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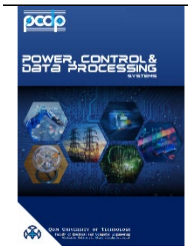

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Enhancing Power Quality in Distribution Networks Integrated with Distributed Generation Sources Using MOPSO and Soft Open Points (SOPs)

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Authors
Raham Nazavar[1]
Reza Ghanizadeh[2,*]

[1,2] Department of Electrical Engineering, Ur.C, Islamic Azad University, Urmia, Iran.

*** Correspondence**
Address: Department of Electrical Engineering, Ur.C, Islamic Azad University, Urmia, Iran.

reza.ghanizadeh@iau.ac.ir

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ABSTRACT

This paper introduces a novel approach to improving voltage profiles in a 22-bus radial distribution network by integrating distributed generation (DG) sources with advanced optimization techniques. By leveraging multi-objective particle swarm optimization (MOPSO) alongside soft open points (SOP) devices, this study effectively reduces power losses, total harmonic distortion (THD), and voltage imbalance. The proposed method not only optimizes the allocation and sizing of DG units but also strategically deploys SOP devices to enhance operational flexibility. Simulation results conducted in MATLAB environment demonstrate that the integration of SOPs significantly improves the overall voltage profile, minimizes active power losses, and substantially reduces THD levels across the network. Furthermore, the coordinated optimization approach enhances the resilience and stability of the distribution system under varying load conditions. The improvement in power quality indices, including voltage regulation and harmonic performance, highlights the practical viability and technical effectiveness of combining MOPSO optimization techniques with SOP deployment for resilient and efficient distribution network management.

Keywords: Soft open points, Multi-objective particle swarm optimization, Voltage source converters, Power loss, Voltage unbalance, Total harmonic distortion

1 Introduction

Modern distribution networks are increasingly challenged by rising load demands, high penetration of distributed generation (DG), and the imperative need for enhanced power quality. To address these issues, various strategies have been proposed, including network reconfiguration, the integration of flexible AC transmission systems (FACTS) devices at the distribution level, and the development of advanced control methods. Among these, the concept of soft open points (SOPs) has garnered significant attention in recent years. SOPs are installedsc at normally open switches (NOS) and utilize power electronic converters to enable flexible control of active and reactive power exchange between feeders. In the realm of multi-objective optimization, the multi-objective particle swarm optimization (MOPSO) method has emerged as a popular choice due to its ease of implementation, ability to generate high-quality solutions, and rapid convergence rate. The application of MOPSO for the optimal management of radial distribution networks equipped with DGs and power control devices has seen substantial growth in recent years.

The concept of SOPs was initially introduced by Siemens AG in Germany in 2001 under the name siemens multifunctional power link (SIPLINK). The term SOP was formally adopted in 2010, highlighting the transition from conventional normally open points to intelligent electronic interfaces within distribution networks. Over time, various alternative nomenclatures have been used to describe similar devices, each emphasizing specific operational aspects. These include:

a. DC-Link [1]
b. DC Interlink [2].
c. MVDC-Link [3], [4].
d. Soft Multi-State Open Point (SMOP) [5].
e. Loop Balance Controller (LBC) [6], [7].
f. Back-to-Back Active Power Controller (APC) [8].
g. Back-to-Back System [9].
h. Flexible Interconnection Device (FID) [10].
i. Partition Flexible Interconnection Converter Station (PFICS) [11].

In recent years, research has also focused on developing protection mechanisms for SOPs, reflecting their growing importance in the last four years. Additionally, some studies on benefit quantification incorporate control methods aimed at enhancing specific performance metrics, such as loss reduction, voltage improvement, and power flow balancing. However, these studies are typically categorized under “benefit quantification” rather than “control,” as their primary focus is on analyzing the advantages of SOPs in distribution networks. Conversely, research that explicitly designs control strategies, modulation schemes, or control loops for SOPs falls under the “control” category.

Despite over a decade of research on SOPs, comprehensive reviews in this field remain limited [12]. The study in [12] discusses implementation challenges and outlines modern operational standards for SOPs. Furthermore, it provides an extensive review of SOP topologies, control methods under normal and abnormal network conditions, and optimization problems in SOP-based networks.

In this paper, MOPSO method has been employed to determine the optimal configuration of a 22-bus radial network by minimizing power losses, THD and voltage imbalance. Subsequently, an SOP is strategically placed at the optimal location within the network to assess its impact on power quality indices, including THD, voltage imbalance, and losses, as well as voltage sag performance. SOPs are power electronic devices strategically installed at normally open points in electricity distribution networks, providing flexible and precise control of power and voltage. Their real-time controllability has proven highly effective in addressing the challenges faced by modern distribution networks, thereby enhancing overall system efficiency and reliability.

2 Topologies of Soft Open Points

SOPs are commonly used to interconnect different AC feeders or buses in an electricity distribution network. Fig.1 ilustrates schematic of sop installation. Their primary function is AC/AC power conversion, and based on their structure, SOPs can be classified into four topologies:

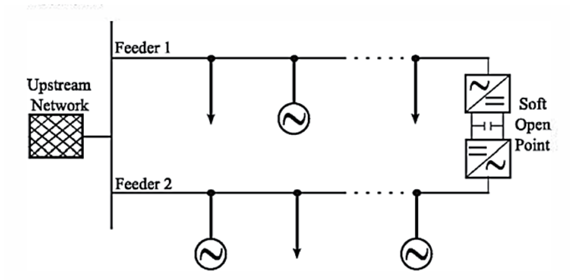

Fig.1. schematic of sop installation [12].

a. Back-to-Back Voltage Source Converters (VSCs)
b. Multi-Terminal VSCs [13].
c. Unified Power Flow Controller (UPFC) [14], [15].
d. Direct AC-to-AC Modular Multilevel Converter (MMC) [16].

In the comparison of SOP topologies, back-to-back Voltage Source Converters (VSCs), multi-terminal VSCs, and Unified Power Flow Controllers (UPFCs) are categorized as indirect AC-to-AC SOP topologies, distinguishing them from direct AC-to-AC Modular Multilevel Converters (MMCs). Unlike direct MMCs, these three indirect topologies utilize multiple VSCs to facilitate AC-to-AC conversion between interconnected feeders. This multi-VSC approach enhances the flexibility and efficiency of power transmission and distribution, enabling more effective management of electrical flows and improving the overall stability of the power system. The key advantages of using VSC-based Systems Optimization Problems include flexibility in active and reactive power control, as these VCS can independently regulate both active and reactive power. Additionally, VSC-based SOPs contribute to fault current limitation, helping to mitigate fault currents and enhance system stability. Moreover, they offer support for isolated areas and possess black-start capabilities, enabling them to supply power to isolated network segments and assist in system restoration. These advantages make VSC-based SOPs a valuable component in modern power systems, enhancing both operational flexibility and reliability.

Back-to-back VSCs and multi-terminal VSCs are connected via a common DC bus to facilitate high DC current and low DC voltage operation, reducing insulation requirements and enabling compact SOP designs. Additionally, energy storage systems can be integrated via the DC bus to enhance network flexibility [17-21].

However, these topologies differ in network isolation characteristics:

Back-to-Back and Multi-Terminal VSC-Based SOPs allow connection between asynchronous distribution networks, ensuring fault isolation between feeders via the DC bus. UPFC-Based SOPs consist of one series and one shunt converter without a DC bus, requiring synchronous networks. Consequently, faults in one feeder directly impact the interconnected feeder unless a robust control strategy is implemented.

Despite these limitations, UPFC-based SOPs provide higher power transfer efficiency at a lower cost

To enhance cost-effectiveness, transformerless topologies have been proposed for back-to-back and multi-terminal VSC-based SOPs [6], [22].

Emerging SOP Topologies

New SOP topologies continue to evolve:

a. Transformerless UPFCs – These designs aim to reduce implementation costs while maintaining power flow control capabilities [21], [22].
b. SOPs with DC/DC Converters – Future hybrid AC/DC distribution networks are expected to integrate DC-based SOP topologies to improve efficiency and flexibility.

3 The Problem of Network Reconfiguration

Distribution networks are typically configured in a radial structure to leverage their operational advantages [23-26]. However, in medium-voltage networks, tie and sectionalizing switches are integrated to enable reconfiguration based on operational requirements.

Impact of network reconfiguration altering the network configuration changes the power flow paths, resulting in modifications to line currents, node voltages, system unbalance levels, and harmonic distortion of node voltages. Additionally, reconfiguration affects the impedance of power flow paths, thereby influencing the available voltage at nodes, especially during voltage sag conditions. This variation can impact sensitive loads, making improved voltage sag performance essential to minimize system losses under such circumstances. Moreover, changes in the effective impedance of power paths and induced voltage fluctuations due to altered current distributions influence the harmonic content of node voltages. Therefore, an optimal reconfiguration strategy must address these challenges to maximize network performance while ensuring improved power quality.

The primary objectives of network reconfiguration can be formulated as follows:

- **Minimization of Power Losses**

$$P_{loss}=\sum_{m=1}^{l}\sum_{j=a}^{c}\left(V_j(p)-V_j(k)\right)I^*(m) \qquad \text{Eq.1}$$

where,

(l) = number of lines

$(V_j(p))$=voltage at node (p) for phase (j)

$(V_j(k))$=voltage at node (k) forphase (j)

$(I^*(m))$=conjugate current in line (m)

- **Minimization of Voltage Harmonic Distortion (THD)**

$$\%V_{THD,i}=\frac{V_{d,i}}{V_{rms,i}}\times 100 \qquad \text{Eq.2}$$

For the minimization of the voltage harmonic distortion, the maximum value among all the node voltage *THD*’s are minimized.

where,

$(V_{rms,i})$=voltage at node (i)

$(V_{d,i})$=distortion component of voltage at node (i)

- **Minimization of System Unbalance**

$$V_{unb,\,avg}=\frac{1}{n}\sum_{i=1}^{n}\sum_{j=a}^{c}\frac{100|V_{Neg,i}|}{|V_{Pos,i}|} \qquad \text{Eq.3}$$

where,

$(V_{Pos,i})$=positive sequence voltage at node (i)

$(V_{Neg,i})$=negative sequence voltage at node (i)

Constraints:

$$P_i+jQ_i=V_{ai}I_{ai}^*+V_{bi}I_{bi}^*+V_{ci}I_{ci}^*,\ \ i=1,2,3,\ldots,n \qquad \text{Eq.4}$$

Voltage limits:

$$V_{min}\le V_{pi}\le V_{max},\qquad p=a,b,c \qquad \text{Eq.5}$$

$i=1,2,3,\ldots,n$ Line Capacity Limits

$$I_{pl}\le I_{max,pl},\quad p=a,b,c,\quad l=1,2,3,\ldots,L \qquad \text{Eq.6}$$

Voltage unbalance limits:

$$\frac{|V_{Neg,i}|}{|V_{Pos,i}|}\le V_{unb,\,max},\quad i=1,2,3,\ldots,n \qquad \text{Eq.7}$$

THD limits:

$$V_{THD,i}\le V_{THD,\,max} \qquad \text{Eq.8}$$

3.1 Solution Method and Application of MOPSO

In fig. 2, three tie-lines, which are normally open, are highlighted. After reconfiguration, the network topology changes to the structure shown in fig. 3. Subsequently, an SOP is installed between bus 2 and bus 18, transforming the network from a radial structure into a looped configuration.

To solve the above multi-objective problem, the MOPSO algorithm Has been employed. The core idea of MOPSO is to iteratively update the position and velocity of a swarm of particles in the search space to identify the Pareto-optimal solutions. Voltage sag under different fault scenarios is calculated.

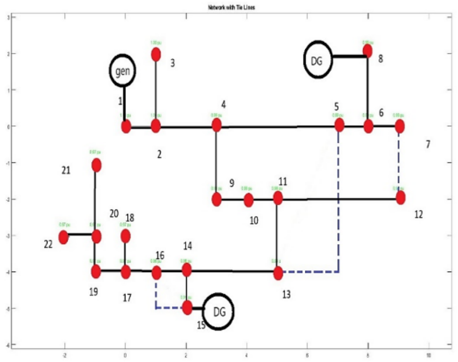

Fig.2. before reconfiguration(blue lines are tie lines)

Finally, the objective function vector is obtained. Following classical PSO rules, the velocities and positions of the particles are updated based on the current Pareto-optimal solutions stored in the archive and the local best positions of each individual particle. To ensure the maintenance of a diverse Pareto front, a non-overlapping network structure and speed limits on switch state changes are implemented. Additionally, for systems optimization problems, constraints on rated capacity and installation feasibility are enforced. The algorithm continues iterating until a stopping criterion is met, such as reaching a predefined number of generations or observing no significant improvement in the solutions. fig. 3 illustrates network topology after reconfiguration.

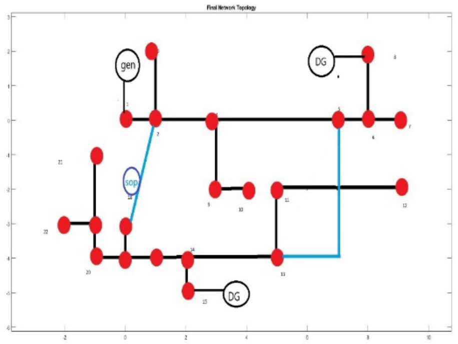

Fig.3. after adding SOP and reconfiguration

4 Solution of the problem

Solving the above problems requires addressing the power flow problem, harmonic flow analysis, and voltage sag assessment. An optimization technique is essential to search for the optimum network configuration, while the performance of the generated configuration is evaluated using the aforementioned analyses.

In this study, the MOPSO algorithm is employed alongside the Newton-Raphson power flow method to optimize and reconfigure the network. MOPSO simultaneously explores multiple configurations, ensuring a globally optimized solution. The proposed methodology effectively enhances power quality indices by strategically placing SOPs and refining the distribution network topology. The following sections briefly discuss the applied analysis techniques. The detailed procedure is shown in the form of a flowchart in fig.4.

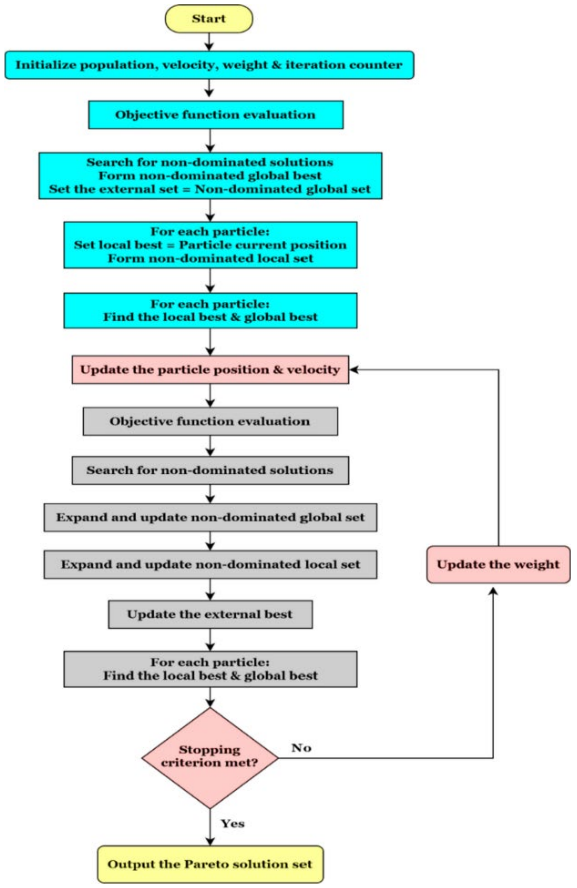

Fig.4. MOPSO optimization Flowchart

5 Simulation and results

In this section, a radial 22-bus network is analyzed using the Newton-Raphson power flow method in MATLAB. Initially, the base case of the network is considered, and key indices including voltage sag, THD, voltage unbalance, and power loss were calculated. The results indicate that, while the network generally maintains acceptable voltage stability under the initial configuration, further reductions in power losses and improvements in power quality indices specifically, lower THD and reduced voltage unbalance remain as primary objectives.

Next, a multi-objective optimization using the MOPSO method was performed to determine optimal control parameters (e.g., compensator placement and sizing, control device settings, etc.). The optimized configuration led to considerable reductions in THD, voltage unbalance, and power losses compared to the base case. Consequently, the power quality of the network improved noticeably.

To further enhance these indices, a SOP was introduced into the system. The SOP was connected to buses 2 and 18 to facilitate more effective load sharing, voltage profile regulation, and reactive power control. The results show that by integrating the SOP, voltage sag increased slightly, whereas other indices such as power loss, THD, and voltage unbalance decreased. Although this minor increase in voltage sag is noted, the significant reductions in power losses and the improvement in power quality offer substantial benefits to the network.

Following the MOPSO-based optimization, network reconfiguration was carried out, modifying the network topology to achieve more optimal power distribution. Comparing the performance before and after reconfiguration reveals further improvements,fig.5 illustrates power loss comprasion before and after Sop and optimization including additional power loss reduction and an enhanced voltage profile. In fig. 6, we compare the THD before reconfiguration, after reconfiguration, and following the installation of SOP. Additionally, Figure 7 illustrates the comparison of voltage unbalance before reconfiguration, after reconfiguration, and after the installation of SOP. Overall, employing the combination of multi-objective optimization via MOPSO, SOP integration, and network reconfiguration led to improved operation and performance of the 22-bus radial network. Numerical results, including voltage profiles and values of THD, voltage unbalance, and power loss, confirm the effectiveness of the proposed methodology in enhancing network operation.

6 Conclusion

The impact of network reconfiguration and SOP installation on various power quality issues, such as harmonic distortion, power loss, and voltage unbalance, has been investigated. this study employs MOPSO to achieve an optimized reconfiguration of the network. The MOPSO-based reconfiguration is formulated as a multi-objective optimization problem, incorporating power loss, harmonic distortion, voltage unbalance, and voltage sag into the objective function. The results indicate that network reconfiguration significantly improves power quality in addition to reducing power losses. Furthermore, the integration of SOPs in the distribution system transforms the network from a radial to a looped configuration, providing additional flexibility and enhancing the overall system stability. The study also reveals that the effectiveness of network reconfiguration depends on the presence of DG and reactive power compensation sources. When DG units are present, reconfiguration alone may have a reduced impact; however, an integrated approach considering DG placement, and reconfiguration simultaneously could maximize the overall network performance. By strategically optimizing SOP locations alongside network topology adjustments, further enhancements in voltage profile, power loss reduction, and harmonic mitigation can be achieved. Thus, network reconfiguration combined with SOP installation serves as a viable solution for enhancing power quality and optimizing distribution system operation, ensuring a more stable, reliable, and efficient power network.

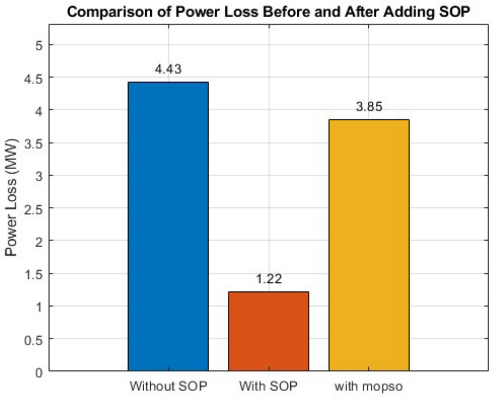

Fig.5. Comparison of Power LOSS before and after Sop and optimization

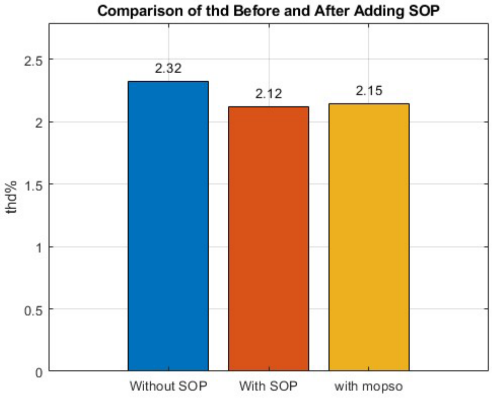

Fig.6. Comparison of THD before and after Sop and optimization

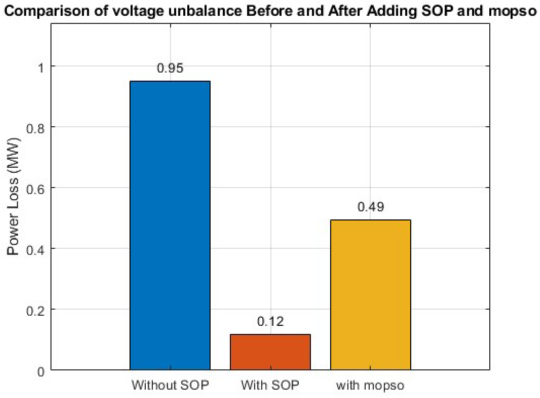

Fig.7. Comparison of voltage unbalance before and after Sop and optimization.

Disclosure of Potential Conflicts of Interest

The Authors declare that there is no conflict of interest.

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