum voltage profile deviation, depending on whether CHIO1 or CHIO2 are used, when the compensator is positioned at a specific location within the system. CHIO1 is first used to find optimal powers of the SOP device. Then those optimal powers are inserted at the SOP location. Finally, the power losses are evaluated. A scan of the voltage profile at buses is conducted. If both the minimum and maximum voltages are within the specified range (0.95-1.05), the algorithm terminates as CHIO1.

Conversely, if voltage boundaries are breached, i.e. if the minimum voltage is below 0.95 or the maximum voltage exceeds 1.05, the nested algorithm, CHIO2, is applied. CHIO2 is similar to CHIO1 but modified to enhance voltage regulation. The flow charts for CHIO1, CHIO2, is depicted in Figure 6. Table 1 shows procedures of nested CHIO. Since both cost functions need to be evaluated at each iteration for a population that has achieved herd immunity, a load flow algorithm is necessary. In this work, load flow calculations are performed using MATPOWER 7.0 [31].

The proposed method was applied to the IEEE 69-Bus test system, a comprehensive radial distribution feeder comprising 69 buses and 68 branches [32]. This test system, of depicted in Figure 7, operates at a voltage of 12.66 kV [33] with a base power rating of 100 MVA. It encompasses an active power load of 3790.69 kW and a reactive power load of 2694.1 KVAR. The line and load data for this system are obtained from the study [32].

Table 1. Steps of CHIO

Algorithm: CHIO1/SOP converter
1: Set number of SOP converters.
2. SOP location n & m.
3: Intililize population and determine spread rate.
4: Obtain solutions of individual who have gained herd immunity.
5: Select the minimum of these solutions.
6: Find the optimal power flows, $S_{PE(n)}$ & $S_{PE(m)}$
7: Examine buses with more than ±5% violation / d_1, d_2 are the number of buses that violate minimum or maximum voltage.
8: If d_1 *and* d_2 =0, Disable SSSC.
9: Else, activate CHIO2/connection of SSSC converter
10: Identify the buses experiencing issues with mimimum or maximum voltage violations.
11: The optimal value of Q, for sssc is determined.

5. RESULTS AND DISCUSSIONS

This study utilizes the IEEE 69-bus distribution network as a case study to illustrate the efficacy of the power electronics back-to-back and SSSC converters in mitigating power losses and stabilizing the voltage profile using the Herd Immunity Optimization (CHIO) algorithm [19]. Specifically, one variant of the algorithm (CHIO1) is employed with the back-to-back (SOPs) converter to optimize power losses, while another variant (CHIO2) is used with the Static Synchronous Series Compensator (SSSC) to optimize voltage levels. The algorithm is implemented in MATLAB and tested across various locations within the system. In this distribution network, four normally-open switches, located between buses 50-59, 27-65, 43-11, and 46-15 are identified as potential sites. The Static Synchronous Series Compensator (SSSC) is applied to buses exhibiting voltage deviations, with no predefined locations or specific numbers for SSSC application in this study prior to execution of CHIO1.

The (CHIO1) algorithm is utilized to optimize the distribution network by evaluating various SOP configurations and based on anaylises of bus voltage profiles, another optimization problem is formulated (CHIO2) that optimizes a power electronics converter which remidies any deviations that violates the standard limits imposed. Distributed Generation (DG) sources are introduced at buses 11, 12, 64, and 65 within the IEEE 69-bus system [2].

The parameters utilized in the simulations are outlined in Table 2. This study focuses exclusively on scenarios involving various configurations of converters (1SOP, 2 SOPs) and a limited number of Static Synchronous Series Compensators (SSSCs), with Distributed Generation (DG) penetration levels set at 10% and 30% of the total load capacity of the system under study. The objective is to assess the accuracy and effectiveness of the (CHIO1) algorithm in reducing electrical power losses and the (CHIO2) algorithm in enhancing the voltage profile.

Table 2. Parameters of SOP, SSSC system used in simulation

Parameter	Value
VSC apparent power, $S_{rated(SOP)1}$ & $S_{rated(SOP)2}$	5MVA
VSC apparent power, $S_{rated(SSSC)}$	3MVA
Nominal voltage	12.66 KV [33]
Number of populations	30
Number of variables	4
Corona virus C0	1
Number of iterations	1000
Spreading Rate	0.05 [19]
MaxAge	120

The response of the CHIO is evaluated by varying the percentage of distribution generator in the optimization process. The integration of Distributed Generation (DG) inherently bolsters the electrical network, and Type (1) DG, which provides real power [34], is employed in the analysis. For brevity, the performance of the (CHIO1), (CHIO2), is demonstrated for only two locations.

A. Simulation Results with10% Distributed Generation Penetrations

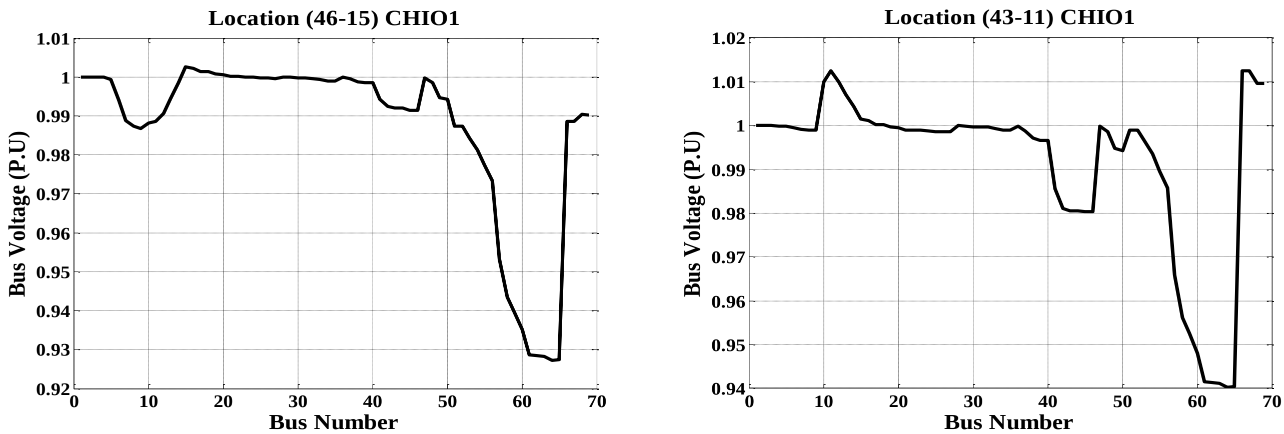
The optimal minimum power loss and improved voltage profile were determined using the SOP and SSSC devices across various testing scenarios. The performance of the CHIO1 algorithm was evaluated based on its ability to minimize losses. Subsequently, the CHIO2 algorithm was employed to adjust and improve voltage levels that exceeded permissible limits (maximum: 1.05 P.U, minimum: 0.95 P.U). The effectiveness of this algorithm was assessed to ensure voltage levels remained within acceptable limits. The results of the algorithm are presented numerically in Table 3, with all possible locations tested.

For instance, connecting a back-to-back converter at location 46-15 resulted in a total system loss of 156.9 kW. However, minimal losses were observed at location 50-59, where losses were recorded at just 49.2 kW. This indicates that the SOP connection is advantageous across all tested locations. The reduction in losses is significant when compared to the 225 kW of Ohmic losses observed without any converter connections.

Regarding voltage improvement, Table 3 shows that at location 50-59, minimum during implementation of CHIO1 was 0.9781 P.U recorded at bus 27 while the maximum is 1.0114 P.U at bus 59. Since both are within the limits, the SSSC is disabled. and maximum voltages remained within permissible limits. At location 46-15, the minimum was recorded to be 0.9272 P.U which was improved to 0.9458 P.U, nearly to the minimum permissible value.

Table 3. The result of CHIO optimization for 1SOP & SSSC

1sop_ SSSC	Bus Number			CHIO 1				CHIO 2			
With 10% dg	n	m	P(Loss)(kW)	Min Volt	Max Volt	Location-min	Location-max	Min Volt	Max Volt	Location-min	Location-max
1	50	59	49.2	0.9781	1.0114	27	59	Disable SSSC			
2	46	15	156.9	0.9272	1.0026	64	15	0.9458	1.0076	64	15
3	43	11	151.1	0.9403	1.0125	64	11	0.9582	1.0154	61	11
4	27	65	116.4	0.9474	1.0038	61	27	0.9522	1.0056	61	27



(a) (b)

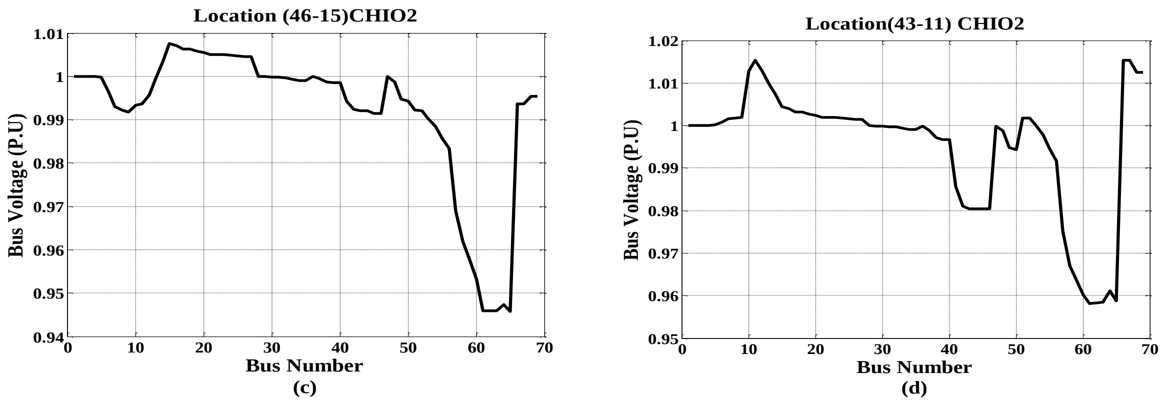


Figure 8. CHIO performance of the IEEE 69 with 10% DG capacity, (a,b) bus voltage (P.U) versus bus index for considered locations by CHIO1 and (c,d) Bus voltage (P.U) versus index at locations for CHIO2

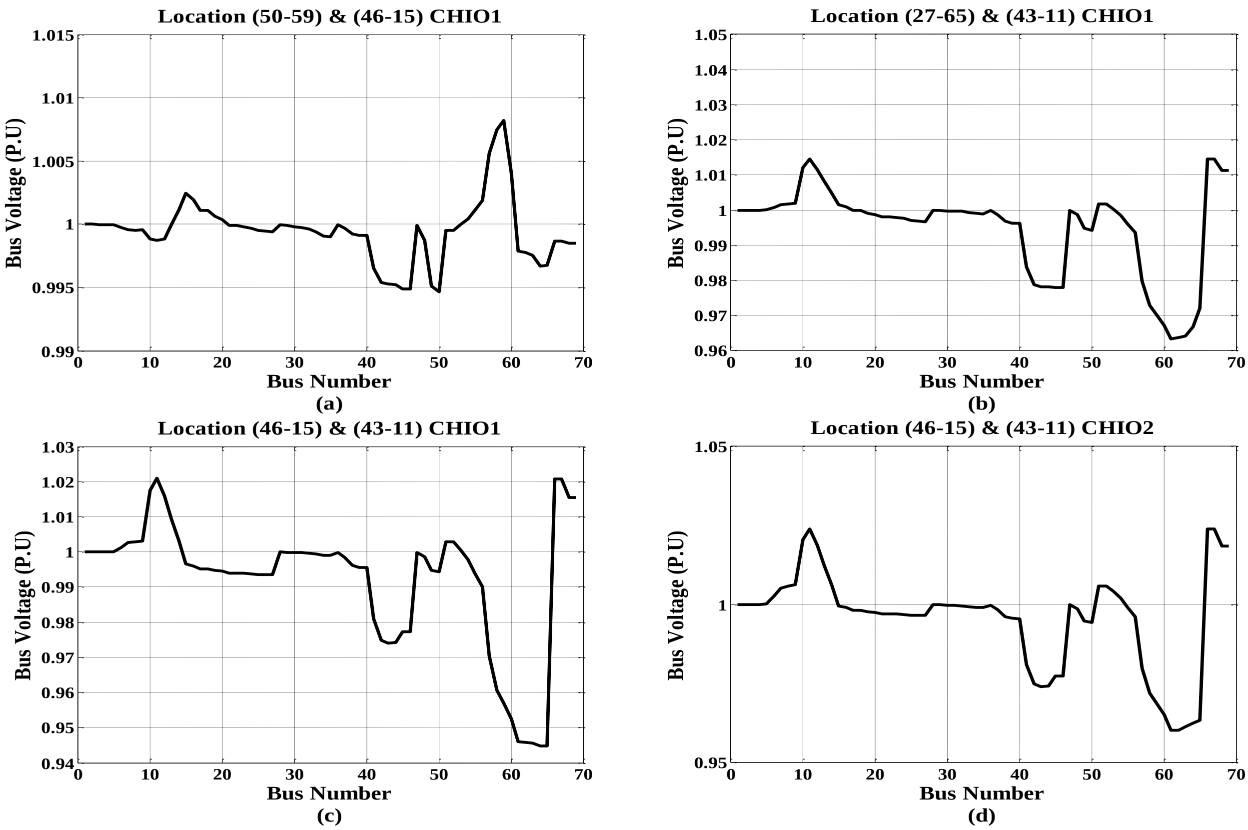


Figure 9. CHIO performance of the IEEE 69 with 10% DG capacity, (a,b,c) bus voltage (P.U) versus bus index for considered locations by CHIO1 and (d) bus voltage (P.U) versus bus number at locations for CHIO2

For buses 27-65, the voltage values ranged from a minimum of 0.9474 P.U at location 61 to a maximum of 1.0038 P.U at location 27. To address the issue of violating voltage limits, an SSSC was connected at location 61. Using the CHIO2 algorithm, the minimum 0.9522 P.U and the maximum 1.0056 P.U at bus 27. Figure 8 (a & b) shows the voltages at locations 46-15 and 43-11 based on results obtained from CHIO1. As, the CHIO2 algorithm is activated, the targeted voltages are improved as shown in Figure 8 (c & d).

Table 4 shows the results of employing two SOPs at selected locations, with a 10% DG power. At all locations, the real power losses decrease to values lower than the condition of one SOP. For an SOP at location 50-59 and 27-65 the losses are 41.2 kW. Results revel that in all but one case, the SSSC was disabled, confirming that employing more than one SOP implicitly impact voltage deviations. However, in locations 46-15 and 43-11, with CHIO1, minimum voltage was recorded to be 0.9447 P.U at location 64, hence the CHIO2 was activated. Figure 9 (a, b, c) shows voltage profile of the IEEE69 bus with SOPs at locations (50-59)/(46-15), (27-65)/(43-11) and (46-15)/(43-11) respectively, which indicates no violations of minimum or maximum limits, hence no CHIO2 action for (50-59)/(46-15) and (27-65)/(43-11). However, the CHIO2 is operative at location 46-15)/(43-11) and the P.U voltages are shown in Figure 9 (d).

B. Simulation Results with Incorporation of 30% Distributed Generation

The performance of the CHIO algorithm was also tested when raising the level of Distributed Generation using different test scenarios with SOP. The performance of the CHIO1 algorithm was evaluated based on its ability to reduce losses, and the performance of the CHIO2 algorithm was evaluated based on adjusting and improving voltage levels.

The results of the algorithm for this case are shown in Table 5, with all possible locations tested. For example, when connecting the SOP device at location 46-15 results in total system losses of 109.6 kW, However, minimal losses were observed at site 50-59, where losses were recorded at only 34.5 kW. Regarding the voltage improvement, Table 5 shows that at location 50-59 the minimum during CHIO1 execution was 0.9825 P.U registered at bus 27 while the maximum was 1.0079 P.U at bus 59. Since both are within limits, SSSC is disabled. Maximum voltages remained within permissible limits. At site 46-15 the minimum was recorded to be 0.9441 P.U. Hence, an SSSC was connected at site 61. Voltage improved to 0.9629 P.U which is within acceptable limits. Optimal reactive power was determined from CHIO2. Figure 10 (a, b, and c) shows voltages at locations 50-59, 46-15 and 43-11 based on the results obtained from CHIO1. When the CHIO2 algorithm is activated, the target voltages are optimized as shown in Figure 10 (d). Table 6 shows the results of using two SOPs at selected locations, with DG power injections of 30%. At all sites, the real energy losses fall to values below a single SOP case. For site SOPs 50-59 & 27-65, losses are 26.8 kW. The results reveal five out of the six cases considered, SSSC was disabled, confirming that the use of more than one SOP implicitly addresses any voltage deviations. However, at sites 46-15 and 43-11, with CHIO1, the minimum voltage is0.9456 P.U at position 61, thus CHIO2 was activated to be 0.9617 P.U. Figure 11 (a, b, c) shows the voltage profile of the IEEE69 bus with SOPs at locations 50-59 & 27-65 and 27-65 & 43-11 respectively, which indicates no violations of minimum or maximum limits, hence no CHIO2 action for 50-59 & 27-65 and 27-65 & 43-11. This indicates that increasing the number of SOP connections to two is beneficial in all tested sites. The reduction in losses is noticeable when compared to the reduction in losses observed when connecting a single unit of this device.

However, the CHIO2 is operative at location 46-15 & 43-11 and the voltages are shown in Figure 11 (d).

Table 4. The result of CHIO optimization for 2 SOP & SSSC

2sop_ SSSC With 10% dg	Bus Number n	Bus Number m	P(Loss)(kW)	CHIO 1 Min Volt	CHIO 1 Max Volt	CHIO 1 Location-min	CHIO 1 Location-max	CHIO 2 Min Volt	CHIO 2 Max Volt	CHIO 2 Location-min	CHIO 2 Location-max
1	50 27	59 65	41.2	0.9842	1.0128	65	59	Disable SSSC			
2	27 43	65 11	93.5	0.9634	1.0116	61	11	Disable SSSC			
3	27 46	65 15	77.1	0.9809	1.0104	61	15	Disable SSSC			
4	50 43	59 11	41.7	0.9825	1.0079	27	59	Disable SSSC			
5	50 46	59 15	37.7	0.9947	1.0082	50	59	Disable SSSC			
6	46 43	15 11	146.2	0.9447	1.0209	64	11	0.9602	1.0239	62	11

Table 5. The result of CHIO optimization for 1SOP & SSSC

1sop_ SSSC With 30% dg	Bus Number n	Bus Number m	P(Loss)(kW)	CHIO 1 Min Volt	CHIO 1 Max Volt	CHIO 1 Location-min	CHIO 1 Location-max	CHIO 2 Min Volt	CHIO 2 Max Volt	CHIO 2 Location-min	CHIO 2 Location-max
1	50	59	34.5	0.9825	1.0079	27	59	Disable SSSC			
2	46	15	109.6	0.9441	1.0026	61	15	0.9629	1.0066	61	15
3	43	11	161.1	0.9541	1.0114	61	11	Disable SSSC			
4	27	65	70	0.9595	1.0036	61	27	Disable SSSC			

Table 6. The result of CHIO optimization for 2 SOP & SSSC

2sop_ SSSC With 30% dg	Bus Number n	Bus Number m	P(Loss)(kW)	CHIO1 Min Volt	CHIO1 Max Volt	CHIO1 Location-min	CHIO1 Location-max	CHIO2 Min Volt	CHIO2 Max Volt	CHIO2 Location-min	CHIO2 Location-max
1	50 27	59 65	26.8	0.9933	1.0038	50	27	Disable SSSC			
2	27 43	65 11	60.5	0.9561	1.0010	61	27	Disable SSSC			
3	27 46	65 15	90.6	0.9655	1.0065	61	65	Disable SSSC			
4	50 43	59 11	65	0.9839	1.0073	27	59	Disable SSSC			
5	50 46	59 15	65.2	0.9911	1.0116	50	15	Disable SSSC			
6	46 43	15 11	147.7	0.9456	1.0021	61	15	0.9617	1.0055	63	15

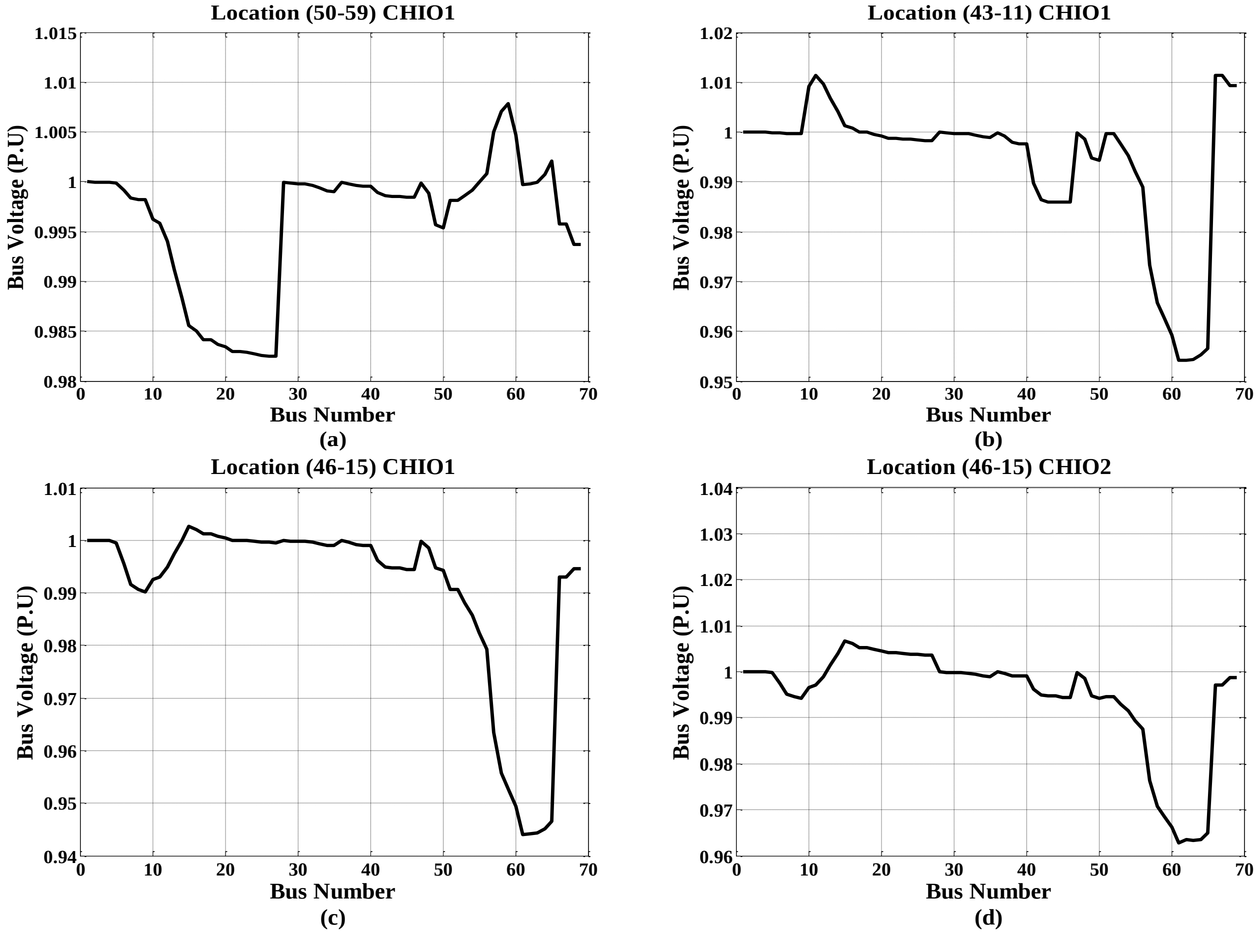


Figure 10. CHIO performance of the IEEE 69 with 10% DG capacity, (a,b,c) bus voltage (P.U) versus bus number for considered locations by CHIO1 and (d) bus voltage (P.U) versus bus number at locations for CHIO2

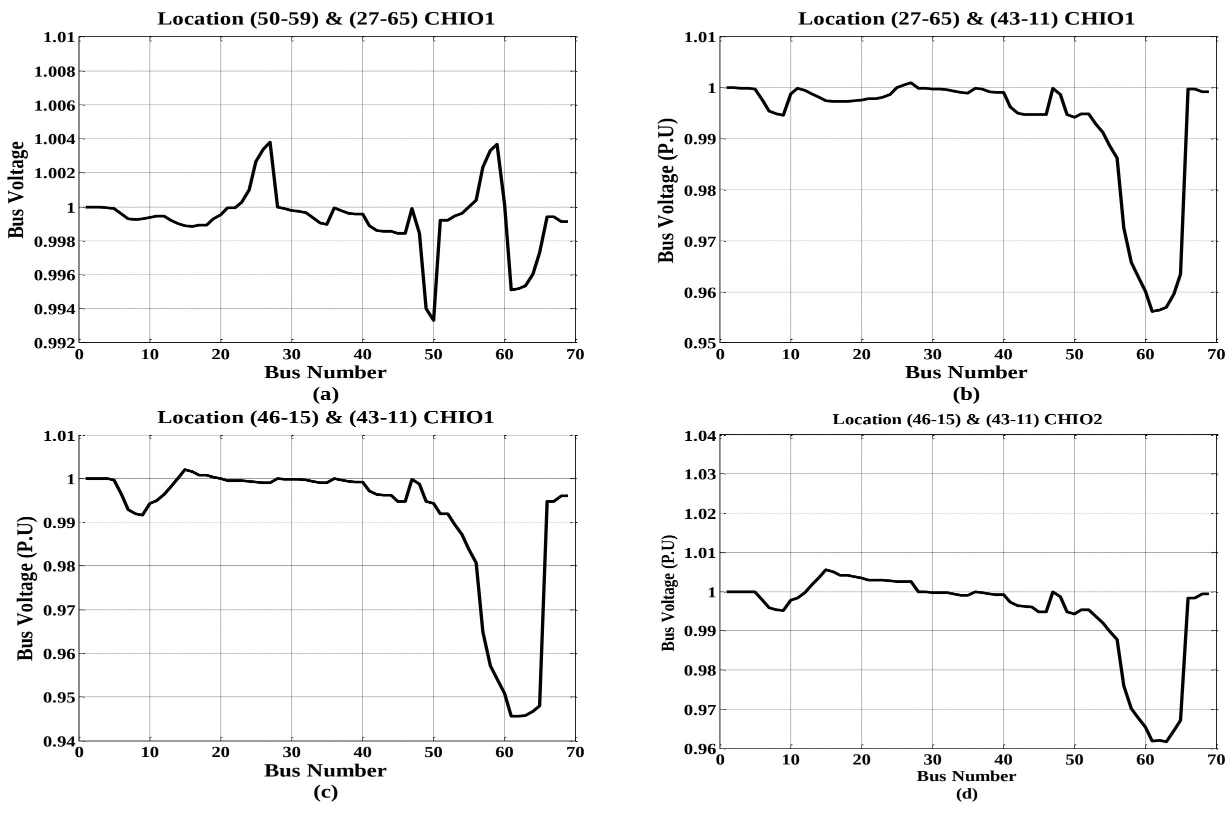


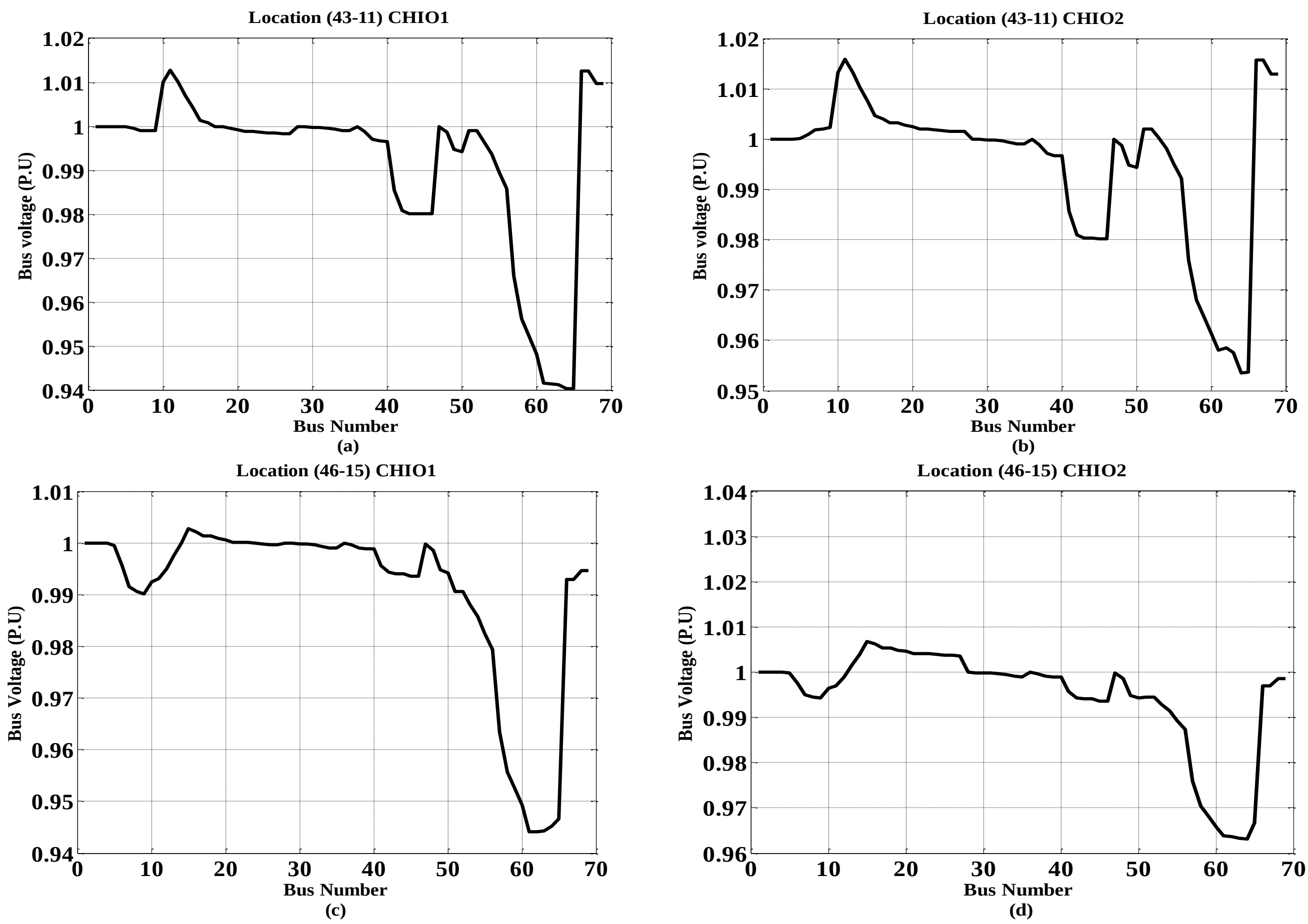
Figure 11. CHIO performance of the IEEE 69 with 30% DG capacity, (a, b, c) bus voltage (P.U) versus bus number for considered locations by CHIO1 and (d) bus voltage (P.U) versus bus number at locations for CHIO2

C. Simulation Results for Over Load Conditions

In this part of the simulation, the proposed nested CHIO algorithm is tested during abnormal conditions. These conditions include an overload at certain buses of the distribution system under study. The apparent powers at buses, 5, 10, 18, 25, and 45 were increased by 20% to simulate an overload condition. Two cases are studied in this part; one SOP and two SOPs with 10% and 30 % DG injection respectively. For the case of one SOP, locations 43-11 and 46-15 for the 10% and 30% case respectively. Two SOPs are considered at locations (50-59)/(43-11) for the 10% DG and (50-59)/(43-11)in the 30% analysis. Table 7 summarizes the results in this case. For the considered cases, all cases have CHIO2 operation this is due to the drop in voltage resulting from the overload case. In location 43-11, when there is a 10% of the Distributed Generation, the minimum voltage was recorded at 0.9256 P.U on bus 64, and the maximum was 1.0028 P.U on bus:15, when activating CHIO1, and due to violation of the minimum voltage limit, CHIO2 is activated. The voltage improved to 0.9501 P.U. For a Distributed Generation ratio of 30% and two SOPs, on site 46-15 the minimum voltage was recorded as 0.9427 P.U, and using CHIO2, the voltage reached a value of 0.9610 P.U which is acceptable. By increasing the number of SOP to two, at sites (50-59)/(43-11), the minimum voltage was 0.9231 P.U, which is significantly corrected by SSSC, optimized through CHIO2 to become 0.9764 P.U. As for sites (50-59)/(43-11), CHIO1 recorded a minimum voltage of 0.9195, and it was improved by CHIO2 to 0.9709 P.U. Thus, CHIO demonstrated its effectiveness by improving the distribution system in terms of losses and improving the voltage profile even at abnormal conditions of overloaded buses. Figure 12 show the various voltage profiles at buses throughout the IEEE69 system.

Table 7. Results of CHIO1 and CHIO2 for over load conditions

sop_ SSSC With dg	Bus Number			CHIO1				CHIO2			
	n	m	P(LOss)(kW)	Min VOLt	Max VOlt	Location-min	Location-max	Min VOlt	Max VOLt	Location-min	Location-max
1sop_ SSSC _10% dg	43	11	157.4	0.9256	1.0028	64	15	0.9501	1.0066	64	15
1sop_ SSSC _30% dg	46	15	110	0.9427	1.0028	61	15	0.9610	1.0073	61	15
2sop_ SSSC _10% dg	50 43	59 11	39.8	0.9231	1.0360	27	43	0.9764	1.0425	23	59
2 SOP _sssc_30%dg	50 43	59 11	57.9	0.9195	1.0361	27	43	0.9709	1.0361	67	43



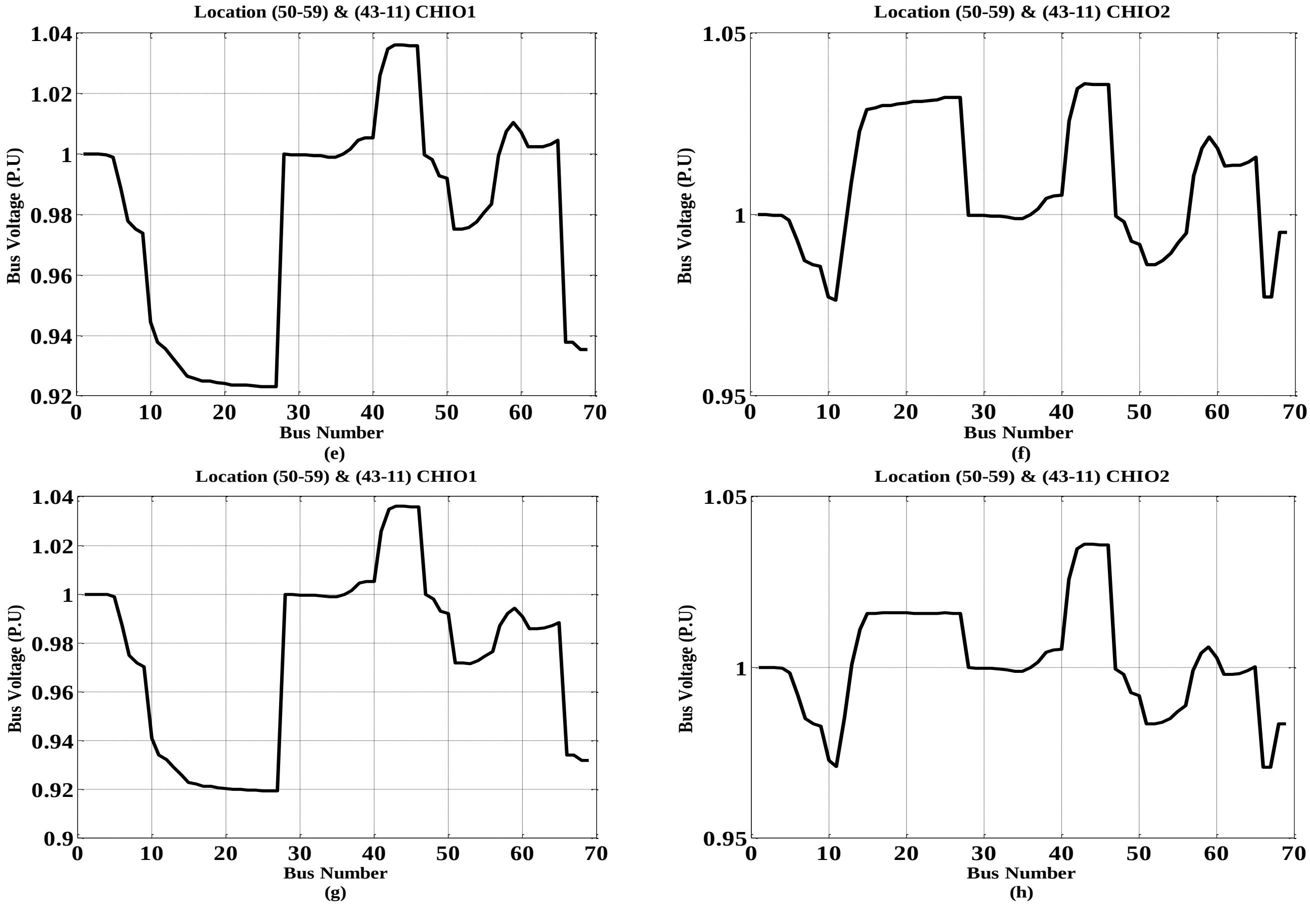


Figure 12. CHIO performance of the IEEE 69 with 10% DG capacity, (a, c, e, g) bus voltage (P.U) versus bus number for considered locations by CHIO1 and (b, d, f, h) bus voltage (P.U) versus bus number at locations for CHIO2

6. CONCLUSIONS

This study presents enhancements to the performance of a power distribution system by reducing energy losses and voltage deviations through the application of power electronic devices. Two CHIO based algorithms are employed. CHIO1 was developed to reduce active energy losses, aiming to enhance system efficiency through connection of back- back converters or SOPs. Additionally, CHIO2 produced effective solutions for maintaining voltage levels within the systems operational limits, thereby preserving system stability. Results from various test locations demonstrates a significant reduction in losses due to SOP-controlled energy flow within the radial network and accepted voltage profiles. For example, in location (27-65) the losses were reduced to 116.4 kW compared to 225 kW when no SOP is installed. At the same time, the minimum voltage is 0.9474 P.U resulting from CHIO1 and is enhanced to 0.9522 P.U when an SSSC is used which is optimized by CHIO2.

Moreover, analysis was extended to installation of two SOPs devices. Results, obtained with two DG penetration capacities, proves the feasibility and effectiveness of the suggested nested approach in fulfilling the objective for each individual algorithm. For instance, at location 50-59, energy losses were reduced from 49.2 kW for one SOP to 41.2 kW for two SOPs. It is noted that as the number of SOPs increase, the voltage deviation remains within limits for nearly all cases considered, hence SSSC become deactivated.

Furthermore, the suggested approach is tested with abnormal system conditions such as overloads on certain buses. In this case the lower limit voltage violations are much more pronounced. Hence in all cases the CHIO2 was activated to remedy these deviations.

Nested CHIO demonstrates significant optimization capabilities in reducing active losses and voltage profile improvements which subsequently enhances overall efficiency and stability of the electrical system.

Potential future work includes setting up the controls for SOP and SSSC converters for each of the considered scenarios. Moreover, implementation of these power electronic devices will be investigated based on two level and multiple level converter topologies.

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