Proactive Voltage Regulation in Distribution Systems with High Penetration of Distributed Energy Resources: A Centralized Control Approach Using Step Voltage Regulators

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***Abstract*—During the last few decades, extensive research has been conducted to mitigate potential voltage-related problems that high penetration of Distributed Energy Resources (DERs) may cause. One of these problems is the voltage variation caused by the disconnection of the DERs due to their anti-islanding protection action after a temporary fault. This issue has not been deeply studied so far and it may pose severe voltage variations to distribution systems' consumers. In this context, this paper proposes a new formulation aiming at the preventive voltage regulation strategy for step voltage regulators considering the impacts triggered by a sudden disconnection of DERs. The voltage control is accomplished by a specialized Particle Swarm Optimization that selects control actions predicting the possibility of the DERs being disconnected. Results show that voltage violations were minimized after the disconnection of DERs, keeping the nodal voltages within statutory limits.**

***Index Terms*—distributed energy resources, step voltage regulator, particle swarm optimization, voltage regulation.**

I. Introduction

Distribution utilities must incorporate technical requirements into their standards to address the inclusion of Distributed Energy Resources (DERs). These requirements are related safety, operation, and performance [1]–[6]. Generally, a DER is required to disconnect from the grid during disturbances [1], [2], such as temporary short circuits that may momentarily impact the voltage [7]. As a result, when the DER stops exporting power and loads throughout the grid continue with their usual consumption, the voltage across the distribution system decreases, potentially leading to voltage violations. In such cases, Step Voltage Regulators (SVR) operate. An SVR is an essential component in power systems used to regulate voltage and ensure that it stays within statutory limits. It consists of a transformer equipped with on-load tap changers, which adjust the transformer's turns ratio to regulate voltage. However, SVRs are designed to regulate gradual voltage variations and may take up to 135 seconds to initiate their operation [8]. This delay may result in some consumers having inadequate voltage levels [7].

The coordination of SVRs with DERs has become a common practice in improving voltage regulation in distribution systems with high penetration of DERs [9]. A coordination methodology that dynamically calculates the reference voltage to SVRs based on real-time measurements was introduced in [10]. This approach differentiates itself from conventional voltage regulation by obtaining voltage setpoints based on system conditions and DER operation, ensuring coordination between DERs and SVRs. The hourly consumer load demand and photovoltaic generation profile can be used to coordinate the tap positions of SVRs and DERs, as proposed in [11]. Similarly, the available reactive power capacity of DERs can be used to regulate voltage and minimize the frequency of SVR operations [12], [13]. Reducing the number of SVR operations is necessary to preserve their longevity, especially in the presence of high DER penetration. Frequent tap changes can accelerate wear and tear on mechanical components, especially the tap changer, resulting in higher maintenance costs and shorter equipment lifespan. Therefore, minimizing tap changes is essential to decrease maintenance expenses and improve the overall reliability of the power system [14].

Although extensive research has explored voltage regulation when DERs are supplying active power, there is still a need for further investigation into the effects of unpredictable DER disconnections and the mitigation of power quality issues that may arise from this scenario. This issue gains importance as certain methodologies rely on DER capacity to assist in voltage regulation [15]. The presence of voltage sags caused by DERs anti-islanding protection has been investigated in [7], which introduced a methodology for evaluating the effects of such events. In [16], an algorithm was introduced to

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classify and characterize voltage dips and swells associated with anti-islanding protection. Since many distribution systems are weak, the voltage variations caused by DER islanding and subsequent reconnection can be severe.

The impact of climate change has led to an increase in disruptive events, which can impact the resilience of distributed systems [17]. Addressing this challenge requires the development of new models to evaluate potential disturbances and the implementation of methodologies to mitigate their consequences. This evolving scenario in distribution systems demands careful consideration and innovative solutions to maintain grid reliability and stability [18]. Anticipating disruptive events is important in providing resilience to the operation of the distributed system [19]. In this context, a proactive voltage regulation approach that contemplates the disconnection of DERs can provide a resilient operation, particularly in cases with high penetration of DER. This paper introduces a novel solution to address this challenge. The proposed approach involves controlling the voltage setpoints of SVRs on an hourly basis, minimizing voltage violations that may arise when DERs are disconnected and no longer supply active power to the main grid. This involves selecting a voltage setpoint that simultaneously regulates voltage both during DER connection and disconnection, thereby avoiding voltage violations triggered by recloser operations as a result of temporary short circuits. Additionally, the approach reduces tap changes, thereby improving SVRs' longevity.

The proposed methodology models the voltage variation arising from DER disconnection as an optimization problem, which is solved by using Specialized Particle Swarm Optimization (SPSO). The SPSO uniquely accounts for SVRs voltage regulation when updating particle velocities in each iteration, and results show the efficacy of the proposed approach in minimizing voltage violations and tap changes. The main contributions of the paper are, as follows:

1) The introduction of a proactive centralized control scheme for SVRs, minimizing voltage violations after DER disconnection using optimized voltage setpoints of SVRs. By continuously optimizing the voltage setpoints of SVRs, this centralized approach effectively regulates the voltage and mitigates any potential disruptions caused by DER disconnections.

2) The presentation of a new formulation, the SPSO, which is capable of addressing voltage regulation, allowing for effective determination of the voltage setpoints for SVRs, making it a valuable tool for voltage regulation in distribution systems with high penetration of DERs.

II. VOLTAGE CONCERNS DUE TO THE OPERATION OF DERS

This section provides an overview of concerns related to voltage that arise due to the integration of DERs.

A. Overvoltage due to power injection by DER

The power consumed by loads ($S_{Load} = P_{Load} + jQ_{Load}$) in a typical radial system without DERs always flows in the same direction: from the substation to load nodes, causing a voltage drop at the consumers' terminals. However, if a DER is connected to a radial system, the injection of power ($S_{DER} = P_{DER} + jQ_{DER}$) can affect the direction of power flowing through the distribution lines, causing voltage variations influenced by the lines' parameters (R and X) and by the power flowing through the SVR ($S_{SVR} = S_{Load} - S_{DER}$) [20].

A simplified system with a concentrated load and a DER connected to the same point of common coupling (PCC) is shown in Fig. 1. An SVR keeps the voltage at the PCC (V_{PCC}) within statutory limits. Since it is a distribution system, the angular difference between the voltage at the secondary of the SVR (V_{SVR}) and (V_{PCC}) is minimal, the voltage variation ($\Delta V_{PCC} - V_{SVR}$) caused exclusively by a DER, without considering the influence of loads ($P_{Load} = Q_{Load} = 0$) is:

$$\Delta V_{PCC} = \frac{R \cdot P_{DER} + X \cdot Q_{DER}}{V_{PCC}}. \tag{1}$$

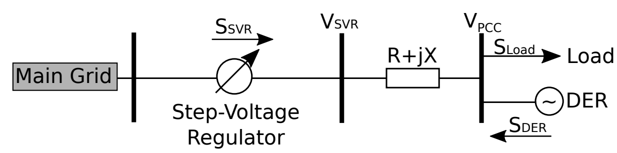

Fig. 1. A simplified circuit is used to demonstrate the power flowing through an SVR with a cable connecting a PCC with a concentrated load and a DER.

Distribution system lines have a high R/X ratio, so a DER injecting active power typically increases the voltage at the PCC. Active power curtailment of DERs can mitigate this voltage rise. If maximizing the injection of active power is desired, using SVRs to mitigate the voltage variation caused by DERs operation is a useful solution, since it does not reduce the active power delivered by DERs.

B. Voltage sags due to DER Disconnection

Voltage sags caused by the disconnection of DERs have been investigated in [6] and will be briefly discussed in this paper. Typically, loads slowly vary their demand, so SVRs are expected to regulate the voltage when there are gradual changes in the loads' demand. During a typical operation of a distributed system with the presence of DERs, the voltage at the PCC rises due to the injection of active power, as described in (1). To accommodate these changes, SVRs adjust their tap positions to regulate the voltage and keep it close to a predefined voltage setpoint, effectively mitigating the voltage variations caused by DERs.

Temporary short circuits are common occurrences in aerial distribution lines, leading to the quick disconnection of DERs and impacting voltage regulation. In the event of a short circuit, a recloser operates to isolate the affected portion of the system for a brief period before reconnecting it. It is a requirement in most distribution utilities that DERs be disconnected from the system by anti-islanding protection before the first reclose attempt [1], [2]. Following the recloser operation, loads continue to consume power, but with DERs disconnected, voltage levels in the distribution system can significantly decrease. In this situation, SVRs are not suitable for regulating quick voltage variations due to their initial delay to start operating, which can take up to 135 seconds [8]. After this delay, SVRs begin adjusting their taps to regulate the voltage, with each tap change occurring after a smaller time delay of typically 3 seconds. Consequently, during this short period, there may be voltage variations that exceed statutory voltage limits, resulting in voltage sags [7].

III. Proposed Methodology

In this paper, the centralized control of voltage setpoints of SVRs is used to minimize voltage violations caused by a sudden disconnection of DERs while also ensuring a reasonable number of SVR operations. This approach requires communication infrastructure to update voltage setpoints periodically and receive voltage measurements from the distribution system. It is assumed that load and generation forecasts are available, which are essential for day-ahead operation planning. Obtaining them is not within the scope of this paper and there is abundant literature on this topic [21], [22].

The core of the proposed methodology lies in the optimization of voltage setpoints using forecasted data, which is performed in a day-ahead optimization. The methodology simulates a fault at every planned interval to prevent temporary faults from causing voltage variations throughout the day. In situations where there are deviations in consumption or generation throughout the day, a snapshot optimization is performed to adjust the voltage setpoints based on the current state of the distribution system. This snapshot optimization is necessary to ensure effective voltage regulation, especially in the context of high DERs penetration.

A flowchart illustrating the proposed methodology is presented in Fig. 2. In Phase 1, a day-ahead optimization is carried out, and it obtains voltage setpoints for SVRs to be used for the entire day. In Phase 2, the algorithm continuously receives real-time voltage measurements from selected buses. Careful consideration is given to the choice of these buses, as they serve to assess the effectiveness of voltage regulation. Buses that have DERs, and capacitors banks are potential candidates for monitoring. Power flow calculations, taking into account varying load and generation, can be employed to identify additional critical buses that may experience voltage violations, and these buses should be included in the monitoring process. If any measured voltage falls outside the acceptable range defined by the distribution system operator, a snapshot optimization is triggered to recalculate the voltage setpoints. This allows for the rapid determination of new setpoints that can regulate the voltage when loads or DERs deviate from the forecasted values, thereby preventing voltage violations following their disconnection. In Phase 2, this cycle is repeated continuously to ensure that the voltage is consistently regulated, even in the presence of significant changes in load consumption or DER generation. In this paper, hourly updates are made to the voltage setpoints.

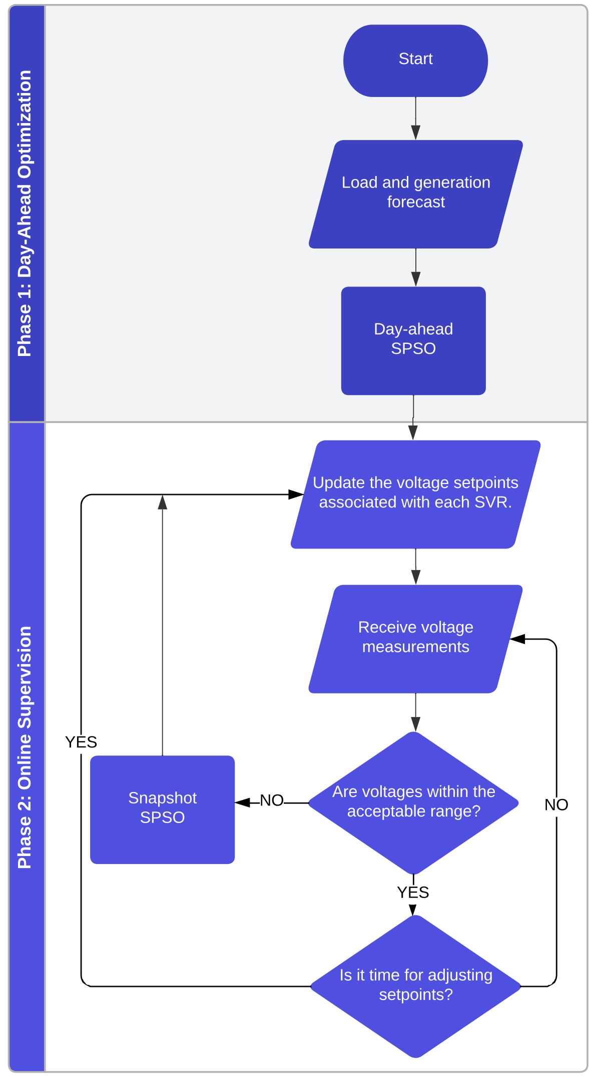

Fig. 2. Flowchart of the proposed approach.

A. Problem formulation

The problem is characterized by an objective function denoted as f^s_{Total}, which evaluates the effectiveness of a given solution s in resolving the issue. This is accomplished by combining two auxiliary functions: $f^s_{Violation}$, which focuses on the main goal of eliminating voltage violations after DERs are disconnected, and a secondary objective function $f^s_{\Delta Tap}$, which is aimed at minimizing tap adjustments to ensure their durability. This secondary objective was introduced to preserve the longevity of SVRs; otherwise, the obtained solutions could lead to a considerable increase in tap adjustments compared to the conventional SVR operation.

The function $f^s_{Violation}$ assesses voltage violations at each bus within the distribution system before and after the DER disconnection. It quantifies these violations by comparing the voltage with the specified voltage limits. The function $f^{s,t,p,N}_{Before}$ evaluates the voltage violation before the DER disconnection, while $f^{s,t,p,N}_{After}$ quantifies the violation after its disconnection.

These functions consider overvoltage and undervoltage scenarios and provide a comprehensive assessment of the voltage violations. Voltage violations before the DERs disconnection are quantified by:

$$f_{Before}^{s,t,p,N} = \begin{cases} V_{Before}^{s,t,p,N} - L_{max}, if \quad V_{Before}^{s,t,p,N} > L_{max}, \\ 0, if \quad L_{min} \leq V_{Before}^{s,t,p,N} \leq L_{max}, \\ L_{min} - V_{Before}^{s,t,p,N}, if \quad V_{Before}^{s,t,p,N} < L_{min}, \end{cases} \quad (2)$$

where $V_{Before}^{s,t,p,N}$ is the voltage before the disconnection of DERs at bus N, phase p, and period t. L_{max} and L_{min} correspond to the upper and lower voltage limits that must be satisfied. Similarly, voltage violation after DERs disconnection is quantified by:

$$f_{After}^{s,t,p,N} = \begin{cases} V_{After}^{s,t,p,N} - L_{max}, if \quad V_{After}^{s,t,p,N} > L_{max}, \\ 0, if \quad L_{min} \leq V_{After}^{s,t,p,N} \leq L_{max}, \\ L_{min} - V_{After}^{s,t,p,N}, if \quad V_{After}^{s,t,p,N} < L_{min}, \end{cases} \quad (3)$$

where $V_{Before}^{s,t,p,N}$ is the voltage after the disconnection of DERs at bus N, phase p, and period t.

The term $f_{WeightedSum}^{s,t,p,N}$ is obtained by combining $f_{Before}^{s,t,p,N}$ and $f_{After}^{s,t,p,N}$, incorporating different weights w_{Before} and w_{After} to allow for a focus on voltage regulation either before or after DER disconnection:

$$f_{WeightedSum}^{s,t,p,N} = w_{Before} \cdot f_{Before}^{s,t,p,N} + w_{After} \cdot f_{After}^{s,t,p,N}. \quad (4)$$

This leads to the objective function $f_{Violation}^{s}$, which sums $f_{WeightedSum}^{s,t,p,N}$ across all planned periods t_{max}, phases p_{max}, and buses N_{max}:

$$f_{Violation}^{s} = \sum_{t=1}^{t_{max}} \sum_{p=1}^{p_{max}} \sum_{N=1}^{N_{max}} f_{WeightedSum}^{s,t,p,N}. \quad (5)$$

The calculation of tap changes for each SVR, denoted as $\Delta_{Tap}^{s,SVR}$, involves measuring the absolute difference between consecutive tap positions $Tap^{SVR,t}$, as indicated in:

$$\Delta_{Tap}^{s,SVR} = \sum_{t=1}^{t_{max-1}} |Tap^{SVR,t} - Tap^{SVR,t+1}|. \quad (6)$$

When SVRs operate independently per phase, each phase's tap adjustments are accounted for individually. The incorporation of different weights $w_{\Delta Tap}^{SVR}$ allows for prioritizing fewer tap changes for specific SVRs when evaluating the secondary objective function $f_{\Delta Tap}^{s}$ in:

$$f_{\Delta Tap}^{s} = \sum_{SVR=1}^{SVR_{max}} w_{\Delta Tap}^{SVR} \Delta_{Tap}^{s,SVR}, \quad (7)$$

where SVR_{Max} represents the total number of SVRs within the distribution system. By adjusting the weights $w_{Violation}$ and $w_{\Delta_{Tap}}$ to prioritize each objective, the final objective f_{Total}^{s} combines the voltage violation and tap adjustment objectives. It is determined by:

$$f_{Total}^{s} = w_{Violation} \cdot f_{Violation}^{s} + w_{\Delta_{Tap}} \cdot f_{\Delta Tap}^{s}, \quad (8)$$

The optimization problem seeks to find a solution that minimizes f_{Total}^{s} while satisfying the power flow equations, so the formulation is as follows:

$$min(f_{Total}^{s}), \quad (9)$$

$$s.t: \quad g_{Before}^{P^t,Q^t,x^{s,i}} = 0, \quad (10)$$

$$g_{After}^{P^t,Q^t,x^{s,i}} = 0, \quad (11)$$

where $g_{Before}^{P^t,Q^t,x^{s,i}}$ and $g_{After}^{P^t,Q^t,x^{s,i}}$ are the power flow equations for the situation before and after the disconnection of the DER. P^t and Q^t correspond to the active and reactive power balance at each bus during a period t. The control variables $x^{s,i}$ represent the voltage setpoints of SVRs, which are determined to achieve a specific voltage level downstream of each SVR hourly. These setpoints are calculated based on the SVRs' voltage-sensing circuit, with a base voltage of 120V. For example, a setpoint of 108V corresponds to a 0.9 reduction in the SVR's turns ratio, while a setpoint of 132V corresponds to a turns ratio of a 1.1 increase. The solution vector is defined as:

$$x^{s,i} = [V_{Setpoint}^{1,1}, \ldots, V_{Setpoint}^{SVR,t}, \ldots, V_{Setpoint}^{SVR_{max},t_{max}}], \quad (12)$$

$$108 \leq V_{Setpoint}^{SVR_{max},t_{\max}} \leq 132. \quad (13)$$

Both day-ahead and snapshot optimization share the same framework, differing only in their input data: day-ahead optimization employs forecasted load and generation for a full day, while snapshot optimization utilizes real-time load and generation data. Current load and generation information must be gathered via measurements or state estimation algorithms, which are out of the scope of this paper.

The introduced objective functions serve to obtain solutions that effectively maintain voltage within limits during regular operation and post-DER disconnection scenarios. To achieve this, the Particle Swarm Optimization (PSO) algorithm was selected and enhanced. The PSO was chosen due to its suitability for optimization problems in power systems [23]. The capability of swarm intelligence algorithms, including PSO, has been greatly improved in recent years due to abundant research in this field. The low computational cost makes PSO a popular choice across different fields, enabling its easy adoption in real-world applications. The strength of PSO lies in its simplicity and efficiency, requiring fewer parameters to tune compared to other optimization algorithms [24]. It can operate effectively without needing detailed knowledge about the specific problem's characteristics. PSO relies on the externally calculable objective function value, making it straightforward to implement in various applications. The power flow analysis was conducted using OpenDSS, a widely adopted tool in the distribution system operator community. This choice facilitated a seamless integration with PSO, offering benefits to both researchers and industry professionals. The modifications made to the PSO algorithm are elaborated as follows.

B. Specialized Particle Swarm Optimization (SPSO)

Traditionally, a PSO is initiated by creating random solutions s, which have their properties represented by a particle position $x^{s,i}$ at each interaction i. In the formulation proposed in this paper, a particle is defined by (12) and (13). During the iterative process, particle positions are updated using velocity vectors $v^{s,i}$. The optimization process refines solutions by making them progressively resemble the best solutions identified in preceding iterations. Each particle has a distinct velocity, making it move in a search space.

The velocity updates guide particles closer to the best individual position x^s_{Best} obtained for each solution, as well as the best swarm position g acquired by all solutions up to the present optimization phase. These positions x^s_{Best} and g are updated at each iteration, thereby guiding particles towards previously successful outcomes.

The velocity of each particle is updated using the following equation:

$$\begin{aligned} v^{s,i+1} = {} & w_{Inertia} v^{s,i} + c_1 r_1 [x^s_{Best} - x^{s,i}] \\ & + c_2 r_2 [g - x^{s,i}] + c_3 r_3 Correction^{s,i}. \end{aligned} \tag{14}$$

New velocity $v^{s,i+1}$ is influenced by the current velocity $v^{s,i}$ of the particle at iteration i. The inertial factor $w_{Inertia}$ maintains the particle's trajectory. Coefficients c_1,c_2, and c_3 quantify how much each term affects the new velocity. Random coefficients r_1,r_2, and r_3 vary between 0 and 1, determining the effect of the terms on particle movement within the search space. The term $c_1 r_1 [x^s_{Best} - x^{s,i}]$ uses the particle position $x^{s,i}$ and the best individual position x^s_{Best} to guide the search. Similarly, the term $c_2 r_2 [g - x^{s,i}]$ uses the best swarm position obtained g.

Furthermore, a novel term $c_3 r_3 Correction^{s,i}$ has been introduced as a modification to the conventional PSO. Due to the nature of the problem addressed in this paper, in which particle movement aims to regulate voltage, an adjustment to the PSO was proposed: the velocity of each particle is directly influenced by voltage violations detected at downstream buses regulated by each SVR. This correction modifies the velocity to decrease or increase the voltage setpoint, thereby minimizing voltage violations. Integrating this correction enhances the solution quality. The correction term is calculated as follows:

$$C^{s,t,BD}_{Before} = \begin{cases} L_{max} - V^{s,t,BD}_{Before}, if \quad V^{s,t,BD}_{Before} > L_{max}, \\ 0, if \quad L_{min} \leq V^{s,t,BD}_{Before} \leq L_{max}, \\ L_{min} - V^{s,t,BD}_{Before}, if \quad V^{s,t,BD}_{Before} < L_{min}, \end{cases} \tag{15}$$

$$C^{s,t,BD}_{After} = \begin{cases} L_{max} - V^{s,t,BD}_{After}, if \quad V^{s,t,BD}_{After} > L_{max}, \\ 0, if \quad L_{min} \leq V^{s,t,BD}_{After} \leq L_{max}, \\ L_{min} - V^{s,t,BD}_{After}, if \quad V^{s,t,BD}_{After} < L_{min}, \end{cases} \tag{16}$$

$$Correction^{s,i} = C^{s,t,BD}_{Before} + C^{s,t,BD}_{After}, \tag{17}$$

where $V^{s,t,BD}_{Before}$ is the voltage after the disconnection of DERs at bus BD during period t. $V^{s,t,BD}_{After}$ is the voltage after the disconnection of DERs. The set BD includes all buses downstream of each SVR, ensuring that only corresponding buses contribute to the correction of their respective SVR.

IV. Results

The proposed approach was applied to the IEEE 34-bus distribution system [25], which operates with a nominal voltage of 24.9 kV and has long lines. The system has unbalanced loads and some single-phase lines, hence the SVRs control each phase individually. Voltage regulation is carried out by six single-phase SVRs, three of which are located at bus 814 and the other three at bus 852, as indicated in Fig. 3. Additionally, a three-phase SVR was added at the substation to enhance voltage regulation, resulting in a total of seven SVRs within the distribution system. Voltage limits were defined between 0.95 p.u. and 1.05 p.u.

To test the proposed approach, a 250 kW diesel generator was connected to bus 824, along with three 100 kW photovoltaic (PV) generators at buses 808, 840, and 848. The diesel generator maintains constant power output, while the PV generators operate based on the irradiation curve corresponding to clear sky conditions on a typical day in the Southeast region of Brazil [26]. To model the load consumption for a typical weekday, a commercial load profile was employed [27]. This load profile, together with the output of the generators, was utilized as a day-ahead forecast, which was then integrated into the algorithm, as depicted in Fig. 2.

Furthermore, five reclosers (R1 to R5) were introduced into the system, as illustrated in Fig. 3. The operation of each recloser will be considered when evaluating $f^s_{Violation}$. When each recloser operates, the DERs downstream of it are disconnected, affecting the voltage violations differently. The most severe scenario occurs when recloser 5 is activated, immediately disconnecting all DERs from the distribution system. Since $f^s_{\Delta Tap}$ is designed to calculate changes in tap position due to slow load variations, it remains unaffected by recloser operations after temporary faults.

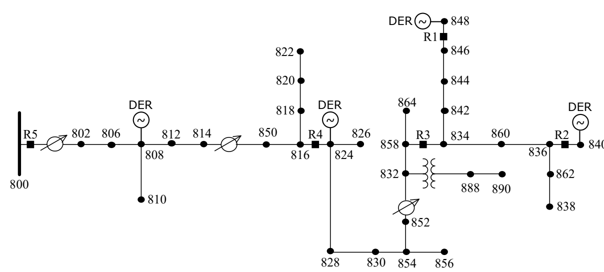

Fig. 3. Modified IEEE 34 bus test feeder [25].

Updates to voltage setpoints occurred at hourly intervals. The initial solutions were randomly generated, with one specific solution setting all setpoints to 120 V (each voltage regulator is equipped with a potential transformer of 24.5 kV:120 V). This particular solution aided in obtaining better results with fewer iterations. The optimization process was terminated based on two criteria: reaching the maximum allowable number of iterations (40) or encountering three consecutive iterations without any improvement of the objective function value.

Power flow calculations were executed using OpenDSS [28], while the SPSO and traditional PSO algorithms were implemented in MATLAB. For the optimization, the parameters w_{Before} and w_{After} were both set to 1, ensuring equal minimization of voltage violations before and after the disconnection of DERs. The tap operation was equally minimized, resulting in $w_{\Delta Tap}^{SVR} = 1$ for all SVRs. Each term in the velocity equation was given equal consideration, leading to $c_1 = c_2 = c_2 = 1$ and inertia was set to $w_{Inertia} = 0.25$.

To calculate the final objective function, the following weights were utilized: $w_{Violation} = 10000$ and $w_{\Delta_{Tap}} = 1$. This configuration allowed for an appropriate balance between voltage violation reduction and voltage setpoint deviation. The optimization process used 15 solutions per iteration and was executed on a computer equipped with an AMD Ryzen 7 2700 Eight-Core processor, running at 3.20 GHz, and equipped with 32 GB of RAM.

A. Base Case

In the base case, no optimization was performed to facilitate comparison. The setpoints for all SVRs were based on the original values from [25], while the three-phase SVR introduced at the substation had its setpoints set at 120 V.

Table I presents the values of $f_{Violation}^{s}$ for each recloser operation. In all cases, voltage violations ($f_{Violation}^{s} > 0$) were observed after the disconnection of DERs. Throughout the 24-hour simulation, there were a total of 112 tap changes across all seven SVRs.

To illustrate the severity of the most critical scenario when recloser 5 is activated, Fig. 4 shows the voltage profile at Bus 890. This bus was selected due to its substantial load, which leads to significant voltage variations. The voltage levels labeled as "Steady-state regime" represent the expected voltages if the load profile is accurate, and the DERs are operating at their maximum capacity. When recloser 5 opens due to a temporary short-circuit, all DERs are disconnected, leading to a situation where the SVRs do not immediately regulate the voltage due to their initial delay. This paper's primary objective is to mitigate voltage violations during this period before the SVRs can regulate the voltage. During periods close to peak demand (between 9:00 AM and 6:00 PM), voltage violations were observed after the disconnection of DERs.

B. Results

During the optimization process, the algorithm was executed 10 times, and the best solution was selected. As a result, voltage setpoints for all SVRs were obtained for each hour, ranging between 108 V and 132 V. The number of changes in tap positions was reduced in comparison to the base case (112 changes), resulting in only 92 tap changes during the 24-hour simulation. The obtained setpoints from the optimization for the SVR at bus 800 are shown in Fig. 5, the setpoints from other SVRs are not shown due to space limitation. The chosen setpoints were strategically aimed at mitigating voltage violations during the period of peak load consumption, occurring between 9:00 AM and 6:00 PM.

The positive outcome of the optimization process is evident in Table I, where it is shown that voltage violations ($f_{Violation}^{s} = 0$) were successfully eliminated in all cases of each recloser operation. This indicates that the voltage levels across the system remained within the permissible limits after the disconnection of DERs.

Furthermore, when considering the operation of recloser 5, Fig. 6 demonstrates that there were no voltage violations at bus 890 after the disconnection of DERs. Although there was a voltage variation following the disconnection, the voltages remained within the defined voltage limits. This outcome indicates the effectiveness of the proposed optimization approach in maintaining voltage levels within an acceptable range, even during challenging scenarios such as the operation of recloser 5.

C. Sensitivity analysis

The proposed solution was subjected to additional tests to evaluate its performance under load and solar irradiance forecast deviations during Phase 2 of the algorithm, as illustrated

TABLE I
VOLTAGE VIOLATIONS: BASE CASE VS. OPTIMIZATION

Recloser Operation	$f_{Violation}^{s}$ Base Case	$f_{Violation}^{s}$ Optimization
1	0.5356	0
2	0.5355	0
3	0.7044	0
4	1.2949	0
5	1.3556	0

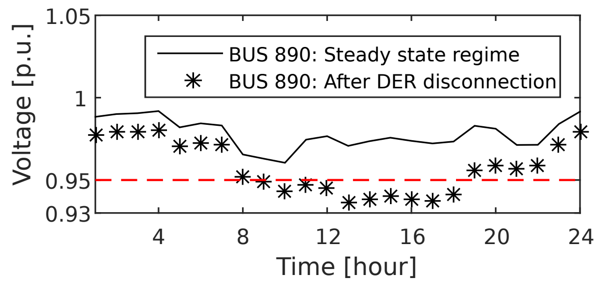

Fig. 4. Voltage profile during a day (phase A): base case.

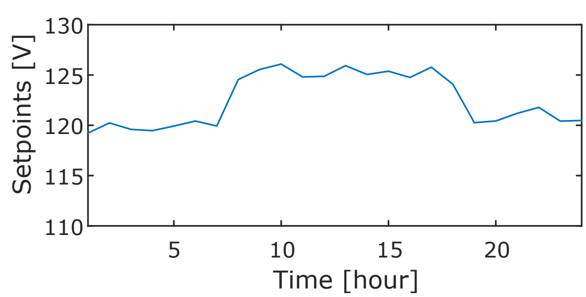

Fig. 5. Voltage Setpoints for SVR at bus 800 during a day.

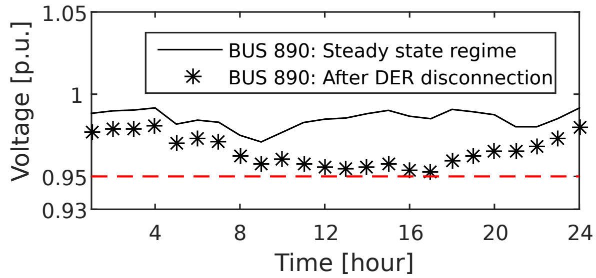

Fig. 6. Voltage profile during a day (phase A): optimized setpoints.

in Fig 2. Snapshot optimizations were performed whenever voltages fell outside an acceptable range to prevent voltage violations. To test a variety of generation conditions, real solar radiance curves obtained over the course of a year [26] were randomly selected and utilized. For the load forecast deviations, a normal distribution was employed, using the mean values from the load profile utilized during optimization. Different standard deviations were applied to replicate distinct forecast deviations. The standard deviations selected for testing were 1%, 2.5%, 5%, 10%, and 20%. For each standard deviation, 1000 cases were generated and examined.

When the load consumption varied with a standard deviation between 1% and 2.5%, it was observed that, on average, only one snapshot optimization per day was necessary after the operation of recloser 5. In the worst-case scenario of load variation with a standard deviation of 20%, an average of 4.5 snapshot optimizations per day were required. All cases successfully mitigated voltage violations, demonstrating the robustness of the proposed methodology in maintaining voltage regulation, even under challenging load and generation variations.

D. Performance analysis of the SPSO

Each optimization was executed 100 times to obtain a representative average of the results. Fig. 7 illustrates the performance of the best day-ahead optimizations calculated by the SPSO and traditional PSO. The SPSO consistently achieved a solution with no voltage violations before interaction 4, effectively eliminating them. On the other hand, the traditional PSO only managed to minimize voltage violations, leading to a final result that was worse compared to the SPSO. Across the 100 optimizations performed, the SPSO always succeeded in eliminating voltage violations, whereas the traditional PSO could only minimize them. The traditional PSO prioritized minimizing voltage violations without significantly addressing the secondary objective of minimizing tap changes. Consequently, tap changes were increased, resulting in an impractical operation of SVRs. However, the SPSO gradually reduced tap changes, yielding, on average, a better result than the base case.

In Phase 1, the SPSO required an average of 89.22 seconds and 13.61 iterations to solve the day-ahead optimization, while the traditional PSO took 104.49 seconds and 15.43 iterations. In Phase 2, the SPSO took 6.19 seconds, while the traditional PSO took 7.52 seconds to complete the snapshot optimizations.

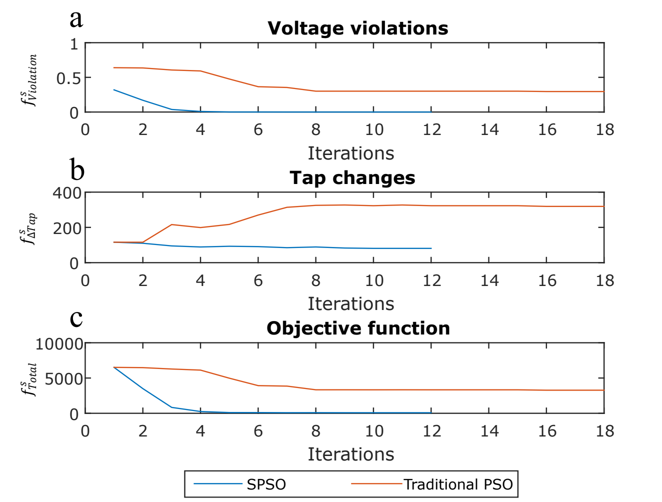

Fig. 7. Performance comparison of SPSO (blue line) and traditional PSO (red line). (a) Voltage violations. (b) Tap changes. (c) Final objective function.

V. Conclusions

This paper presents a novel approach to minimize voltage violations arising from the sudden disconnection of DERs. The proposed methodology enhances the PSO algorithm, effectively reducing the incidence of voltage violations immediately after DER disconnections while also minimizing tap changes of SVRs as a secondary objective.

Under ideal conditions, where load and generation profiles are accurate, the number of operations of SVRs is minimized, resulting in efficient voltage regulation without voltage violations in Phase 1. However, if load or generation profiles deviate from forecasts, new setpoints are obtained in Phase 2. In such cases, voltage violations are still mitigated.

Running 10 snapshot optimizations would yield results in approximately one minute and 11 seconds. This duration could be further reduced by employing an alternative software, as MATLAB may not be the most suitable choice. By achieving results within this short period, the proposed approach can be employed in real-time scenarios.

Distribution systems with high penetration of DERs are expected to become more prevalent, making temporary faults a potential cause for voltage violations following DER disconnections. However, the formulation proposed in this paper provides a robust and efficient solution to address this issue effectively. By eliminating voltage violations and minimizing tap changes, the proposed approach offers a reliable and practical solution to ensure stable voltage regulation in distribution systems with significant DER integration.

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