

# Transient Overvoltage Assessment of Renewable Energy Multi-Station Systems Under Outer Loop Control Delay

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## Abstract

The transient overvoltage issue during fault recovery in renewable energy multi-station systems severely constrains the accommodation and development of renewable energy; however, existing research lacks corresponding quantitative indicators and methods. Therefore, this paper proposes a transient overvoltage risk quantification method for renewable energy grid-connected systems considering reactive power saturation characteristics, starting from the transient overvoltage mechanism. First, an analysis model under the influence of various factors during fault recovery is established based on the transient overvoltage mechanism of renewable energy multi-station systems, demonstrating the rationality of evaluating transient overvoltage using a quasi-steady-state phasor model. After fully considering the saturation characteristics of post-fault converters and the interactions among renewable energy sources, an evaluation method for transient overvoltage in renewable energy multi-station systems is derived. By analyzing the relationship between system overvoltage levels and short-circuit ratio, an overvoltage short-circuit ratio index applicable to renewable energy multi-station systems and its practical application procedure are proposed. Case study results demonstrate that the proposed index and method can effectively evaluate the transient overvoltage risk and system security margin of renewable energy multi-station systems.

## Full Text

### Preamble

**Assessment of Temporary Overvoltage in Multiple Renewable Energy Station Systems with Control Lagging**

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## Abstract

The temporary overvoltage (TOV) problem during fault recovery in multiple renewable energy station systems (MRESS) severely constrains renewable energy accommodation and development, yet existing research lacks corresponding quantitative indicators and methods. This paper proposes a risk quantification method for TOV in renewable energy grid-connected systems considering reactive power saturation characteristics, starting from the TOV mechanism. First, based on the TOV mechanism of MRESS, an analysis model is established under different factors during fault recovery, demonstrating the rationality of assessing TOV using a quasi-steady-state phasor model. After fully considering the saturation characteristics of converters post-fault and the interactions among renewable energy generators, an evaluation method for TOV in MRESS is derived. By analyzing the relationship between system overvoltage level and short-circuit ratio, a temporary overvoltage short-circuit ratio (TOVSCR) indicator for MRESS and its practical application procedure are proposed. Simulation results show that the proposed indicator and method can effectively evaluate the TOV risk and safety margin of MRESS.

**Keywords:** Multiple renewable energy station system; reactive power saturation characteristic; temporary overvoltage; temporary overvoltage short-circuit ratio

## 0 Introduction

In recent years, China's renewable energy installed capacity has continued to grow rapidly. By the end of 2020, both wind power and photovoltaic installations had exceeded 250 GW [1]. The large-scale grid integration of renewable energy units, represented by wind power and photovoltaic systems, has led to a significant decrease in the proportion of synchronous generators in the power grid and increased the reactive power-voltage sensitivity of the power system [2-4]. When an AC short-circuit fault in a renewable energy station collection area is cleared, renewable energy units cannot promptly withdraw the reactive current injected during low-voltage ride-through (LVRT), resulting in reactive power surplus in the AC system. If the AC grid has weak voltage support capability, this may trigger temporary overvoltage problems in the grid near the fault location [5-7].

Instantaneous large voltage increases may cause irreversible damage to the insulation of renewable energy equipment. Therefore, grid codes for renewable energy equipment stipulate that when the grid-connection point voltage exceeds 1.3 times the rated voltage, the corresponding units are permitted to trip [8]. If a large number of units trip due to overvoltage, it will seriously threaten voltage stability and active power balance during the fault recovery phase, potentially triggering more severe cascading reactions that endanger the safe and stable operation of the power system. Consequently, accurately quantifying the temporary overvoltage level at the grid-connection points of various equipment in MRESS is crucial for grid security.

The TOV level in MRESS is primarily determined by the voltage support capability of the AC grid and the magnitude of surplus reactive power provided by renewable energy equipment [9]. The short-circuit ratio (SCR) is commonly used to analyze the voltage support capability and stability of AC grids with a single renewable energy device [10], where a larger SCR indicates a stronger AC grid and more stable system. However, the traditional SCR is determined solely by equipment capacity and the parameters of the external equivalent AC grid at the grid-connection point, without considering equipment control parameters or internal grid parameters, and lacks clear physical meaning when characterizing grid TOV levels.

To address this, scholars have proposed various indicators and methods for evaluating TOV in single-infeed systems [11-13], but these only reflect TOV during HVDC blocking when reactive compensation equipment serves as the surplus reactive power source, making it difficult to assess TOV caused by reactive power surplus due to control delays in renewable energy equipment after AC fault clearance. Moreover, since the interaction among converters in multi-infeed systems is not fully considered, these single-infeed TOV analysis methods are difficult to extend to multi-infeed systems. Reference [14] attempts to extend the applicability of these methods by decoupling multi-infeed systems, treating power electronic devices in hybrid multi-infeed systems as constant impedance to equivalently analyze multi-infeed systems as single-infeed systems. However, as the voltage at each equipment's grid-connection point and the reactive power injected into the grid mutually influence each other, the dynamic interaction among equipment and between equipment and the grid after a fault cannot be reflected through static voltage ratios in a certain state. Therefore, this method cannot accurately characterize TOV magnitude in multi-infeed systems.

On the other hand, since the electromagnetic transient process of the circuit after fault clearance affects system TOV magnitude, the rationality of evaluation methods based on quasi-steady-state phasor models in existing literature needs further examination. Additionally, considering converter saturation characteristics, the reactive power emitted by renewable energy has strong nonlinearity, and the pattern that the closer the fault point, the more severe the reactive power surplus after fault clearance, and the more severe the overvoltage may not hold. Therefore, existing literature yields conservative TOV assessment results

after ignoring converter reactive power saturation characteristics, but determining the fault location causing the most severe overvoltage through exhaustive enumeration also presents challenges after considering saturation characteristics.

To address these issues, this paper first analyzes the TOV mechanism in renewable energy station grid-connected systems and establishes mathematical models under different influencing factors. On this basis, the rationality of evaluating system TOV through quasi-steady-state phasor models is demonstrated. Furthermore, a TOV assessment method for multi-station grid-connected systems based on quasi-steady-state phasor models is proposed, and combined with its characteristics, a TOVSCR indicator is defined along with corresponding practical application methods. Finally, simulations verify the effectiveness of the proposed assessment method under different scenarios.

## 1 TOV Mechanism in Multiple Renewable Energy Station Grid-Connected Systems

In the MRESS shown in [Figure 1: see original paper], when an AC line fault occurs, renewable energy stations near the fault point enter LVRT status and inject large amounts of reactive current to support AC voltage according to grid code requirements, with reactive current references adjusted in real-time based on grid-connection point voltage magnitude. Although renewable energy units typically switch to reactive power-voltage droop control during faults to achieve faster reactive response [8], the reactive current reference that varies with grid-connection point voltage magnitude still introduces voltage magnitude detection delay. Combined with communication and actuator action time, renewable energy units typically require 20-40 ms delay (hereinafter referred to as control delay) after fault clearance to detect voltage magnitude changes [7]. Therefore, during fault recovery, the converter's reactive current reference can be considered consistent with that during the fault, causing renewable energy stations to inject large surplus reactive current and resulting in system TOV. Additionally, fault clearance causes grid topology changes, altering the energy storage state of internal inductors and capacitors and generating zero-input responses, which may also cause TOV. This paper focuses on TOV under the combined effects of these two factors.

Notably, the current injected by converters during faults has saturation effects, so the linear relationship between reactive power emitted by renewable energy and grid-connection point voltage does not always hold. In this case, the fault location causing the most severe TOV should be determined after comprehensively considering the above nonlinear factors and interactions among multiple stations to assess the system's TOV risk.

Since the inner loop time scale of renewable energy controllers with ideal feed-forward compensation is typically at the millisecond level, and the phase-locked loop (PLL) can be switched to "fast PLL" during transients to accelerate its response [15], it can be assumed that the current injected by renewable energy

during the detection delay period can effectively track its reference value, and the PLL can quickly track the grid-connection point voltage phase. Under these assumptions, the TOV response characteristics under controller outer loop delay should be the primary consideration after fault clearance, with inner loop and PLL dynamics approximately ignored.

To verify this analysis, the model and parameters of a single-infeed system from the case study are used, where the grid SCR = 2. When a three-phase metallic short-circuit fault occurs near the station's grid-connection point, the waveforms of grid-connection point voltage phase and station injected current after fault clearance are shown in [Figure 2: see original paper].

[Figure 2: see original paper] shows that: (1) There is a significant delay in the LVRT control switching of renewable energy stations, with voltage limit detection and control switching occurring approximately 40 ms after fault clearance; (2) Throughout the entire recovery process after fault clearance, both the grid-connection point phase and PLL angle change minimally, with inner loop current dq components remaining basically stable. Therefore, to analyze the mechanism of the most severe TOV generation, this paper ignores the influence of active components and PLL tracking errors, and considers that TOV after fault clearance is primarily caused by circuit dynamics and renewable energy control delay.

## 2.1 Dynamic Modeling of Renewable Energy Station Systems

To simplify analysis, this section models based on the single renewable energy station system shown in [Figure 3: see original paper]. For renewable energy stations with full-power converter grid integration such as direct-drive wind power or photovoltaic systems, the DC-side capacitor voltage during transients can be approximated as constant under the action of DC-side chopper circuits and DC voltage outer loop controllers. Therefore, the dynamics on both sides of the converter DC capacitor are decoupled, and the focus should be on the transient characteristics of the grid side.

In the synchronous rotating coordinate system, the node voltage equation of the renewable energy station grid-connected system during fault recovery can be expressed as:

$$\begin{bmatrix} U_t(s) \\ E(s) \end{bmatrix} = \begin{bmatrix} Y_1(s) & -Y_2(s) \\ Y_2(s) & Y_1(s) \end{bmatrix}^{-1} \begin{bmatrix} I_{vsc}(s) \\ I_{vqf}(s) \end{bmatrix} \quad (1)$$

$$I_{vsc}(s) = I_{vqf}(s) \quad (2)$$

where  $U_t(s)$  and  $E(s)$  are the column vectors of the renewable energy station's grid-connection point voltage and grid voltage, respectively;  $I_{vsc}(s)$  is the

column vector of the renewable energy station's output current, and  $I_{vqf}$  is the output current column vector during the fault, i.e., the renewable energy station maintains the fault-period output current unchanged during fault recovery; the admittance matrices  $Y_1$  and  $Y_2$  are respectively:

$$\begin{cases} Y_1(s) = \frac{1}{R_{l1} + sL_{l1}} + \frac{1}{R_{l2} + sL_{l2}} + sC_f \\ Y_2(s) = \frac{\omega_0}{R_{l1} + sL_{l1}} + \frac{\omega_0}{R_{l2} + sL_{l2}} \end{cases}$$

where  $\omega_0$  is the power frequency;  $R_{l1}, L_{l1}$  and  $R_{l2}, L_{l2}$  are the resistances and inductances of the lines on the left and right sides of the fault point, respectively;  $R_l$  and  $L_l$  are the resistance and inductance of the non-fault line, with  $R_l = R_{l1} + R_{l2}$  and  $L_l = L_{l1} + L_{l2}$ .

The above analysis shows that when considering the transient components of system voltage, TOV assessment must be performed in a high-order system, making the proposed method computationally complex and difficult to generalize to multi-machine systems. Therefore, it is necessary to evaluate the impact of overvoltage dynamic components on actual system safe operation and make reasonable simplifications to the renewable energy station system to obtain an applicable and practical assessment scheme.

## 2.2 Evaluation of Dynamic Component Effects

To analyze the influence of overvoltage dynamic components, the grid-connection point voltage of the renewable energy station system during fault recovery is solved from Equation (1) as:

$$U_t(s) = \frac{A_d(s)}{G_u(s)} I_{vqf}(s) + \frac{A_q(s)}{G_u(s)} E(s)$$

where  $A_d(s)$  and  $A_q(s)$  are the numerator expressions of the transfer function's dq axes, with detailed derivation and expressions provided in Appendix A;  $G_u(s)$  is the closed-loop characteristic equation of the transfer function:

$$G_u(s) = s^4 + Ds^3 + Ks^2 + Js + H$$

The characteristics of the grid-connection point voltage dynamic components are primarily determined by the poles of Equation (4). In addition to the pole at  $s = 0$ , Equation (4) can be decomposed into two second-order systems with damping ratios and undamped natural oscillation frequencies of:

$$\begin{cases} \xi_1 = \frac{1}{2\tau_1\omega_{n1}}, & \omega_{n1}^2 = \omega_0^2 + \omega_1^2 + \omega_2^2 - \tau^2 \\ \xi_2 = \frac{1}{2\tau_2\omega_{n2}}, & \omega_{n2}^2 = \omega_0^2 - \omega_1^2 - \omega_2^2 - \tau^2 \end{cases}$$

Therefore, the time-domain expression of the grid-connection point voltage dq dynamic components can be obtained through inverse transformation of Equation (3), which can be further synthesized into the amplitude expression of the grid-connection point voltage, i.e., the voltage envelope. The dq dynamic components each contain two oscillatory decay components with oscillation frequencies of  $\omega_{d1} = \omega_{n1}\sqrt{1-\xi_1^2}$  and  $\omega_{d2} = \omega_{n2}\sqrt{1-\xi_2^2}$ . Under typical parameters with SCR=2 in the case study of Section 4, these two oscillatory decay components have frequencies of 230 Hz and 315 Hz, with overvoltage spikes lasting no more than 3 ms per cycle. According to IEEE 2800-2022, renewable energy equipment should be able to withstand 1.6 p.u. overvoltage for at least 1 ms and 1.4 p.u. overvoltage for at least 3 ms [16]. Therefore, TOV caused by circuit dynamics typically does not pose a safety threat to equipment.

On the other hand, high-frequency harmonics affect the response speed of PLL and voltage magnitude detection, which is detrimental to renewable energy unit control and operation. Therefore, units typically employ filtering to obtain grid voltage information. For example, when using a first-order low-pass filter with a time constant of 1 ms, the cutoff frequency is only 159 Hz, making it difficult for units to detect the above high-frequency overvoltage. The obtained voltage information approximates the TOV under control delay. Considering the impact of voltage magnitude detection algorithms (e.g., full-wave Fourier) or control switching confirmation delays, unit control switching or protection typically does not act on TOV caused by circuit dynamics.

Therefore, TOV caused by circuit dynamics does not affect unit safe operation from the perspectives of equipment safety and protection action, and has limited impact on system-level TOV risk assessment. In contrast, TOV caused by control delay has a duration primarily determined by the delay length, with its magnitude depending on surplus reactive power, potentially causing equipment damage or tripping from the perspectives of equipment withstand time and protection detection action, posing a relatively greater threat to system safety. Consequently, TOV risk assessment in MRESS should primarily focus on TOV caused by control delay, making the quasi-steady-state phasor model appropriate for TOV assessment.

### 2.3 Quasi-Steady-State Modeling of Renewable Energy Station Systems

When ignoring overvoltage dynamic components, the complex frequency-domain expression of TOV caused by converter control delay can be obtained from Equation (3) as:

$$U_t(s) = \frac{H_d}{s} + \frac{J_d}{s^2} + \frac{K_d}{s^3} + \frac{D}{s^4}$$

where  $U_s$  is the AC grid equivalent potential, and the derivation of Equation (5) and definitions of constant terms ( $H_d$ ,  $J_d$ ,  $K_d$ ,  $D$ ) are detailed in Appendix B.

According to grid code requirements, when the grid-connection point voltage magnitude ( $U_t$ ) drops below 0.9 p.u. during a fault, the renewable energy station's output current reference phasor is [8]:

$$\begin{cases} I_{vdf} = -I_{max} \sin \theta_f \\ I_{vqf} = I_{vq0} + k(0.9 - U_t) \\ I_{vdf} = I_{max} \cos \theta_f \end{cases}$$

where  $I_{max}$  is the maximum allowable current of the renewable energy station,  $I_{vq0}$  is the pre-fault reactive current reference,  $k$  is the reactive gain coefficient, and  $\theta_f$  is the phase angle at the station's grid-connection point during the fault.

In inductance-dominated networks, reactive power has a far greater impact on voltage than active power. Since this paper focuses on the most severe overvoltage scenarios, it can be assumed that the converter capacity is entirely used to provide reactive power during faults, i.e.,  $I_{vdf} = 0$ . Additionally, since the station has no active power output during faults,  $\theta_f$  can be approximated as 0. In this case, the renewable energy station's control coordinate system aligns with the system's global coordinate system, and Equation (6) becomes:

$$I_{vqf} = I_{vq0} + k(0.9 - U_t)$$

The power-frequency steady-state value of TOV can then be obtained as:

$$U_t = U_s - X_g I_{vqf}$$

where  $X_g$  is the equivalent reactance from the voltage source to the grid-connection point. The derivation of Equation (7) is provided in Appendix B. It can be seen that TOV magnitude is primarily determined by the reactive current injected by the renewable energy station during faults and  $X_g$  (grid strength).

Considering that the output reactive current is controlled by the grid-connection point voltage, to avoid iterative solving in multi-infeed systems [18], the renewable energy station can be equivalently represented as a parallel combination of a constant reactive current source  $I_{vsc} = k + I_{vq0}$ , a virtual reactance  $X_k = 1/k$ , and a variable reactive current source  $I_v$ , as shown in [Figure 4: see original paper]. The specific proof of this equivalence is provided in Appendix C.

In the figure,  $X_{vsc} = X_k // X_{cf}$ ,  $X_{cf} = 1/(\omega C_f)$ , and  $R_g$  and  $X_g$  are the equivalent resistance and reactance of the AC system, respectively. This model uses the abrupt change of  $I_v$  to characterize the two operating conditions before and after the fault, enabling decoupling of the renewable energy station from the grid in voltage calculations. Since pre-fault grid node voltages are close to 1 p.u. and VSCs operating at unity power factor generate current  $I_{vsc0} = I_{vd0} = P_{vsc0}/U_{t0}$ ,

the change in reactive current magnitude injected by the renewable energy station in the system global coordinate system during fault recovery compared to pre-fault is:

$$\Delta I_{vq} = I_{vqf} - I_{vq0} = 0.9k - 0.1kU_t$$

## 2.4 TOV Assessment for Multiple Renewable Energy Station Systems

Consider an n-bus power system with m renewable energy stations and k synchronous generators, as shown in [Figure 1: see original paper], where buses  $i (i = 1, \dots, m)$  are renewable energy station grid-connection buses, bus  $f$  is the fault bus, buses  $j (j = m + 1, \dots, m + k)$  are synchronous generator buses, and the remaining buses are passive. The original system impedance matrix is  $Z$ . When using the equivalent model described in Section 2.1, with each station  $L_{vsci}$  attributed to the AC grid side, the AC grid node impedance matrix  $Z$  is modified to  $Z'$ .

When a three-phase metallic short-circuit fault occurs at bus  $f$  of the AC grid, the node equation gives the voltage changes at each bus as:

$$\Delta U = Z' \Delta I$$

where  $\Delta U = [\Delta U_1, \dots, \Delta U_f, \dots, \Delta U_n]^T$  and  $\Delta I = [0, \dots, \Delta I_{qi}, \dots, \Delta I_f, \dots, 0]^T$ .

From Equation (9), the reactive current injected by renewable energy stations during faults is:

$$I_{vqf} = \Delta I_q + \Delta I_{vq} + I_{vsc}$$

where  $\Delta I_q = [-I_{d01} \sin \theta_{0i} - 0.1k_1, \dots, -I_{d0i} \sin \theta_{0i} - 0.1k_i, 0, \dots, 0]^T$ ,  $S = \text{diag}(S_i)$ , and  $K = \text{diag}(k_i)$ .

Under converter saturation constraints:  $I_{vqfi} \leq I_{max} S_i$ . The influence of multi-station interaction can be considered by solving for the equivalent reactive gain coefficient of renewable energy stations:

$$k_{li} = \begin{cases} a_i, & I_{vqfi} \leq I_{max} S_i \\ \frac{b_i}{I_{eqi} - I_{vqfi}} + a_i, & I_{vqfi} > I_{max} S_i \end{cases}$$

where  $a_i$  and  $b_i$  are constants related to fault location,  $S_i$  is the ratio of rated capacity to system base capacity, and  $I_{eqi} = I_{max} - I_{vq0i}$  is the equivalent saturation value considering initial reactive current. Therefore, the pre-fault operating state of converters also affects TOV magnitude. When  $I_{vq0}$  is smaller,

the converter's operating range is larger under severe near-end faults, the surplus reactive current injected is greater, and the system TOV is more severe.

From Equations (10) and (11), the surplus reactive current considering converter saturation is:

$$\Delta I_{vq} = K_l \Delta I_q$$

where  $K_l = \text{diag}(k_{l1}, k_{l2}, \dots, k_{lm}, \dots, 0)$ . The specific form of surplus reactive current injected by the  $i$ -th station is:

$$\Delta I_{vqi} = \sum_{j=1}^m Z'_{ij} \Delta I_{qjj} + \sum_{j=m+1}^{m+k} Z'_{ij} \Delta I_{qjj}$$

where  $Z'_{ij}$  is the element in the  $i$ -th row and  $j$ -th column of the modified node impedance matrix, and  $S_{eq}$  is the equivalent transient capacity of renewable energy stations under fault conditions.

Since renewable energy stations in LVRT status after fault clearance are surplus reactive power sources, the transient voltage rise caused during the control delay period is the TOV to be solved. Therefore, the TOV at the grid-connection point of the  $i$ -th station in MRESS is:

$$\Delta U_i = \sum_{j=1}^m \text{MIIF}_{ij} \Delta I_{vqj}$$

where  $\text{MIIF}_{ij}$  is the voltage interaction factor between stations  $i$  and  $j$  [17].

### 3.1 TOVSCR Indicator

Equation (14) shows that when grid strength is greater, grid nodes are more tightly connected (smaller  $Z'_{ij}$ ), and system TOV is smaller. Therefore, grid strength is inversely proportional to system TOV. Based on Equation (14), the following short-circuit ratio indicator can be defined to quantify TOV risk in MRESS:

**Definition:** The reciprocal of the maximum grid-connection point TOV caused by control delay during fault recovery in MRESS is defined as the Temporary Overvoltage Short-Circuit Ratio (TOVSCR):

$$\text{TOVSCR} = \frac{1}{\max(\Delta U_i)} = \frac{1}{\sum_{j=1}^m \text{MIFIF}_{ij} S_{eqj}}$$

where the Multi-Infed Fault Interaction Factor (MIFIF) can be expressed as:

$$\text{MIFIF}_{ij} = \alpha_{ij} \times \text{MIIF}_{ij}, \quad \alpha_{ij} = \frac{Z'_{ff}}{Z'_{if}Z'_{jf}}$$

$\alpha_{ij}$  is the fault effect coefficient, which fully considers the interaction among multiple machines under fault conditions by modifying the MIIF proposed by CIGRE.

It is worth noting that the TOVSCR proposed in this paper has the same form as the gSCR proposed in references [19-20], both based on the concept of weighted grid sensitivity. TOVSCR and gSCR determine appropriate weighting coefficients based on the mechanisms of system TOV and small-signal stability, respectively, making system safety and stability assessment more accurate and theoretically rigorous.

The above analysis shows that the proposed TOVSCR indicator is defined based on system static characteristics and is a linear indicator, yet it can characterize TOV risk under large disturbances. Through reasonable equivalent modeling, the change in network topology before and after faults is cleverly transformed into changes in equivalent constant current source magnitude.

It should be noted that the assessment approach proposed in this paper is not limited to TOV caused by renewable energy control delay. From Equations (15) and (16), for TOV problems caused by untimely switching of reactive compensation equipment during DC blocking or commutation failure, the corresponding indicator can be obtained by simply adjusting the surplus reactive current magnitude according to its mechanism.

When a station trips due to its grid-connection point voltage reaching the limit ( $U_{t\_limit}$ ), other stations may face cascading trip risk. Therefore, the system can be considered to be in a critical safety state when the maximum voltage at each station's grid-connection point equals  $U_{t\_limit}$ . The TOVSCR value at this point is defined as the critical TOVSCR (CTOVSCR):

$$\text{CTOVSCR} = \frac{1}{U_{t\_limit} - 1}$$

### 3.2 Application Method for TOVSCR Indicator

Equation (17) shows that after considering converter reactive power saturation characteristics, the TOVSCR value has a nonlinear relationship with fault location, making it difficult to directly determine the fault location corresponding to the most severe overvoltage. Therefore, all nodes in the system must be traversed to obtain the maximum TOVSCR under all operating conditions to assess system TOV risk. To improve efficiency and practicality, a practical application method for TOVSCR should be proposed.

Using the decoupled equivalent modeling method for renewable energy stations described in Section 2.3, the corresponding modified network can be obtained. If the equivalent renewable energy stations are treated as constant-current loads injecting current, the network contains two types of nodes: load nodes composed of converters and passive nodes, and voltage source nodes composed of generators and synchronous condensers. Therefore, the network admittance matrix can be partitioned according to load nodes and voltage source nodes:

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} B_{LL} & B_{LG} \\ B_{GL} & B_{GG} \end{bmatrix} \begin{bmatrix} U_L \\ U_G \end{bmatrix}$$

where matrix  $B_{LL}$  characterizes the connection relationship and interaction among loads, and  $B_{LG}$  characterizes the connection relationship and interaction between voltage sources and loads.

From the system's reactive power flow equations:

$$Q_L(U_L) + I_{vq} = B_{LL}U_L + B_{LG}U_G$$

where  $Q_L$  and  $I_{vq}$  are the reactive power demand column vectors of passive nodes and reactive current injection column vectors of converters, respectively, and  $U_L$  and  $U_G$  are the voltage column vectors of load nodes and synchronous generator nodes, respectively.

When the network is unloaded,  $Q_L = 0$ , and the voltage at each load node, i.e., the no-load voltage, is:

$$U_{L0} = -B_{LL}^{-1}B_{LG}U_G$$

Therefore, the reactive power demand of passive nodes under any system condition is:

$$Q_L(U_L) = B_{LL}(U_L - U_{L0})$$

From Equation (21), the system's reactive power-voltage sensitivity matrix is:

$$J = \frac{\partial Q_L}{\partial U_L} = B_{LL} + \text{diag}(I_{vq}) \frac{\partial I_{vq}}{\partial U_L}$$

When the system operates under light or no-load conditions,  $U_L = U_{L0}$ , and:

$$J_0 = B_{LL}$$

Since overvoltage at each node in multi-feed systems is typically slightly higher than no-load voltage, the reactive power-voltage sensitivity matrix obtained

from Equation (23) can approximately characterize the relationship between voltage and reactive power at each node after fault clearance.

When the small  $\Delta I_q$  is ignored, the magnitude of surplus reactive power injected by each converter under any node voltage can be expressed as:

$$\Delta Q_{vsc} = \text{diag}(U_L) \Delta I_{vq}$$

At this point, the influence of converter saturation is reflected in limiting the elements in the modified impedance matrix:

$$Z'_{ij} = \begin{cases} Z_{ij}, & I_{vqfi} \leq I_{max} S_i \\ \frac{I_{max} S_i}{I_{vqfi}} Z_{ij}, & I_{vqfi} > I_{max} S_i \end{cases}$$

The relative magnitude of TOV caused by faults at different nodes in the system can be evaluated using the reactive power-voltage sensitivity matrix weighted by the corresponding surplus reactive power input:

$$J_e = J_0^{-1} \text{diag}(\Delta I_{vq}) Z'$$

The above analysis shows that the row and column corresponding to the maximum element of matrix  $J_e$  respectively characterize the renewable energy station grid-connection point with the most severe TOV and the fault location causing that overvoltage. Therefore, the system TOV assessment method based on matrix  $J_e$  proposed in this paper is applicable to networks of any structure and has strong adaptability.

It can be seen that although renewable energy station control systems contain strong nonlinearities such as saturation, the influence of these nonlinearities on TOVSCR can be eliminated by determining the fault point corresponding to the most severe condition and selecting appropriate converter reactive power output coefficients.

### 3.3 TOV Assessment Process

[Figure 5: see original paper] Evaluation process of temporary overvoltage

Based on the above analysis, the TOV assessment for renewable energy station grid-connected systems can be summarized as the process shown in [Figure 5: see original paper], with key steps as follows:

- 1) Determine the power of each equipment during pre-fault steady state, and obtain the network topology and parameters during normal operation.
- 2) Use Equation (26) to calculate the weighted sensitivity matrix  $J_e$ , identifying the grid-connection point with the most severe overvoltage and the corresponding fault location.

- 3) Use Equation (15) to calculate the system' s TOVSCR.
- 4) Compare TOVSCR with its critical value; the difference can characterize the system' s TOV safety margin.

## 4 Case Study

To verify the effectiveness of the proposed TOV calculation method for renewable energy power systems, simulation models are built on the PSCAD platform. As shown in [Figure 6: see original paper], TOV in both single-infeed and multi-infeed systems is analyzed. The single-infeed system structure is shown in Figure (a), where multiple devices in the same station can be equivalently represented as a single device. The multi-infeed system uses the IEEE New England 39-bus test system, with its structure shown in Figure (b), where all stations use full-power renewable energy equipment. System parameters are shown in Table D in Appendix D, and network parameters are consistent with the standard test system [21].

### 4.1 Validation of Quasi-Steady-State Modeling Rationality

To verify the effectiveness of the system TOV calculation method during fault recovery, the short-circuit ratio of the equivalent AC system is set to 2 and 3, respectively. A three-phase short-circuit fault lasting 0.2 s occurs near the grid-connection point at  $t = 1$  s. Simulation analysis yields the RMS waveform of the high-frequency transient component of the grid-connection point voltage and the corresponding power-frequency steady-state component RMS waveform. Equations (3) and (7) can be used to calculate the overvoltage transient component envelope and power-frequency steady-state value, respectively, with comparison results shown in [Figure 7: see original paper].

Figures (a) and (c) show that under different grid strengths, the calculated envelopes of TOV caused by circuit dynamics can effectively reflect the trend of RMS value changes. Figures (b) and (d) show that the calculated power-frequency steady-state components under different conditions are basically consistent with simulation results, with a maximum error of only 3.17%, proving that the proposed overvoltage calculation method has good accuracy.

It should also be noted that the oscillation frequency of TOV caused by circuit dynamics is very high (mainly containing 230 Hz and 310 Hz components when SCR=2 in the figure). Equipment control systems typically include filters to remove high-frequency harmonics to ensure stable control. Using a first-order low-pass filter with a time constant of 10 ms as an example, its cutoff frequency is 16 Hz, and the voltage components at 230 Hz and 310 Hz are attenuated to 6.92% and 5.13% of their original amplitudes, respectively. Therefore, the voltage information obtained by equipment control and protection systems is mainly the power-frequency component of overvoltage caused by control delay after filtering (Figures 7(b) and (d)), which is also the main factor affecting equipment

tripping. Therefore, TOV risk assessment for MRESS oriented toward system safety is more suitable for calculation methods dominated by control delay.

## 4.2 Validation of Multi-Station TOV Risk Assessment Method Effectiveness

To verify the effectiveness of the proposed short-circuit ratio indicator, this section evaluates the TOV risk of grids with different strengths. To maintain the relative voltage support capability among grid nodes, the system strength can be equivalently adjusted by proportionally changing equipment capacity. When equipment capacity is consistent with Table D in Appendix D, the weighted sensitivity matrix calculation results for the multi-infeed system are shown in [Figure 8: see original paper].

[Figure 8: see original paper] shows that the most severe TOV at renewable energy station 3 occurs when bus 17 faults. Therefore, at  $t = 1$  s, a three-phase ground fault lasting 0.1 s is applied at bus 17, and renewable energy units continue to maintain LVRT status for 30 ms after the fault.

Calculation shows that the system's TOVSCR is 2.51 at this time, meaning the most severe TOV reaches 1.4 p.u., indicating system TOV risk. The grid-connection point voltage curves of each renewable energy unit during fault recovery are shown in [Figure 9: see original paper].

The figure shows that under the effect of control delay after fault clearance, since each converter maintains the reactive current injected during LVRT, the voltage at each grid-connection point rapidly rises under the excitation of surplus reactive power sources and reaches a steady-state peak of 1.41 p.u., consistent with the analytical calculation results.

When each equipment capacity is proportionally reduced by 0.24 times, i.e., the grid strength is effectively increased by the corresponding factor, the weighted sensitivity matrix calculation results for the multi-infeed system are shown in [Figure 10: see original paper].

Since the system's  $MIOSCR = CMIOSCR = 3.33$  when bus 17 faults, the system is in a critical safety state in terms of TOV. The grid-connection point voltage curves of the system's renewable energy stations are shown in [Figure 11: see original paper].

In summary, the calculation results of the proposed indicator are consistent with time-domain simulation results. The distance between the TOVSCR of MRESS and its critical value can reflect the system's TOV safety margin, verifying the effectiveness of the proposed indicator.

## 5 Conclusion

This paper analyzes the TOV mechanism of renewable energy station grid-connected systems, proposes a TOV calculation method for different stages of

fault recovery, and introduces a TOVSCR indicator applicable to multi-station systems. The main conclusions are:

- 1) From the perspectives of renewable energy unit withstand time and protection action, control delay is the main factor affecting system-level TOV risk assessment, and quasi-steady-state phasor models should be used for evaluation.
- 2) The critical TOVSCR is a constant value. The TOVSCR indicator proposed from the perspective of power system static equivalence can accurately characterize the system's TOV safety margin through its distance from the critical value.
- 3) After considering converter reactive power saturation characteristics, the weighted sensitivity matrix can directly identify the renewable energy station grid-connection point with the most severe TOV and the corresponding fault node location, avoiding cumbersome exhaustive calculations and making the proposed assessment method applicable to arbitrary network structures.

Excessive surplus reactive current and weak grid strength are the main causes of system TOV. The risk of TOV should be fully considered in the rapid development of renewable energy, and adequate grid strength should be maintained to avoid cascading failures caused by overvoltage. Future work will focus on extending the assessment approach to more scenarios by studying additional TOV mechanisms, and on suppressing TOV by improving control structures and strategies during fault and recovery periods.

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## Appendix A

Solving  $U_t(s)$  from Equation (1) yields:

$$U_t(s) = \frac{A_d(s)}{G_u(s)} I_{vqf}(s) + \frac{A_q(s)}{G_u(s)} E(s)$$

Substituting each variable expression gives:

$$G_u(s) = s^4 + Ds^3 + Ks^2 + Js + H$$

The characteristic equation is:

$$G_u(s) = s^4 + 2\tau s^3 + (\omega_0^2 + \omega_1^2 + \omega_2^2)s^2 + 2\tau\omega_0^2 s + \omega_0^2\omega_2^2$$

The numerator expression of Equation (A.28) is:

$$A_d(s) = s^2 + 2\tau s + \omega_0^2 + \omega_1^2$$

where the transfer function matrix  $Y_3(s)$  is:

$$Y_3(s) = \frac{1}{R_{l1} + sL_{l1}} + \frac{1}{R_{l2} + sL_{l2}}$$

Under typical line parameters,  $\tau$  is very small, and the second term of Equation (A.29) is positive. After factorization, the two second-order factors have:

$$\omega_{n1,2}^2 = \omega_0^2 \pm \sqrt{\omega_0^4 - \omega_1^2\omega_2^2}$$

It is evident that both constant terms are positive and much larger than  $\tau$ , resulting in underdamped oscillations in both second-order factors obtained from the decomposition.

## Appendix B

First, ignoring the dynamic components and energy storage of dynamic elements in Equation (1), i.e., the  $s$  terms in the transfer function  $G(s)$ , and the initial currents and voltages of inductors and capacitors, we obtain:

$$U_t(s) = \frac{H_d}{s} + \frac{J_d}{s^2} + \frac{K_d}{s^3} + \frac{D}{s^4}$$

After matrix inversion and rearrangement, the analytical expression for the grid-connection point voltage is:

$$U_t(s) = \frac{H_d}{s} + \frac{J_d}{s^2} + \frac{K_d}{s^3} + \frac{D}{s^4}$$

The definitions of  $H_d$ ,  $J_d$ ,  $K_d$ , and  $D$  are as follows:

$$\begin{cases} H_d = R_l I_{vd} \\ J_d = \omega L_l I_{vq} - \omega C_f R_l I_{vd} \\ K_d = \omega^2 L_l C_f I_{vd} - \omega R_l C_f I_{vq} \\ D = \omega^2 L_l C_f R_l \end{cases}$$

From Equations (B.2)-(B.6) and applying the final value theorem:

$$\lim_{s \rightarrow 0} sU_t(s) = H_d$$

Considering that the active current of equipment remains unchanged during the delay period after fault clearance, i.e.,  $i_{vd} = i_{vdf} = 0$ , and since the network is inductance-dominated with small resistance, system TOV is primarily the d-axis component, i.e.,  $U_t \approx U_{td}$ . Ignoring line resistance, the expression for  $U_t$  can be written as:

$$U_t = U_s - X_g I_{vqf}$$

where  $B_f = \omega C_f$  and  $X_l = \omega L_l$ . Considering that the filter capacitor  $C_f$  is very small, the  $B_f$  term can be ignored, giving:

$$U_t \approx U_s - X_g I_{vqf}$$

where  $X_g = 0.5X_l$  is the total reactance of the double-circuit line from the voltage source to the grid-connection point. Since typically  $U_s \approx U_{t0}$ :

$$\Delta U_t \approx -X_g \Delta I_{vqf}$$

## Appendix C

From Equation (7), when ignoring the active current component injected by converters during faults, the injected current can be rearranged as:

$$I_{vqf} = I_{vq0} + k(0.9 - U_t) = (k + I_{vq0}) - kU_t = I_{vsc} - Y_k U_t$$

Therefore, the renewable energy station can be equivalently represented as a parallel combination of a constant reactive current source  $I_{vsc} = k + I_{vq0}$ , a virtual reactance  $X_k = 1/Y_k = 1/k$ , and a variable reactive current source  $I_v$ .

## Appendix D

**Table D Rated Parameters of Multi-Infeed System**

Parameter	AC System 1	AC System 2
Reactive power coefficient (k)	0.1 p.u.	0.1 p.u.
Filter time constant (Tf)	30 ms	30 ms
Current saturation value (Imax)	2 p.u.	2 p.u.
Equipment 1 capacity	1.2 p.u.	0.5; 0.75
Equipment 2 capacity	0.75; 1	0.75; 1
Equipment 3 capacity	0.75; 1	-
Line resistance-reactance ratio	0.1	0.1
Voltage level	230 kV	230 kV
Base capacity	200 MVA	400 MVA

*Note: Figure translations are in progress. See original paper for figures.*

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