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# Utilizing Soft Open Points for Effective Voltage Management in Multi-Microgrid Distribution Systems

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**Abstract:** To enhance stability and reliability, multi-microgrid systems have been developed as replacements for conventional distribution networks. Traditionally, switches have been used to interconnect these microgrids, but this approach often results in uncoordinated power sharing, leading to economic inefficiencies and technical challenges such as voltage fluctuations, delay in response, etc. This research, in turn, introduces a novel multi-microgrid system that utilizes advanced electronic devices known as soft open points (SOPs) to enable effective voltage management and controllable power sharing between microgrids while also providing reactive power support. To account for uncertainties in the system, the two-point estimate method (2PEM) is applied. Simulation results on an IEEE 33-bus network with high renewable energy penetration reveal that the proposed SOP-based system significantly outperforms the traditional switch-based method, with a minimum voltage level of 0.98 p.u., compared to 0.93 p.u. in the conventional approach. These findings demonstrate the advantages of using SOPs for voltage management in forming multi-microgrid systems.

**Keywords:** multi-microgrid formation; soft open points; two-point estimation method; renewable energy; reactive power compensation



**Citation:** Azizivahed, A.; Gholami, K.; Arefi, A.; Arif, M.T.; Haque, M.E. Utilizing Soft Open Points for Effective Voltage Management in Multi-Microgrid Distribution Systems. *Electricity* **2024**, *5*, 1008–1021. https://doi.org/10.3390/electricity5040051

Academic Editors: Murilo E.C. Bento and Hugo Morais

Received: 10 September 2024
Revised: 25 November 2024
Accepted: 5 December 2024
Published: 6 December 2024



## 1. Introduction

Advancements in distribution power system operations have been driven by the increasing integration of Distributed Energy Resources (DERs), including batteries and renewable energy sources (RESs) [1–4]. These grids have become increasingly complicated as a result of the introduction of electronic-based technology. Power electronic devices designed for distribution grids have advanced recently with the introduction of soft open points (SOPs) [5]. The buses in distribution networks are often connected by two switches: closed sectionalizing switches and open tie switches. Because the tie switches are open, no electricity passes among some feeders. However, by substituting tie switches, SOPs can connect several buses and allow advanced functionality such as voltage profile enhancement, active power transferring, and reactive power injection/absorption [6]. However, the management of advanced devices like SOPs adds complexity to the distribution grids with high penetration of DERs. As a result, this research investigates suitable methods of management for these sophisticated devices in the dynamic setting of emerging multi-microgrid networks.

Given the detailed explanation, SOPs are sophisticated devices requiring customized energy management and planning strategies to optimize their benefits, enhance the performance of distribution grids, and minimize costs [7]. The key advantage of SOPs is their rapid response across various conditions, which plays a crucial role in system protection [8]. In more detail, SOPs respond in milliseconds, offering significant speed advantages over electromechanical switches that respond in hundreds of milliseconds. This makes SOPs ideal for network protection. However, if the system does not require such rapid response, the benefits of SOPs may be limited compared to remote control switching [8]. Researchers have investigated many techniques for properly managing SOPs so far. In terms of planning SOPs at the distribution level, researchers in [9] utilized particle swarm optimization for SOP allocation and network reconfiguration. Similarly, in [10], a group of researchers used the growth optimizing method to place both switches and SOPs in order to decrease power loss. These studies highlight that joint planning of SOP and switch placement results in greater power loss reduction and better voltage profile improvements. Additionally, reference [11] explored SOPs for load balancing of distribution networks. A strategy in [12] combined network reconfiguration and SOP integration to boost hosting capacity and cut power loss.

Despite the contributions of the mentioned studies, they mainly address SOP planning and do not investigate the operational schemes of SOPs with other DERs. Towards this end, SOPs were operated in the presence of other DERs for higher energy savings [13]. A study in [14] developed semidefinite programming to manage SOPs in unbalanced grids with high renewable energy penetration for minimizing three objective functions. Additionally, the battery and SOPs were also planned in active distribution networks for unbalances from sources [15]. Moreover, reference [16] demonstrated maintaining network voltage within permissible limits by simultaneous scheduling of OLTC and SOP. An evaluation of SOPs' impact on improving distribution grid typhoon resistance was conducted [17]. The improvement of voltage stability indices in distribution networks using SOPs was also explored through heuristic algorithms for both balanced and unbalanced distribution networks [18]. Power quality enhancement by simultaneous allocation of SOPs and tie switches was investigated [19,20].

In power systems, uncertainties in factors like generation and load can have a considerable impact on system operation and performance. To manage these uncertainties effectively, it is essential to implement suitable uncertainty modeling techniques. Various studies have investigated stochastic modeling methods to address uncertainties. For instance, stochastic approaches have been employed [21–23], but these methods often require significant computational complexity, which limits their practicality for real-time applications. However, the two-point estimation method (2PEM) [24,25] provides an efficient alternative by simplifying the modeling of uncertain variables using two deterministic values—one above and one below the mean. This method offers a good balance between computational efficiency and accuracy, making it a valuable tool for power system analysis, especially in situations where real-time implementation is crucial.

Based on the cited references, extensive research has been conducted on SOPs in various applications. However, the integration of SOPs to connect multiple microgrids into a unified multi-microgrid distribution system requires further exploration. To address this research gap, this paper presents a unique energy management technique for distribution grid service providers to interface microgrids with SOPs. Given the presence of uncertain parameters in the proposed framework, it is essential to evaluate their impact on the model. This study utilizes the two-point estimation method (2PEM) to effectively account for uncertainties in the multi-microgrid formation process. Additionally, the formulation of SOPs is designed in a convex manner, enabling the use of advanced solvers such as CPLEX and GUROBI. This convex formulation ensures the attainment of feasible global solutions with minimal computational burden. The outline of the contributions made in this study:

- Precise SOP Modeling: Developed an accurate model for soft open points (SOPs) to effectively integrate them into multi-microgrid systems.
- Convex Formulation: Created a convex formulation to enhance the use of advanced solvers, improving the computational efficiency and solution accuracy.
- Uncertainty Modeling: Employed the two-point estimation method (2PEM) to effectively model uncertainties in the system.

- Evaluation and case study: Validated the proposed approach through rigorous testing on an IEEE test grid, providing a detailed analysis of its performance.

The remainder of this article is divided into five parts: Section 2 describes the problem formulation. Section 3 discusses how uncertainties are managed using the two-point estimate method (2PEM). Section 4 covers the model's outcomes and findings. Finally, Section 5 summarizes the study's significant results.

## 2. Problem Formulation

In this section, the problem formulation is presented, including the objective function and the corresponding constraints necessary to ensure optimal operation of the system. These elements are crucial for achieving an efficient and safe operation of the distribution network, incorporating factors such as power balance, and the operational limits of distributed energy sources.

### 2.1. Objective Function

For optimal power system operation, objective functions (OF) are defined to achieve specific goals, such as minimizing power losses, voltage fluctuations, and operational costs. In this study, the primary focus is on minimizing voltage deviation across the network, which is crucial for maintaining voltage stability. By reducing voltage variations, the system ensures that voltage levels remain within acceptable limits, thereby preventing equipment damage, enhancing system efficiency, and ensuring the overall stability of the grid.

$$OF = \sum_{n}\sum_{t}\left|1 - V_b^{n,t}\right|, \forall t \in \Omega_{time}, \forall n \in \Omega_{bus} \quad (1)$$

$OF$ stands for the objective function. $V_b^{n,t}$ represents the voltage at the buses. $\Omega_{time}$ and $\Omega_{bus}$ are the sets of times and buses, respectively. The indices $n$ and $t$ correspond to the bus and time, respectively.

### 2.2. Considered Constraints

Constraints that are intended to guarantee network dependability and safety control every optimization task. In this investigation, we include distribution networks, smart Photovoltaic converters, and SOPs as constraints [26–29]. To visually demonstrate these constraints and their integration within the power system, Figure 1 provides a schematic of a sample grid. The diagram illustrates the connections between various DERs, such as smart PV converters, and SOPs, highlighting how these components interact within the distribution network. Equations (2) and (3), respectively, ensure that the balances of active and reactive power are maintained. Formula (4) determines the voltage at each bus in the grid. The generation and demand of the buses are determined by using Ohm's law in Equations (5) and (6). Equation (7) guarantees that bus voltages stay within allowable bounds. Constraint (8) verifies the grid branches' thermal capability. Equations (9) and (10) model the range of reactive power injection and absorption by smart PV inverters. Constrained by Constraint (11), dispatchable generators (DG) generation is scheduled within acceptable bounds, with ramp-rate limitations delineated in (12). Constraints (13) and (14), respectively, are used to model the power balances of SOP converters. The boundaries for the SOPs are set by Constraints (15) and (16). The SOP converter's internal power losses can be computed using Equations (17) and (18). Constraints (19) and (20) keep the reactive power produced by SOP converters within allowable bounds. Eventually, SOP converters must work within the limitations of Constraints (21) and (22).

$$P_{net}^{n,t} = \sum_{m \in \Omega_{par_n}} P_{flow}^{mn,t} - \sum_{k \in \Omega_{chil_n}} P_{flow}^{nk,t}, \forall t \in \Omega_{time}, \forall n \in \Omega_{bus} \quad (2)$$

$$Q_{net}^{n,t} = \sum_{m \in \Omega_{par_n}} Q_{flow}^{mn,t} - \sum_{k \in \Omega_{chil_n}} Q_{flow}^{nk,t}, \forall t \in \Omega_{time}, \forall n \in \Omega_{bus} \quad (3)$$

$$V_b^{n,t} \approx V_b^{m,t} - \frac{\left(R_L^{mn,t} P_{flow}^{mn,t} + X_L^{mn,t} Q_{flow}^{mn,t}\right)}{V_{s_0}}, \forall t \in \Omega_{time}, \forall n, m \tag{4}$$

$\in \Omega_{bus}, s_0$ represents the root substation of Bus $n$ and $m$.

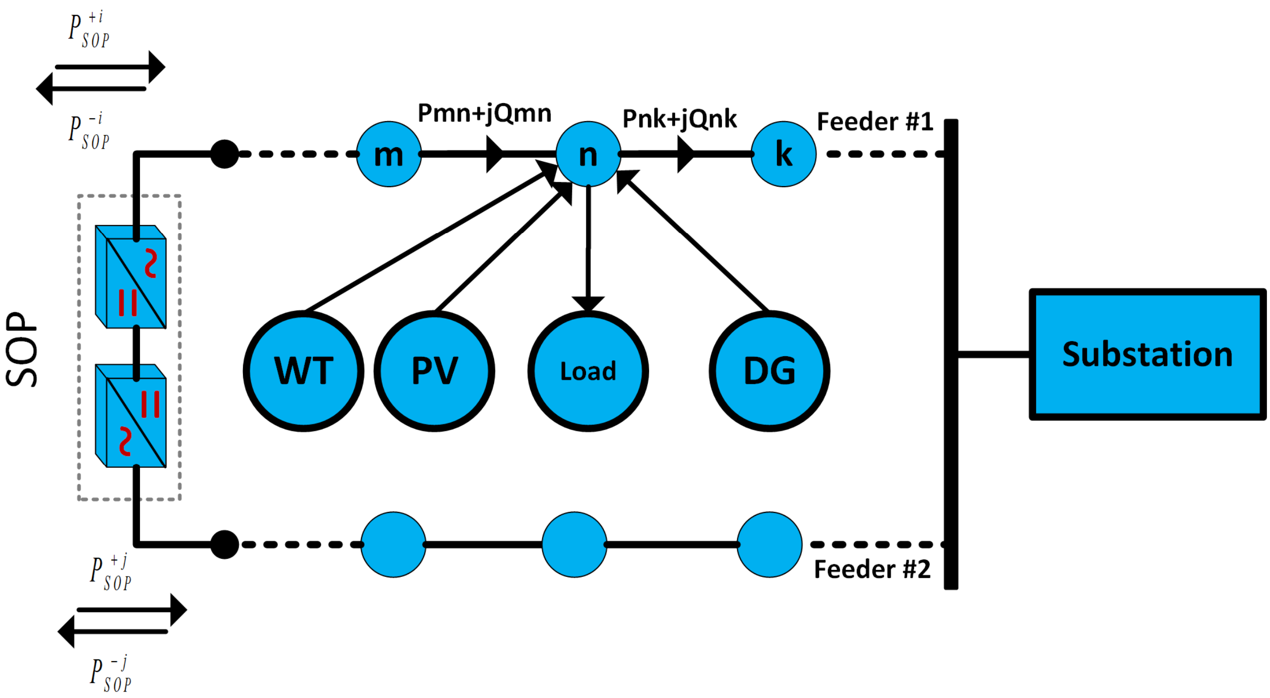


**Figure 1.** The SOP configuration on a sample network.

If Bus $n$ is linked to DG $d$, PV $p$, WT $w$ and SOP, $n \in \Omega_{bus}, d \in \Omega_{dg}, p \in \Omega_{PV}, w \in \Omega_{WT}$

$$P_{net}^{n,t} = P_L^{n,t} - P_{SOP}^{n,t} - P_{DG}^{d,t} - P_{PV}^{p,t} - P_{WT}^{w,t}, \quad \forall t \in \Omega_{time} \tag{5}$$

$$Q_{net}^{n,t} = Q_L^{n,t} - Q_{SOP}^{n,t} - Q_{DG}^{d,t} - Q_{PV}^{p,t} - Q_{WT}^{w,t}, \quad \forall t \in \Omega_{time} \tag{6}$$

$$V_b^{min} \le V_b^{n,t} \le V_b^{max}, \forall t \in \Omega_{time}, \forall n \in \Omega_{bus} \tag{7}$$

$$\left(P_{flow}^{mn,t}\right)^2 + \left(Q_{flow}^{mn,t}\right)^2 \le \left(S_{flow}^{max}\right)^2, \forall t \in \Omega_{time}, \forall n, m \in \Omega_{bus} \tag{8}$$

$$Q_{PV}^{p,t} \le \sqrt{\left(S_{PV}^{p}\right)^2 - \left(P_{PV}^{p,t}\right)^2}, \forall t \in \Omega_{time}, \forall p \in \Omega_{PV} \tag{9}$$

$$Q_{PV}^{p,t} \ge -\sqrt{\left(S_{PV}^{p}\right)^2 - \left(P_{PV}^{p,t}\right)^2}, \forall t \in \Omega_{time}, \forall p \in \Omega_{PV} \tag{10}$$

$$P_{DG}^{d,min} \le P_{DG}^{d,t} \le P_{DG}^{d,max}, \forall t \in \Omega_{time}, \forall d \in \Omega_{dg} \tag{11}$$

$$R_{DG}^{d,down} \le P_{DG}^{d,t} - P_{DG}^{d,t-1} \le R_{DG}^{d,upper}, \forall t \in \Omega_{time}, \forall d \in \Omega_{dg} \tag{12}$$

For SOP $e$ connecting Bus $i$ and $j$, $i, j \in \Omega_{bus}, e \in \Omega_{esop}$

$$P_{SOP}^{i,t} + P_{SOP}^{j,t} + P_{SOP,loss}^{i,t} + P_{SOP,loss}^{j,t} = 0 \tag{13}$$

$$P_{SOP}^{i,t} = P_{SOP}^{+i,t} - P_{SOP}^{-i,t} and P_{SOP}^{j,t} = P_{SOP}^{+j,t} - P_{SOP}^{-j,t} \tag{14}$$

$$\begin{cases} 0 \le P_{SOP}^{+i,t} \le B^{i,t} P_{SOP}^{max} \\ 0 \le P_{SOP}^{-i,t} \le \left(1 - B^{i,t}\right) P_{SOP}^{max} \end{cases} \tag{15}$$

$$\begin{cases} 0 \le P_{SOP}^{+j,t} \le \left(1 - B^{j,t}\right) P_{SOP}^{max} \\ 0 \le P_{SOP}^{-j,t} \le B^{j,t} P_{SOP}^{max} \end{cases} \tag{16}$$

$$P_{SOP,loss}^{i,t} = \begin{cases} A_{SOP}^{i} \sqrt{\left(P_{SOP}^{i,t}\right)^2 + \left(Q_{SOP}^{i,t}\right)^2}, & if\ B^{i,t} = 1 \\ -A_{SOP}^{i} \sqrt{\left(P_{SOP}^{i,t}\right)^2 + \left(Q_{SOP}^{i,t}\right)^2}, & if\ B^{i,t} = 0 \end{cases} \tag{17}$$

$$P_{SOP,loss}^{j,t} = \begin{cases} A_{SOP}^{j} \sqrt{\left(P_{SOP}^{j,t}\right)^2 + \left(Q_{SOP}^{j,t}\right)^2}, & if\ B^{j,t} = 0 \\ -A_{SOP}^{j} \sqrt{\left(P_{SOP}^{j,t}\right)^2 + \left(Q_{SOP}^{j,t}\right)^2}, & if\ B^{j,t} = 1 \end{cases} \tag{18}$$

$$Q_{SOP}^{i,min} \le Q_{SOP}^{i,t} \le Q_{SOP}^{i,max}, \forall t \in \Omega_{time} \tag{19}$$

$$Q_{SOP}^{j,min} \le Q_{SOP}^{j,t} \le Q_{SOP}^{j,max}, \forall t \in \Omega_{time} \tag{20}$$

$$\sqrt{\left(P_{SOP}^{i,t}\right)^2 + \left(Q_{SOP}^{i,t}\right)^2} \le S_{SOP}^{i,max}, \forall t \in \Omega_{time} \tag{21}$$

$$\sqrt{\left(P_{SOP}^{j,t}\right)^2 + \left(Q_{SOP}^{j,t}\right)^2} \le S_{SOP}^{j,max}, \forall t \in \Omega_{time} \tag{22}$$

Equations (17) and (18) among the previously listed expressions are nonlinear and require conversion to a typical linear form. The first step in doing this is converting them in the manner described below:

$$|P_{SOP,loss}^{i,t}| = P_{SOP,loss}^{i,t} / \left(2B^{i,t} - 1\right) = A_{SOP}^{i} \sqrt{\left(P_{SOP}^{i,t}\right)^2 + \left(Q_{SOP}^{i,t}\right)^2} \tag{23}$$

To make the given equation convex:

$$|P_{SOP,loss}^{i,t}| = P_{SOP,loss}^{i,t} / \left(2B^{i,t} - 1\right) \ge A_{SOP}^{i} \sqrt{\left(P_{SOP}^{i,t}\right)^2 + \left(Q_{SOP}^{i,t}\right)^2} \tag{24}$$

Through the following expression,

$$\mathcal{P}^{i,t} = P_{SOP,loss}^{i,t} / \left(2B^{i,t} - 1\right) \tag{25}$$

we obtain $\mathcal{P}^{i,t} \ge A_{SOP}^{i} \sqrt{\left(P_{SOP}^{i,t}\right)^2 + \left(Q_{SOP}^{i,t}\right)^2}$. After reformatting, the following equation is accomplished:

$$\frac{P_{SOP,loss}^{i,t} + \mathcal{P}^{i,t}}{2} = B^{i,t} \mathcal{P}^{i,t} \tag{26}$$

As a result, the following expressions can be derived from it.

$$\left(B^{i,t} - 1\right) \times \mathcal{M} \le \frac{P_{SOP,loss}^{i,t} - \mathcal{P}^{i,t}}{2} \le \left(1 - B^{i,t}\right) \times \mathcal{M} \tag{27}$$

$$-B^{i,t} \times \mathcal{M} \le \frac{P_{SOP,loss}^{i,t} + \mathcal{P}^{i,t}}{2} \le B^{i,t} \times \mathcal{M} \tag{28}$$

The sets $\Omega_{par_n}$ and $\Omega_{chil_n}$ contain the parent and child buses of bus $n$, respectively. $\Omega_{bus}$ includes all buses in the network. $\Omega_{dg}$ refers to distributed generators (DGs), whereas $\Omega_{PV}$ includes photovoltaic (PV) inverters. The $\Omega_{time}$ includes all the considered time periods. The set $\Omega_{WT}$ represents the collection of wind turbines, where w serves as the index for wind turbine. The network buses are denoted by $n, m, i, j$. Diesel generators are denoted by $d$, photovoltaic inverters by $p$, and time as $t$.

$R_L^{mn,t}$ represents the resistance of line $mn$, whereas $X_L^{mn,t}$ represents the reactance of line $mn$. $P_L^{n,t}$ is the active power demand at bus $n$, whereas $Q_L^{n,t}$ is the reactive power demand at bus $n$. $S_{flow}^{max}$ represents the apparent power that can pass through the branches. $P_{DG}^{d,min}$ and $P_{DG}^{d,max}$ represent the lower and upper limits of DG $d$, respectively. $V_b^{min}$ and $V_b^{max}$ represent the network's permissible voltage limitations. $R_{DG}^{d,down}$ represents $d^{\text{th}}$ DG ramp-down rate, whereas $R_{DG}^{d,upper}$ represents its ramp-up rate. $e^{\text{th}}$ SOP lowest and maximum reactive power are $Q_{SOP}^{i,min}$ and $Q_{SOP}^{i,max}$. $S_{PV}^{p}$ represents the rating of the smart PV inverter, whereas $S_{SOP}^{i,max}$ is the rated apparent power of the converter in SOP. $\mathcal{M}$ is a large constant number.

The active power sent across line $mn$ is shown by $P_{flow}^{mn,t}$, and the reactive power on the same line is indicated by $Q_{flow}^{mn,t}$. The voltage level at bus $n$ is represented by $V_b^{n,t}$. $P_{DG}^{d,t}$ and $Q_{DG}^{d,t}$, indicate the amount of active and reactive power production from DG $d$, respectively. The terms $P_{PV}^{p,t}$ and $Q_{PV}^{p,t}$ for PV inverters denote the reactive and active power produced by PV $p$. At bus $n$, the entire active power, including supply and demand, is represented by $P_{net}^{n,t}$, while the reactive power is represented by $Q_{net}^{n,t}$. $V_s$ represents the voltage at substation $s$. $P_{WT}^{w,t}$ and $Q_{WT}^{w,t}$ are, respectively, the active and reactive power provided by wind turbine w at time t. The real power delivered by SOP at bus $i$ is indicated by $P_{SOP}^{i,t}$, whereas $P_{SOP,loss}^{i,t}$ represents SOP's power loss at bus $i$. $Q_{SOP}^{i,t}$ refers to the reactive power injected by SOP at bus $i$. Power flows from the SOP node to bus $i$ are represented by $P_{SOP}^{+i,t}$, while those from bus $i$ to the SOP node are represented by $P_{SOP}^{-i,t}$. The variables $B^{i,t}$ is binary variable, $A_{SOP}^{i}$ is the loss coefficient for the SOP at bus $i$, and $OF$ is the objective function value.

## 3. Two-Point Estimation Method (2PEM)

The two-point estimation method (2PEM) is employed to evaluate the impact of uncertain parameters, specifically the uncertainties in load and renewable energy generation. These uncertainties are critical in energy systems modeling, as both load demand and renewable energy sources (such as solar and wind) are highly variable. The primary reason for choosing 2PEM over methods like Monte Carlo Simulation (MCS) is its low computational burden and simplicity of implementation. Unlike MCS, 2PEM does not require multiple iterations for convergence, making it particularly efficient where computational burden or time is important. However, it is important to note that 2PEM has some limitations: it does not account for correlations between uncertainties, and it cannot produce results in the form of a histogram. The method is by defining two points on either side of the mean for each uncertain parameter, thus providing a simplified approach to modeling the uncertainty. The following algorithm outlines the application of 2PEM in this context [25,30,31]. Let us elaborate on the procedure of this technique as follows:

Step1: Enter the total number of uncertain variables.

Step2: Some parameters must be specified as: $\mathrm{E}(\mathrm{Y}) = 0$, $\mathrm{E}\left(\mathrm{Y}^2\right) = 0$ and $\mathrm{E}\left(\mathrm{Y}^3\right) = 0$;

Step3: Define $k$ as a counter and set its initial step to 1.

Step4: Compute $\varepsilon_{k,1}$, $\varepsilon_{k,2}$, $p_{k,1}$, and $p_{k,2}$ using the subsequent formula.

$$\varepsilon_{k,1} = \frac{\lambda_{k,3}}{2} + \sqrt{n + \left(\frac{\lambda_{k,3}}{2}\right)^2}\ ,\ \ k = 1,2,3,\ldots,n \tag{29}$$

$$\varepsilon_{k,2} = \frac{\lambda_{k,3}}{2} - \sqrt{n + \left(\frac{\lambda_{k,3}}{2}\right)^2}\ ,\ \ k = 1,2,3,\ldots,n \tag{30}$$

$$p_{k,1} = -\frac{\varepsilon_{k,2}}{n\xi_k} \tag{31}$$

$$p_{k,2} = \frac{\varepsilon_{k,1}}{n\xi_k} \tag{32}$$

$$\xi_k = 2\sqrt{n + \left(\frac{\leftthreetimes_{k,3}}{2}\right)^2}\ , k = 1, 2, 3, \ldots, n \tag{33}$$

$$\sum_{k=1}^{n} p_{k,1} + p_{k,2} = 1 \tag{34}$$

$$\leftthreetimes_{k,3} = M_3(\acute{x_k})/\sigma_{x,k}^3 \tag{35}$$

Step5: The concentration values on either side of the uncertain variables, $x_{k,1}$ and $x_{k,2}$, are calculated by:

$$x_{k,1} = \mu_{x,k} + \varepsilon_{k,1}\sigma_{x,k} \tag{36}$$

$$x_{k,2} = \mu_{x,k} + \varepsilon_{k,2}\sigma_{x,k} \tag{37}$$

Step6: Address the problem using the determined concentrations and subsequently compute the mean and variance.

From the above equations, $\varepsilon_{k,1}$ and $\varepsilon_{k,2}$ define the positions of the concentrations, whereas $p_{k,1}$ and $p_{k,2}$ reflect their associated probabilities. The uncertain variables' standard deviations and mean values are denoted by $\sigma_{x,k}$ and $\mu_{x,k}$, respectively. The coefficient of skewness is given by $\leftthreetimes_{k,3}$, and $M_3(x_k)$ represents the third moment of the uncertain parameter $x_k$. Both sides of the uncertain variables' concentrations are indicated by $x_{k,1}$ and $x_{k,2}$. The flowchart of the 2PEM is shown in Figure 2.

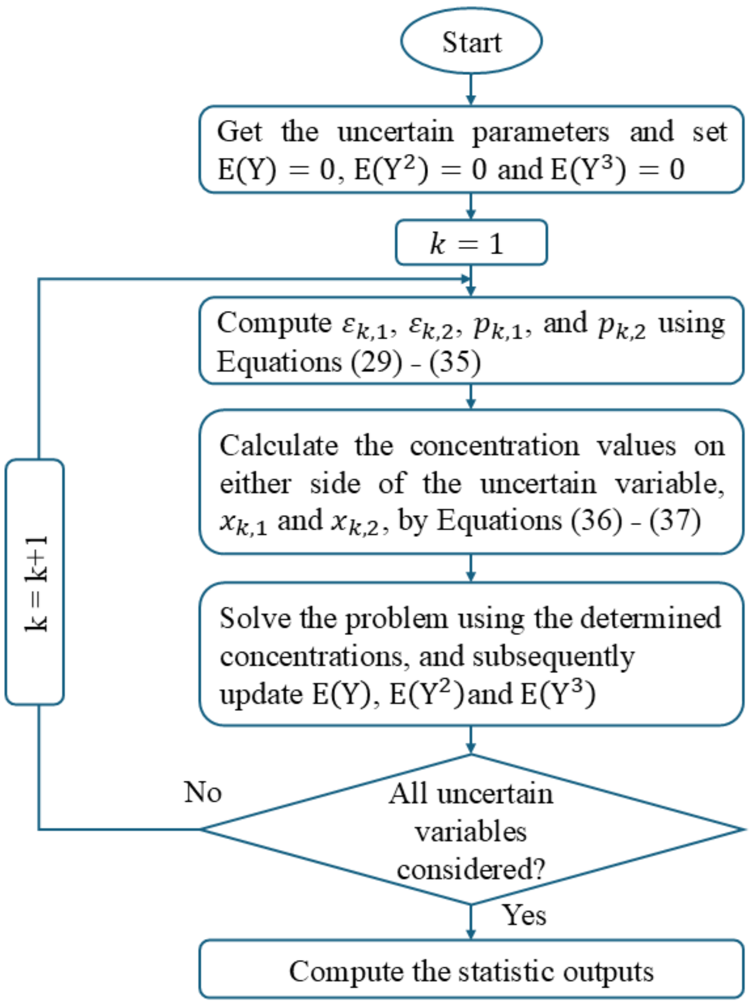


**Figure 2.** The flowchart of the proposed method.

## 4. Results and Discussion

To verify the effectiveness of the suggested paradigm, the IEEE 33-bus grid [32,33] is employed as the validation test system. The system has a total load of 3.7 MW and 2.3 MVAR, along with 5 tie switches, 32 sectionalizing switches, and a base voltage of 12.66 kV. The network includes two 200 kW diesel generators at the 8th and 28th buses, as well as four 150 kW photovoltaic units at the 7th, 22nd, 25th, and 27th buses. To evaluate the effectiveness of the suggested model in-depth, the following case studies are looked at for a full and informative comparison. In detail, Case 1 examines the traditional approach where microgrids are interconnected using switches, resulting in uncoordinated power sharing. This method often fails to effectively manage fluctuations in photovoltaic (PV) generation. Case 2 introduces the proposed method, where conventional switches are replaced by SOPs to facilitate coordinated power sharing among microgrids and provide reactive power support due to their converter-based reactive power capabilities.

- Case 1: This scenario represents the traditional approach, where microgrids are interconnected via switches, as shown in Figure 3. In this setup, each microgrid contains a mix of resources, such as PV units and DGs. The interconnection through conventional switches does not allow for effective coordination of power-sharing, often leading to inefficient handling of fluctuations in PV generation. This lack of coordination can result in instability, voltage deviations, and system performance.
- Case 2: In this scenario, the microgrids are interconnected using SOP converters instead of traditional switches, as illustrated in Figure 4. The SOP converter, rated at 3 MVA, provides several advantages over conventional switches, including the ability to actively manage power sharing between the microgrids. The key feature of the SOP converter is its converter-based reactive power support capability, which allows for better regulation of voltage and improved stability across the interconnected microgrids. This case reflects the proposed approach, where SOPs enable coordinated power sharing and improve the overall efficiency and stability of the system.

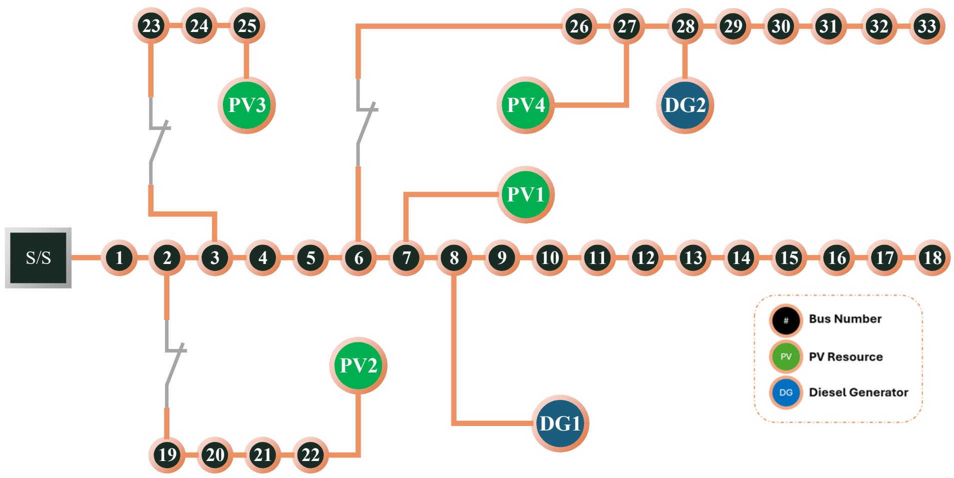


**Figure 3.** Interconnected multi-microgrids with switches (Case 1).

For power networks to operate reliably, it is crucial to maintain the voltage profile within permissible ranges, especially at the distribution level where customers are directly connected. Voltage deviations, whether they exceed or fall short of acceptable levels, can potentially damage equipment and impact overall system performance. Figure 5 illustrates the comparison of voltage profiles between the two cases analyzed.

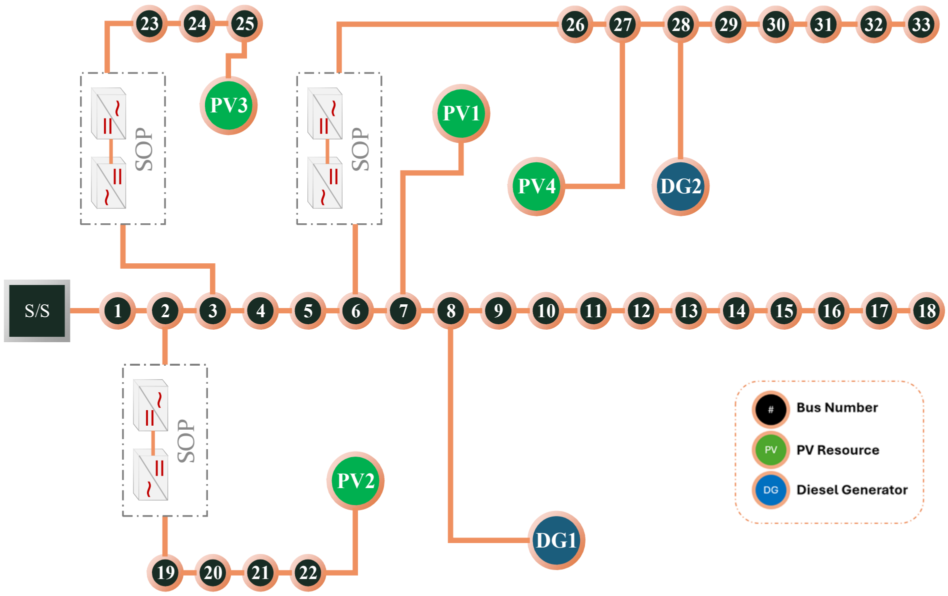


**Figure 4.** Interconnected multi-microgrids through SOPs (Case 2).

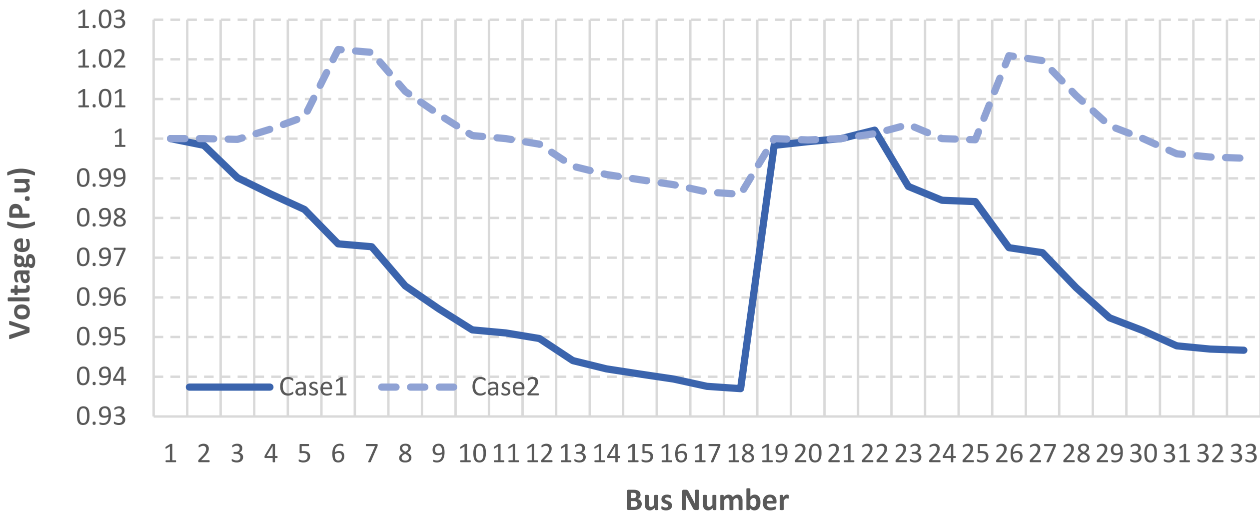


**Figure 5.** Voltage of grid under cases 1 and 2.

In Case 1, where microgrids are interconnected using traditional switches, the voltage at certain buses drops to 0.93 p.u., which is below the minimum acceptable level of 0.95 p.u. This is because the conventions switch cannot control power among microgrids, which leads to poor voltage regulation and presents risks to both equipment and the overall system's stability.

In contrast, Case 2, where microgrids are interconnected using SOP converters, shows a much more stable voltage profile. The voltage remains within acceptable limits (0.95 and 1.05), demonstrating a smoother and more consistent voltage distribution across the network. This improvement is due to the SOPs' ability to manage both reactive and active power more effectively. By compensating for reactive power and enabling coordinated power sharing between microgrids, SOPs enhance voltage regulation, ensuring that voltage levels stay within the permissible range. As a result, the system's overall stability is significantly improved in Case 2, illustrating the benefits of using SOPs for better voltage control and coordination across the network.

Diesel generators are categorized as dispatchable sources, meaning they can be activated or deactivated based on network demands and are typically employed to enhance the reliability and stability of power networks. In both cases depicted in Figure 6, the diesel generators are operating at full load to support network performance. This full-load operation is essential due to the substantial power requirements needed to maintain voltage levels within acceptable ranges. As the network experienced significant power demands to ensure voltage stability, the generators' full capacities were committed to injecting power into the grid.

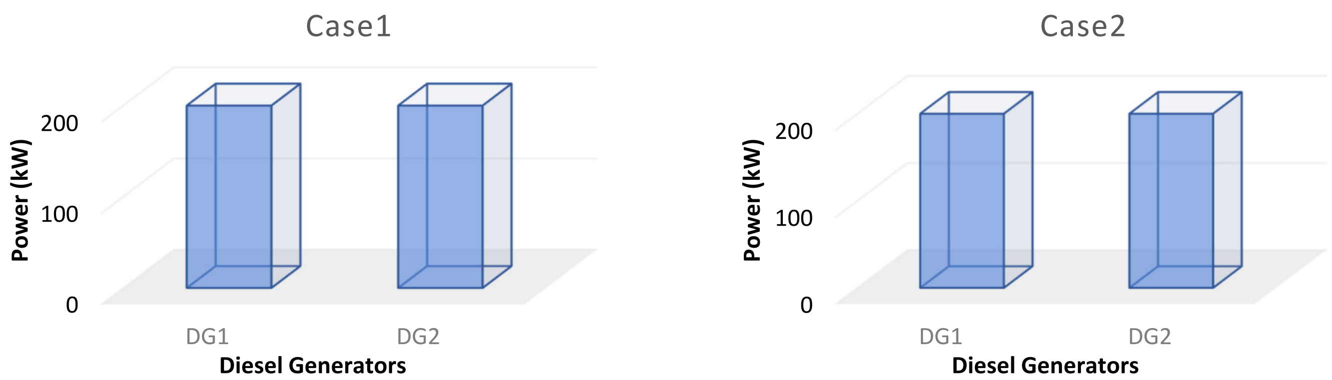


**Figure 6.** Diesel generator commitments.

As PV generations are limited to a specific time (generally, they have daily generation), the extra capacity of PV inverters is deployed to supply or absorb reactive power, which is essential for enhancing the overall functionality and stability of power networks. Figure 7 illustrates the reactive power output of the PV inverters across both cases. The graphs reveal a difference in reactive power between the two cases. Specifically, in Case 2, where SOPs are integrated into the system, there is a reduction in the reactive power output of the second PV inverter compared to Case 1.

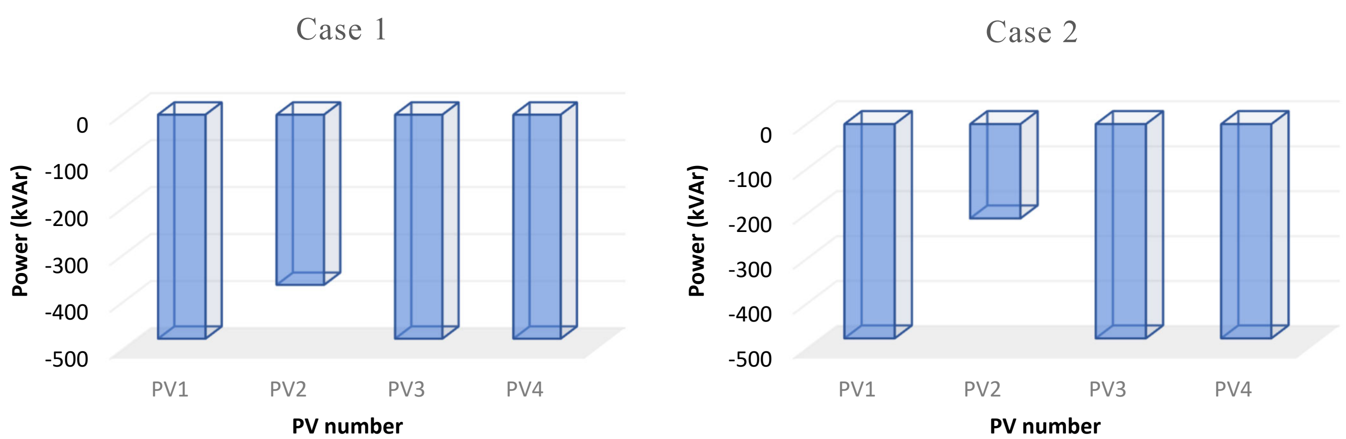


**Figure 7.** Reactive power supplied by solar PV.

This reduction indicates that SOPs play a crucial role in regulating reactive power. Specifically, SOPs aid in reactive power compensation, providing essential support to the network when PV inverters are primarily engaged in active power conversion and lack the capacity to supply adequate reactive power. This capability enhances voltage levels and improves overall network performance.

Effective management of active power across microgrids is crucial for optimizing network performance, especially with the unpredictable nature of renewable energy generation. While SOPs were used for reactive power provision, they also excel in managing active power between microgrids. Specifically, SOPs facilitate controlled power transfer from one microgrid to another, ensuring both technical stability and preservation of techno-economic issues. Unlike traditional switches, which only transmit power without management, SOPs offer dynamic control over power sharing, as shown in Figure 8. Through this figure, power is transferred from one microgrid to another based on the overall system conditions. This process involves subtracting power from one microgrid and adding it to another, ensuring that the distribution of power aligns with the network's current requirements and enhances overall system performance. This dynamic control enhances coordination among microgrids and leverages the advanced capabilities of SOP converters. By managing both active and reactive power, SOPs could be a unified power manager, reducing the need for complex, diverse equipment and simplifying network infrastructure. This approach not only enhances network efficiency but also simplifies overall system operations.

The effective management of reactive power by SOPs enables the network to maintain more stable voltage profiles and enhances overall system stability, even amidst fluctuations in renewable energy generation. Additionally, integrating SOPs reduces the dependence on conventional methods like capacitors, which were previously used to manage voltage levels but often introduced power quality issues. The significant role of SOPs in reactive power management underscores their importance in optimizing network functionality and ensuring reliable and stable power distribution.

As depicted in Figure 9, SOPs demonstrate their versatility by simultaneously supplying and absorbing reactive power, thereby improving system performance. This capability illustrates how SOPs can dynamically manage both reactive and active power in microgrids, leading to enhanced overall system efficiency and performance.

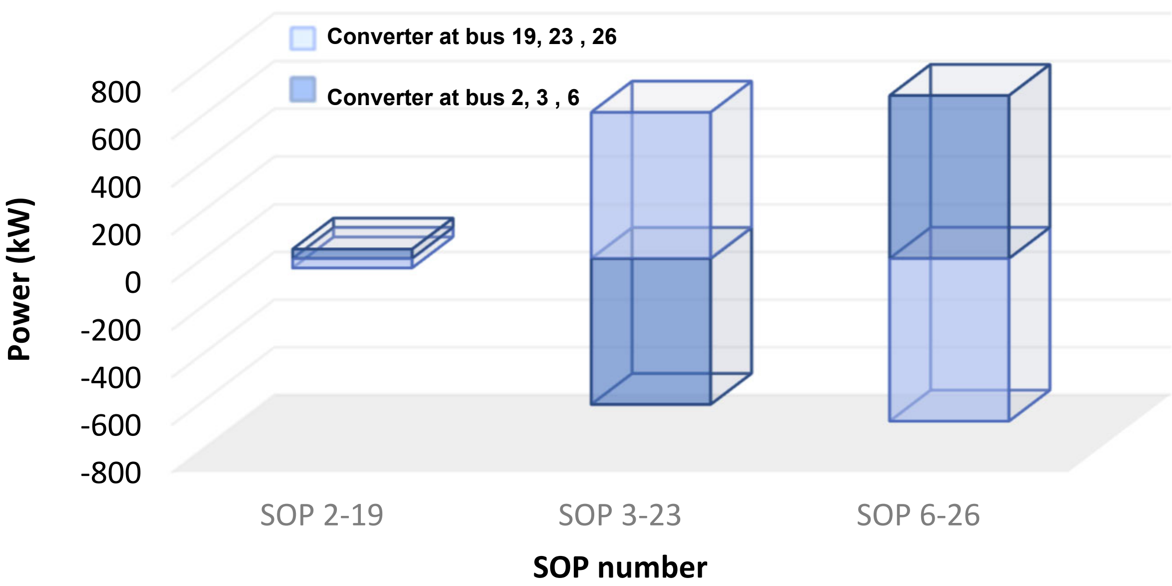


**Figure 8.** Active power transaction among microgrids by SOPs.

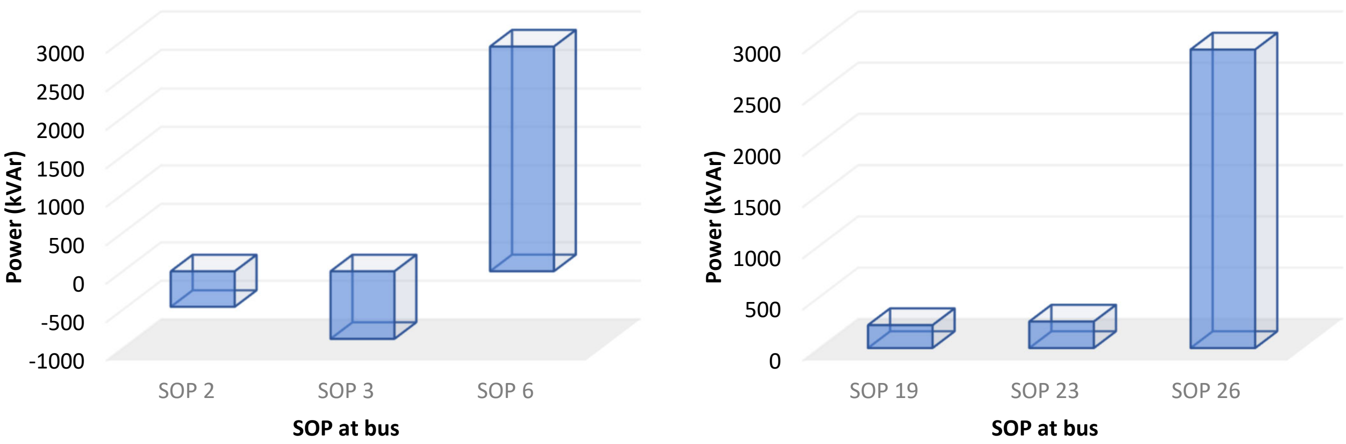


**Figure 9.** Reactive power-supplied SOPs.

## 5. Conclusions

This study proposed a convex formulation that incorporates SOPs to form multi-microgrid distribution grids with high renewable energy penetration while addressing uncertainties using the two-point estimation method. The results demonstrate that utilizing SOPs in multi-microgrid systems significantly enhances overall system performance. Specifically, the SOPs helped flatten and stabilize the voltage profile, ensuring it remained between the standard values. Moreover, SOPs played a critical role in managing both reactive and active power flows within the interconnected microgrids, which contributed to improved power sharing and reduced voltage deviations. This power management capability also led to a notable increase in the network's reliability by minimizing the risks of voltage fluctuations. Additionally, the integration of SOPs allowed for better utilization of renewable energy resources by coordinating power sharing. These improvements underline the potential of SOPs to replace traditional switches in distribution networks, particularly in networks involving a high penetration of renewable energy.

Future work will explore strategies to enhance the resilience of distribution networks by integrating SOPs with advanced network reconfiguration techniques. This could involve dynamic reconfiguration based on real-time grid conditions, enabling the network to adapt more effectively to unforeseen disruptions or changes in power demand and supply. Moreover, deploying a machine learning model to manage SOPs could enable their autonomous operation, presenting an exciting avenue for further research.

**Author Contributions:** Conceptualization, A.A. (Ali Azizivahed) and K.G.; methodology, A.A. (Ali Azizivahed) and K.G.; software, A.A. (Ali Azizivahed) and K.G.; validation, A.A. (Ali Arefi); formal analysis, A.A. (Ali Arefi), M.T.A., and M.E.H.; investigation, A.A. (Ali Azizivahed) and K.G.; resources, M.T.A. and M.E.H.; writing—original draft, A.A. (Ali Azizivahed) and A.A. (Ali Arefi); writing—review and editing, M.T.A. and M.E.H.; supervision, A.A. (Ali Arefi), M.T.A. and M.E.H.; project administration, A.A. (Ali Arefi). All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** All required data have been cited within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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