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DG Placement for Enhanced Voltage Stability in EVCS Integrated Network

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ABSTRACT
Modern distribution networks face increasing voltage stability challenges due to rising power demand and the growing integration of electric vehicles (EVs) and renewable energy sources (RESs). This study investigates the impact of random EV charging station (EVCS) placement and the subsequent optimal integration of RESs on the voltage stability of a distribution network. EVCSs are incorporated at randomly selected locations to assess their impact on network performance. The World Cup Optimization (WCO) algorithm is then employed to determine the optimal locations of solar and wind energy sources based on voltage stability considerations. The proposed methodology is validated on a modified IEEE 33-bus distribution network using MATLAB/Simulink under different operating scenarios. The performance is evaluated using the Voltage Stability Index (VSI), Line Stability Index (LSI), Fast Voltage Stability Index (FVSI), and Line Stability Factor (LSF), which are considered as objective functions for optimal RES placement. The results demonstrate that optimal placement of solar and wind sources using WCO effectively mitigates the adverse voltage stability impacts of EVCS integration and improves the overall performance of the distribution network.
Keywords: *Solar power, wind turbine, optimal placement, EV charging station, distribution network, voltage stability, optimization algorithm.*

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I. Introduction

The rapid growth of population, industrialization, and urbanization has increased electricity demand, leading to greater integration of Renewable Energy Sources (RESs) into modern power networks [1]. The increasing adoption of Electric Vehicles (EVs) and charging infrastructure further increases the loading of distribution networks [2]. Since EV charging can introduce phase imbalance and line overloading, its integration may adversely affect network performance [3]. The integration of renewable energy sources (RESs) can help meet the increasing demand for EV charging; however, their variable generation may adversely affect voltage stability. High power demand, network limitations, and system disturbances can further increase voltage stability concerns [4,5]. In addition, EV charging loads may introduce nonlinear characteristics, resulting in voltage deviations and power-quality problems in distribution networks [6-8]. Hence, effective voltage stability assessment is crucial for ensuring reliable, secure, and efficient operation of modern distribution systems [9]. Voltage stability assessment is essential for determining the capability of a power system to maintain acceptable bus voltages under varying operating conditions and contingencies [10-12]. To facilitate this assessment, several voltage stability indices have been developed, generally with normalized values ranging from 0 to 1, where a value approaching unity represents a higher likelihood of voltage instability. These indices provide useful information for identifying vulnerable buses and critical network sections. Consequently, their integration into OPF, network planning, and renewable energy allocation problems can improve the reliability and voltage stability of distribution systems [13]. Among the commonly employed indices, the FVSI is effective for identifying buses approaching voltage collapse [14]. The LSI provides an indication of the stability margin of individual network lines [15], while the LSF is used to evaluate the voltage stability of distribution feeders [16]. These indices are therefore useful for determining critical locations and optimizing the integration of distributed energy resources in distribution networks.

OPF is commonly employed to achieve secure and economical power system operation while satisfying network constraints [17]. Metaheuristic optimization methods have been increasingly adopted to address power loss, voltage deviation, and voltage stability objectives simultaneously [18-20]. Several optimization-based approaches have also been investigated for DG allocation and voltage stability improvement in EV-integrated distribution systems [21]. Multi-objective optimization has been applied to minimize generation cost, power losses, and voltage instability [22]. The impact of high wind penetration on voltage stability and the reactive power support provided by DFIG-based generation have also been examined [23]. Hybrid renewable generation systems have been evaluated using voltage stability indices under different operating conditions [24]. Furthermore, EV charging uncertainty and charging characteristics have been incorporated into voltage stability assessment [25]. Hybrid metaheuristic techniques have also been utilized for coordinated DG and DSTATCOM placement considering voltage profile, stability indices, and power losses [26]. However, limited attention has been given to the coordinated placement of EV charging stations and renewable energy sources for voltage stability enhancement. Therefore, the present work employs the World Cup Optimization (WCO) algorithm to determine the optimal RES locations in an EVCS-integrated distribution network.

The major objectives of the proposed work are as follows:

- To evaluate the impact of EVCS integration on the voltage profile of the distribution network.
- To improve the voltage profile through the integration of solar and wind energy conversion systems.
- To enhance voltage stability by determining the optimal locations of RES in an EV-integrated distribution network using the WCO algorithm.

The remainder of this paper is organized as follows. Section 2 presents a problem statement based on review of the existing literature. Section 3 describes the proposed methodology and provides details of the optimization techniques employed. Section 4 presents and discusses the simulation results under different operating scenarios using relevant performance metrics. Finally, Section 5 summarizes the major findings of the study and outlines the potential future scope of the proposed approach.

II. Problem statement

Modern power systems increasingly integrate RESs and EV charging loads to meet growing energy demand while supporting clean energy objectives. However, the increasing penetration of EVs introduces challenges such as voltage instability, voltage drops, and power-quality issues, particularly during peak charging periods. Since EV charging demand varies with driving patterns and charging behavior, the resulting load variations can significantly affect distribution network performance. Although several studies have investigated the optimal placement of EV charging stations based on economic and operational objectives, the impact of varying EV charging demand on voltage stability has received comparatively limited attention. Similarly, optimization-based RES placement has been widely studied, but the coordinated integration of RESs with EV charging stations has not been sufficiently addressed. Therefore, there is a research gap in developing an effective approach for voltage stability enhancement in distribution networks with simultaneous integration of EVs and RESs.

III. Proposed methodology

Voltage instability is a critical challenge in modern power systems due to increasing electricity demand and network loading. Maintaining voltage stability is therefore essential for reliable and secure distribution network operation. This study proposes a World Cup Optimization (WCO)-based approach for enhancing voltage stability in an EV-integrated distribution network. EVCSs are considered at selected locations, and the VSI is evaluated across the network. The WCO algorithm is then employed to determine the optimal locations for integrating solar and wind energy sources to improve the voltage profile and stability. The proposed methodology is validated on a modified IEEE 33-bus distribution network using MATLAB/Simulink. Its effectiveness is assessed under different operating conditions using VSI. The results demonstrate that optimal RES placement using WCO can effectively mitigate the voltage stability issues associated with EV integration and improve overall distribution network performance.

3.1 EV charging station

In this study, EVCSs are considered as additional loads at selected buses of the modified IEEE 33-bus distribution network. The EVCS demand is varied according to the number of EVs connected for charging. Random EVCS placement is initially considered to evaluate its adverse impact on the network voltage profile and stability indices. Subsequently, solar and wind energy sources are optimally allocated using the WCO algorithm to compensate for the additional EV demand and improve the voltage stability of the distribution network.

3.1 Electric Vehicle Charging Station (EVCS) Modeling

The increasing penetration of electric vehicles (EVs) introduces additional and variable loading conditions in distribution networks. An EVCS acts as a controllable electrical load whose demand depends on the number of EVs connected, charging duration, battery state of charge, and charger rating. During high-demand periods, simultaneous charging of multiple EVs can significantly increase the loading of distribution feeders, resulting in increased power losses and voltage deviations.

For an EVCS containing N_{EV} vehicles, the total charging power demand can be expressed as,

$$P_{EVCS}(t) = \sum_{i=1}^{N_{EV}} P_{EV,i}(t) \tag{1}$$

where $P_{EV,i(t)}$ represents the charging power of the i^{th} EV at time t. If all connected EVs operate at the same charging power P_{ch}, the EVCS demand can be approximated as,

$$P_{EVCS} = N_{EV} P_{ch} \tag{2}$$

The EVCS is represented as an additional load at the selected distribution-network bus. Its integration changes the bus power balance and may increase feeder current, voltage drop, and system losses. Therefore, the integration of EVCS can increase voltage stability issues in the distribution network due to the additional charging load and associated power demand.

3.2 Solar and wind modelling

In this work, solar photovoltaic (PV) and wind turbine systems are employed as renewable energy sources for the EV charging station. A solar PV cell converts solar energy into electrical energy through the photovoltaic effect. Silicon-based solar cells are the most commonly used PV technology. The performance of a PV system is significantly influenced by environmental conditions, particularly solar irradiance and temperature. The output current and power of the PV system vary with changes in solar irradiation. The power generated by the PV panel can be calculated using the following equation:

$$P_{PV}(t) = A\eta\mu(t) \tag{3}$$

Where, $P_{PV}(t)$ indicates PV power, A denotes area of solar panel placement, η specifies PV panel's efficiency and $\mu(t)$ represent irradiance of solar. Wind turbines convert the kinetic energy of wind into electrical energy. In this work, a doubly fed induction generator (DFIG)-based wind turbine model is employed. The power generated by the wind turbine is calculated using the following equation:

$$P_{wind}(t) = 0.5C_p\rho A v^3 \tag{4}$$

Where, $P_{wind}(t)$ denotes power obtained from wind turbine in kW, A indicates area swept by wind turbine in m^2, C_p power coefficient, ρ signifies air density kg/m^{3}and v represent wind velocity in m/s [35]. The integration of these renewable energy sources with the EV charging station may adversely affect system stability. Therefore, solar and wind energy sources are incorporated to enhance system stability and improve the overall performance of the charging station.

3.4 World Cup Optimization

The WCO algorithm is employed in this work to improve the VSI. The WCO algorithm [36] is inspired by the competitive process of FIFA World Cup matches, where the optimal solution is obtained through a mathematical representation of team competition. In this study, WCO is applied to determine the optimal locations for solar and wind energy sources in the IEEE 33-bus distribution system. The algorithm begins with a randomly generated population and iteratively searches for the global optimal solution. Let N denote the number of decision variables (buses), and M represent the maximum number of iterations.

$$W = \begin{bmatrix} W_{1,1} & W_{2,1} & \cdots & W_{m,1} \\ W_{1,2} & W_{2,2} & \cdots & W_{m,1} \\ \vdots & \vdots & \ddots & \vdots \\ W_{i,N} & W_{j,N} & \cdots & W_{m,N} \end{bmatrix} \tag{5}$$

The objective function considered for the proposed optimization algorithm is defined as follows:

$$F = F_r\left(W_{i,N}, W_{j,N}, \cdots\cdots, W_{m,N}\right) \tag{6}$$

A higher stability index value indicates that the transmission line is operating closer to its instability limit. By setting the discriminant of the quadratic voltage equation to zero, the critical condition

corresponding to the real voltage roots can be determined. A line is considered to be at its critical state when the stability index approaches unity. Therefore, to ensure secure and stable operation, the index
should be maintained below unity. The mathematical expression for the LSI is given as follows:

$$F_1 = \frac{4XQ_R}{Q_R \sin(\alpha - \beta)^2} \tag{7}$$

The LSF should be maintained below unity to ensure stable and secure operation of the system. It is calculated using the following equation:

$$F_2 = \frac{4X}{V_S^2}\left[\frac{XP_S^2}{V_S^2} + Q_R\right] \tag{8}$$

The FVSI should remain within an acceptable range and below unity to ensure stable system operation. As the FVSI approaches unity, the system moves closer to its voltage stability limit and may become susceptible to instability.

$$F = Max(F_1 + F_2 + F_3) \tag{9}$$

$$F_3 = \frac{4ZQ_R}{V_S^2 X} \tag{10}$$

Where, X indicates inductive reactance, Q_R denotes reactive power, V_S represent sending end voltage, α denotes angle at sending end, β indicates angle at receiving end, P_S signifies active power at sending end and Z denotes line impedance [37]. The ranking of the obtained fitness value is set as follows;

$$R = \frac{\chi \times \sigma + \overline{W}}{2} \tag{11}$$

$$\overline{W} = \frac{1}{n}\sum_{i=1}^{n} W_i \tag{12}$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(W_i - \overline{W}\right)^2} \tag{13}$$

Where, R indicates ranking, χ denotes increasing or decreasing values, σ represent standard deviation, W_i population value, $\overline{W}$ specifies mean value and n indicates number of population. In the WCO method, the second-best solution is identified after the first iteration, and the positions are updated for the next iteration using the following equation:

$$W_{new} = [W_{best}, W_{Rand}] \tag{14}$$

Where, W_{new} denotes new population matrix, W_{best} indicates best obtained value and W_{Rand} represent random value. W_{best} is obtained as follows;

$$\left(\frac{1}{2} \times A(u-l)\right) < W_{best} < \left(\frac{1}{2} \times A(u+l)\right) \tag{15}$$

Where, A signifies accuracy parameter, u denotes upper bound and l represent lower bound [38]. The process is repeated until the optimal solution is obtained. The WCO algorithm selects the optimal buses for PV and wind integration based on the defined fitness function. The parameters are randomly initialized within their specified limits, and the fitness value of each solution is evaluated. If a solution exceeds the allowable limit, its position is updated within the feasible range. This iterative process continues until the optimal allocation is achieved. The resulting optimal placement improves the stability of the distribution system. Figure1 illustrates the proposed modified IEEE 33-bus distribution system.

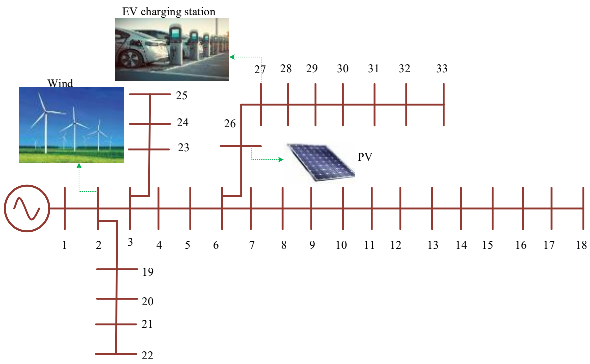


Figure 1: Modified IEEE 33 distribution network

Since the integration of an EV charging station can adversely affect system voltage stability, the WCO algorithm is employed to determine the optimal locations of solar PV and wind energy sources. Their optimal integration enhances the voltage stability and overall performance of the distribution system.

IV. Results and Discussion

The proposed method is implemented in the MATLAB/Simulink environment. The simulation results are evaluated in terms of solar PV power, wind turbine power, voltage profile, and EV charging demand. The convergence characteristics of the WCO algorithm are also analyzed to evaluate its optimization performance. The parameters used for implementing the proposed method are presented in Table 1. In this study, the EVCS is randomly located at selected buses in the distribution network to evaluate its impact on the voltage profile and stability of the system. The charging station is modeled as a load comprising Level-2 Nissan Leaf EVs [40], with a maximum of 35 EVs considered per hour.

Table 1: Implementation parameter

Description	Parameters	Values
PV	Maximum power	775kW
	Current at peak point	5.58A
	Voltage at peak point	54.7V
Wind	Nominal power	1.5MW
	Frequency	50Hz
EVCS	Rating of charging station	770W
	Rating of charging point	22kW
	No. of charging point	35
	Rated capacity	103Ah

The EV charging demand varies according to the number of connected vehicles. In the proposed system, PV and wind energy sources supply a portion of the required charging power, while the remaining power is provided by the utility grid. The specifications of the EV battery used in the study are presented in Table 2.

Table 2**:** EV battery specification

Battery Specification	Rated Value
Available battery energy	36 kWh
Rated battery voltage	350 V
Specific energy consumption	21 kWh/100 km
Maximum driving distance per charge	175 km
Charging duration at 220 V	8 h

As the EV charging load increases, the bus voltage magnitude gradually decreases. The integration of DG units improves the voltage profile by reducing the adverse impact of increased charging demand as shown in Figure 2. The voltage profile is evaluated under different operating conditions as follows:

Case 1: Distribution IEEE 33 Base case
Case 2: Distribution system with EVCS and solar PV
Case 3: Distribution system with EVCS and wind turbine
Case 4: Distribution system with solar PV, wind and EVCS.
Case 5: Distribution IEEE 33 with random EVCS placement

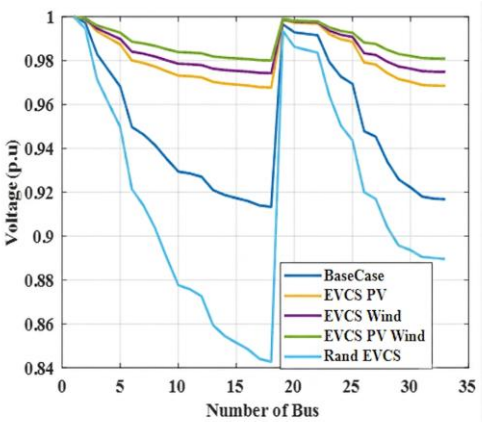


Figure 2: Voltage profile for 33 bus system

The FVSI is impacted in addition of EVCS and DG units to the distribution network. The FVSI is improved when DGs are implemented in distribution networks. Figure 3 illustrates how FVSI characteristics curve for IEEE-33 bus system. For this stability, results are taken for all five cases: base case, optimal PV with EVCS, optimal wind with EVCS, optimal PV-wind with EVCS, and random EVCS placement.

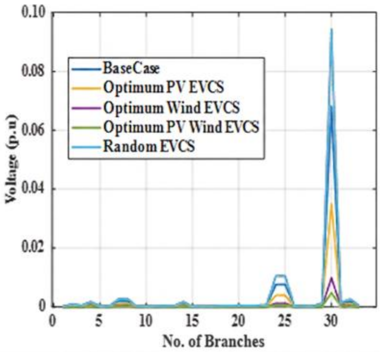


Figure 3: FVSI for 33 bus system

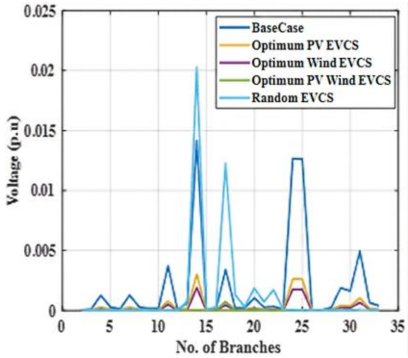


Figure 4: Line stability index for 33 bus system

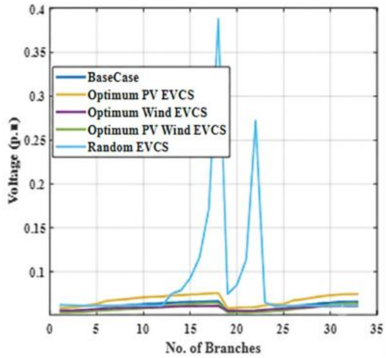


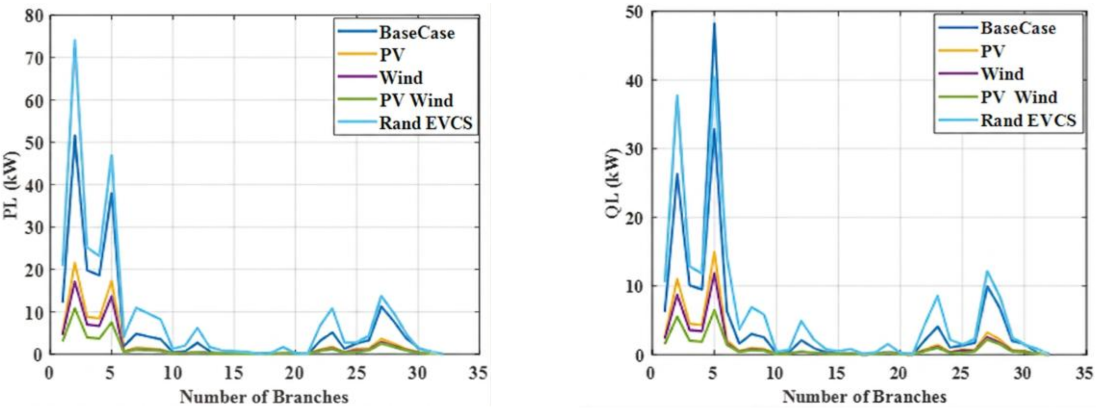
Figure 5: Line stability factor for 33 bus system

Figure 4 compares the LSI for the considered operating cases. The random EVCS case exhibits the highest voltage deviations, while the integration of PV and wind sources significantly reduces the deviations. The optimal PV-wind with EVCS case shows the lowest voltage deviation, confirming improved voltage regulation and enhanced network performance.

Figure 5 presents the LSF profile across the branches of the modified IEEE 33-bus distribution system under five operating conditions: The results indicate that the random EVCS case exhibits significantly higher VSI values, with pronounced peaks around branches 17-18 and 21-22, indicating increased branch stress and deterioration in voltage stability due to the additional EV charging load.

In comparison, the integration of renewable DG sources substantially reduces the VSI values across the network. The PV-wind integrated EVCS case achieves the lowest VSI profile, indicating improved voltage stability compared with the individual PV and wind cases. The reduction in VSI can be attributed to the local power support provided by renewable DG, which reduces power flow through critical branches and mitigates voltage drops. Therefore, the results demonstrate that the proposed optimal PV-wind DG integration is effective in alleviating the adverse impact of EVCS loading and enhancing the voltage stability of the distribution network.

Figure 6 shows active and reactive power loss for each branch. This power loss is considered for five cases and obtained from IEEE 33 distributed system The random allocation causes more losses while compared to others. Thus, power losses are reduced using the proposed algorithms.



(a) (b)

Figure 6: Power loss (a) Active (b) Reactive

Figure 7 presents the comparison of total active power losses for the five considered cases in the modified IEEE 33-bus distribution system. The base case exhibits a power loss of approximately 242 kW, while the integration of PV and wind generation reduces the losses to approximately 100 kW and 80 kW, respectively.

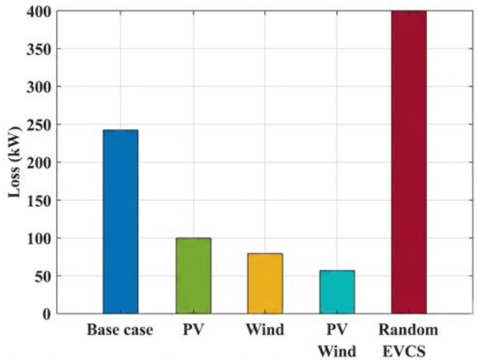


Figure 7: Comparison of losses

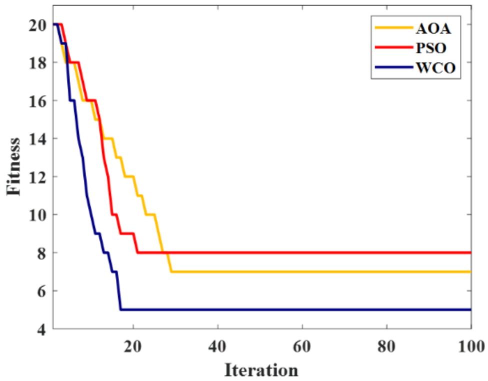


Figure 8: Comparison of proposed algorithm

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The combined PV-wind integration further reduces the power loss to approximately 55-60 kW. In contrast, the random placement of EV charging stations results in the highest power loss, reaching approximately 400 kW, due to the additional loading and unfavorable location of the EVCSs. These results clearly demonstrate that appropriate integration of renewable DG sources can significantly mitigate the increased power losses caused by EV charging loads and improve the overall operating performance of the distribution network.

Figure 8 represent the comparative analysis for proposed algorithm. Proposed algorithm is compared with existing Arithmetic Optimization Algorithm (AOA) [41] and particle swarm optimization (PSO) [42] algorithms. Above figure proves that the proposed method gets stable value with a smaller number of iterations, this shows effectiveness of the proposed method.

V. Conclusion and Future Scope

This study presented a hybrid solar-wind based EV charging system integrated into the modified IEEE 33-bus distribution network to enhance voltage stability and overall network performance. The EV charging stations were considered at random locations, while the WCO algorithm was employed to determine the optimal location and allocation of distributed generation (DG) sources. The proposed WCO-based approach was evaluated and compared with the Arithmetic Optimization Algorithm (AOA) and Particle Swarm Optimization (PSO) using MATLAB/Simulink. The performance was assessed in terms of power loss, bus voltage profile, LSI, FVSI and LSF. The comparative results demonstrate that the proposed WCO-based DG placement provides superior performance compared with AOA and PSO, achieving improved voltage profiles, reduced power losses, and enhanced voltage stability under EV charging conditions. Furthermore, the convergence analysis shows that WCO reaches a stable solution within fewer iterations, demonstrating faster convergence and confirming the effectiveness and computational efficiency of the proposed optimization approach. These results establish WCO as an effective technique for optimal DG placement in EV-integrated distribution networks. Future work will consider additional operational, economic, and power-quality constraints to further enhance the reliability and voltage stability of the system.

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