

Article

Transient Overvoltage Assessment and Influencing Factors Analysis of the Hybrid Grid-Following and Grid-Forming System

Xindi Liu, Jiawen Cao and Changgang Li *

Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education, Shandong University, Jinan 250061, China; liuxindi@mail.sdu.edu.cn (X.L.); caojiawen@mail.sdu.edu.cn (J.C.)

* Correspondence: lichgang@sdu.edu.cn

Abstract

With the large-scale integration of renewable energy devices into the power grid, the voltage stability of the renewable energy base is becoming increasingly weak, and the problem of transient overvoltage is becoming increasingly severe. Grid-forming (GFM) converters can provide strong voltage support. When GFM converters are paralleled with grid-following (GFL) converters, they can effectively reduce transient overvoltage. However, hybrid systems involve many parameters and exhibit complex dynamics, making assessment of transient overvoltage difficult. To address this, this paper first uses Thevenin's theorem to reduce the renewable transmission system to an equivalent model. Next, the voltage assessment of the hybrid system is analyzed across the pre-fault, mid-fault, and post-fault stages of a short-circuit fault. Then, based on the characteristics of a phase-locked loop (PLL), this paper innovatively derives an assessment method for transient overvoltage at the common coupling point (PCC) under different PLL stability conditions. Additionally, the influence of GFL converter parameters, GFM converter parameters, the GFM capacity ratio on transient overvoltage, and the external system reactance are analyzed. Finally, the proposed evaluation method and factor analysis are validated through electromechanical transient simulation using the simulation software STEPS v2.2.0.

Keywords: hybrid GFL and GFM system; transient overvoltage; phase-locked loop; capacity ratio; influencing factors analysis



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1. Introduction

1.1. Background and Motivation

Driven by global energy transition strategies, many countries are accelerating the deployment of power systems dominated by renewable sources such as wind and solar. The rapid increase in renewable energy capacity has profoundly altered the power system dynamics [1,2]. Traditionally, the power grid relies on synchronous generators (SGs) to provide steady voltage support, whereas the large-scale renewable energy base must rely on power electronic converters to support voltage. Converter dynamics depend on their control modes, which can be divided into two main categories: grid-following (GFL) converters [3–5] and grid-forming (GFM) converters [6–8]. These two converters exhibit distinct dynamics, and their interaction makes the hybrid GFL and GFM system characteristics more complicated.

The complex control dynamics of power electronic converters presents critical challenges to power system security and stability. During fault conditions, the control strategies

of different converters have varying responses [9]. While GFL converters maintain grid synchronization through a phase-locked loop (PLL), GFM converters exhibit autonomous voltage source characteristics. The parameters of the hybrid system are numerous and the control characteristics are coupled, resulting in complex voltage transient processes when encountering faults [10]. Therefore, the transient voltage assessment and influencing factors analysis of the hybrid system face severe challenges.

1.2. Literature Review and Research Gap

To address these issues, many studies have been conducted. Regarding hybrid GFL and GFM system analysis, ref. [11] utilized the phase plane method and phasor diagram method to analyze the transient stability of hybrid systems. Ref. [12] focuses on small-disturbance stability, demonstrating that strategically deploying GFM converters in large-scale renewable systems can strengthen the grid and mitigate PLL-related instability risks. Most of the current work, as in [13,14], focuses on studying the stability of PLLs when a GFL converter is used alone. The mechanism of transient overvoltage when GFL and GFM converters are connected in parallel is not clear. In terms of transient overvoltage assessment, ref. [15] proposed a transient voltage stability assessment method that takes into account topological changes by utilizing deep transfer learning and parameter fine-tuning. Ref. [16] proposed a method for effectively calculating overvoltage that only requires the equivalent parameters of the AC system and the operating parameters of the DC system. Ref. [17] starts with the mechanism of transient overvoltage and introduces a method based on generalized short-circuit ratio for overvoltage (gSCR-TOV) to quantify the risk of overvoltage. The mechanisms and influencing factors of transient overvoltage under typical faults such as commutation failure and DC blocking are discussed in Refs. [18,19], and corresponding suppression strategies are proposed. On the influence of factors, ref. [20] analyzed the influence of the key parameters of PLL on the transient characteristics of GFL converters, finding that reducing the integral coefficient of the PLL can enhance the transient stability. Ref. [21] proved the influence of reactive power loops on the transient stability of GFM converters, constructing a stability criterion based on the Lyapunov function. Ref. [22] verified through experimental comparison that standalone inverters have better stability and provide overall better power quality than grid-tied inverters. Ref. [23] demonstrated through experiments that implementing both storage components (i.e., battery and supercapacitor) enhances the voltage in the presence of rapid fluctuations in the renewable station.

At present, research mainly focuses on analysis of transient overvoltage in conventional GFL systems. The current research has not deeply considered the characteristics of the converter and the stability of the PLL, and there is a lack of research on the assessment and influencing factors analysis of transient overvoltage in hybrid GFL and GFM systems.

1.3. Contributions

The contributions of this paper are as follows:

- (1) Based on the characteristics of the renewable energy station, this paper simplifies and makes assumptions for large-scale renewable energy transmission systems, GFL converters, and GFM converters, and it proposes a simplified model of a hybrid GFL and GFM converters station.
- (2) Using phasor diagrams and circuit theorem, we propose a transient overvoltage assessment method applicable to different PLL stability conditions.
- (3) We analyze the influencing mechanisms of the converter parameters, the capacity ratio of GFL and GFM converters, and the external system on overvoltage, and we propose measures to reduce overvoltage for each of them.

1.4. Paper Organization

Section 1 introduces the research background, literature review, and contributions of this paper. Sections 2.1 and 2.2 introduce the modeling methods for hybrid systems, including converter control modes and system simplification assumptions. Section 2.3 presents the transient overvoltage assessment procedure for different PLL stability conditions across the pre-fault, mid-fault, and post-fault stages. Section 2.4 analyzes the influencing mechanisms of different factors on overvoltage. Section 3 validates the theoretical findings and proposed methods through simulations. Section 4 summarizes the research conclusions and suggests directions for future work.

2. Materials and Methods

2.1. Converter Control Mode

Figure 1 illustrates the control mode structure of the GFL converter. The PLL tracks the phase of the voltage $U_1 \angle \theta_1$ at the common coupling point (PCC) and outputs θ_{PLL} . The current control loops yield the active and reactive currents I_d and I_q , respectively. The GFL converter can be represented as an equivalent current source [24]; the magnitude $I_{Terminal}$ and the phase angle φ of its terminal-injected current are calculated according to Equation (1):

$$\begin{cases} I_{Terminal} = \sqrt{I_d^2 + I_q^2} \\ \varphi = \arctan \frac{I_q}{I_d} \end{cases} \quad (1)$$

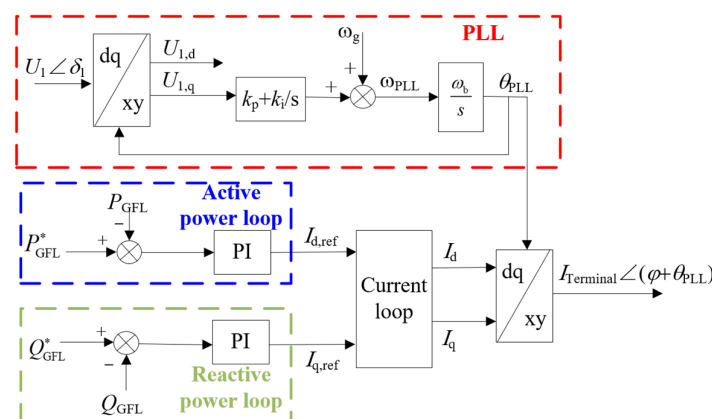


Figure 1. The control mode of the GFL converter.

In Figure 1, $U_{1,d}$ and $U_{1,q}$ are the d-axis and q-axis components of the voltage tracked by the PLL, respectively; k_p and k_i denote the proportional and integral gains of the PLL, respectively; ω_g , ω_{PLL} , and ω_b are the per-unit values of the nominal grid angular frequency, the PLL output angular frequency, and the base angular frequency, respectively; P_{GFL}^* and P_{GFL} represent the commanded and actual active power values of the GFL converter, respectively; Q_{GFL}^* and Q_{GFL} are the commanded and actual reactive power values, respectively; $I_{d,ref}$ and $I_{q,ref}$ are the reference values of the active and reactive currents, respectively; and PI denotes a proportional–integral control block.

The most widely adopted control mode for GFM converters is the virtual synchronous generator (VSG) control, which emulates the operational characteristics of a synchronous machine and provides inertia and damping features [25]. The control modes of GFM converters also include droop control, power synchronization control, virtual oscillator control, and matching control. However, due to their identical external characteristics, this paper only analyzes the VSG-controlled converter. The VSG control structure is shown in Figure 2. Because the inner voltage and current loops respond very quickly, they can

be regarded as ideal. Consequently, the external characteristic of the GFM converter is equivalent to a controlled voltage source [26].

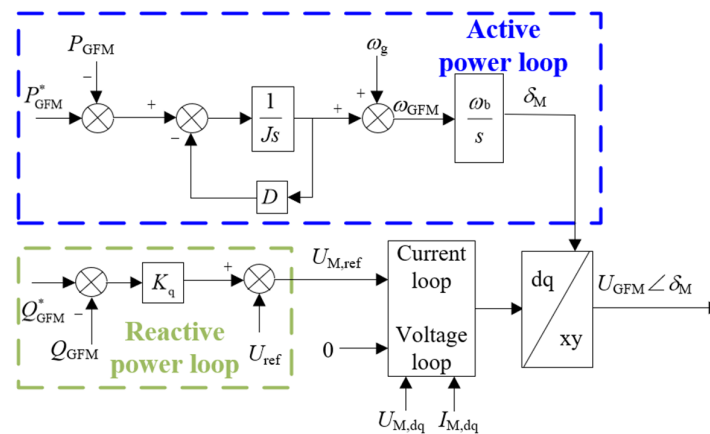


Figure 2. The control mode of the GFM converter.

In Figure 2, P_{GFM}^* and P_{GFM} are the commanded and actual active power values for the GFM converter, respectively; J is the inertia constant; D is the damping coefficient; ω_{GFM} is the angular frequency output by the active power loop; Q_{GFM}^* and Q_{GFM} are the commanded and actual reactive power values, respectively; K_q is the reactive power droop coefficient; U_{ref} is the nominal voltage magnitude; $U_{\text{M,ref}}$ is the reference voltage magnitude; $U_{\text{M,dq}}$ and $I_{\text{M,dq}}$ denote the dq-frame output voltage and current of the GFM converter, respectively; and U_{GFM} and δ_{M} are the magnitude and phase angle of the GFM converter's output voltage, respectively.

2.2. Hybrid GFL and GFM System

Due to differences in terrain conditions, the topology of renewable energy transmission systems exhibits significant diversity. Different landforms, such as mountains, deserts, and coasts, directly affect the layout of power transmission corridors, resulting in different topological structures such as long chains, radiating patterns, or mixed networks. Figure 3 represents the structural diagram of a typical renewable energy transmission system.

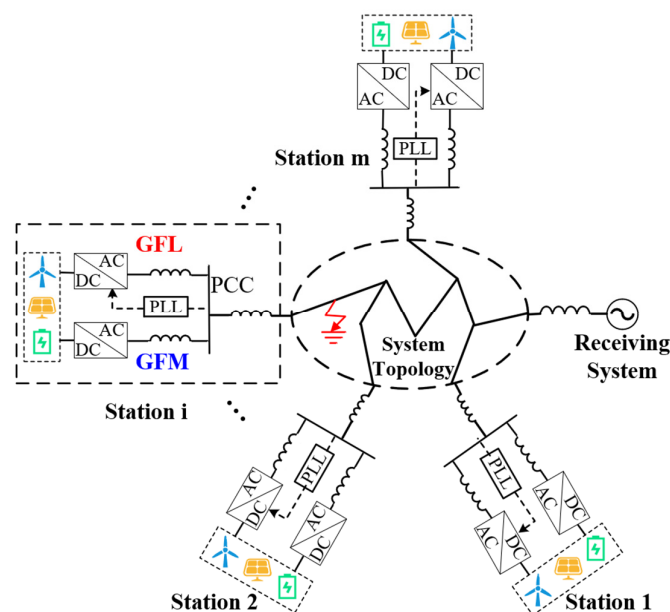


Figure 3. The model of the hybrid GFL and GFM system.

Assuming that the system includes m stations, the stations are connected to the grid and collected through transmission lines. The impedance influence of external station i can be ignored, and only the system topology part should be considered. The resistance value in the system is relatively small and can also be ignored.

Thevenin's theorem applies to networks that only contain linear elements and satisfy the superposition principle. It requires that the network can contain independent sources internally, but the network itself must be linear and time-invariant. The advantage of Thevenin's equivalence lies in the fact that when analyzing an external system, only two components need to be faced, greatly simplifying the circuit and reducing its complexity, which can significantly improve design efficiency. Obviously, the external transmission system in this paper can be simplified as a Thevenin equivalent circuit. Therefore, through equivalence, the external Thevenin reactance of station i is X_i , and the power source is U_{grid} .

Based on the analysis in Section 2.1, the GFL and GFM converters can be represented by an equivalent current source $I_{\text{Terminal}} \angle (\varphi + \theta_{\text{PLL}})$ and an equivalent voltage source $U_{\text{GFM}} \angle \delta_M$, respectively. Therefore, we can equate station i in Figures 3 and 4. The GFL and GFM converters are connected in parallel at the PCC and then collected via transmission lines before being fed into the main grid. To date, the majority of studies on hybrid GFL and GFM systems have adopted this model.

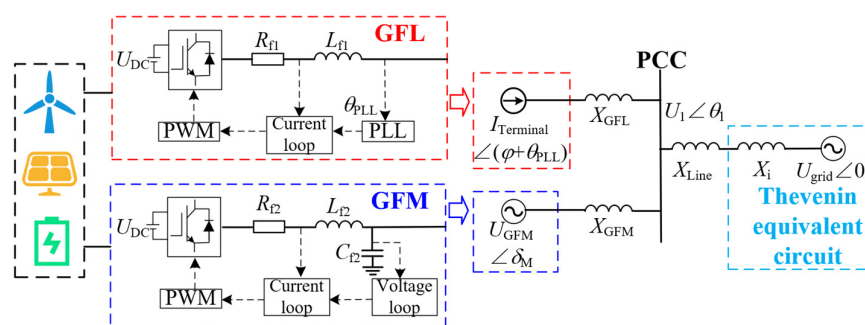


Figure 4. The simplified model of a hybrid GFL and GFM converters station.

In Figure 4, U_{dc} is the DC voltage, while R_{f1} , L_{f1} , R_{f2} , and L_{f2} are the filtering resistance and capacitance of GFL and GFM converters, respectively. The base capacity of the system is S_{base} . The capacity of the GFL converters is S_{GFL} , and their output current magnitude is $I_L = I_{\text{Terminal}}(S_{\text{GFL}}/S_{\text{base}})$. The capacity of the GFM converters is S_{GFM} , and its internal reactance is X_{GFM} . When calculated to the system capacity, $X_M = X_{\text{GFM}}(S_{\text{base}}/S_{\text{GFM}})$. The outgoing transmission-line reactance is X_{Line} . The external system's Thevenin reactance is X_i . The total reactance of the line $X_g = (X_L + X_i)$, and the grid voltage is $U_{\text{grid}} \angle 0^\circ$.

The hybrid system involves numerous parameters and complex control dynamics. To simplify the analysis, the following assumptions are made:

- (1) A three-phase short-circuit fault occurred in the transmission line outside the station. Assuming that the voltage at the PCC drops below the low-voltage ride-through (LVRT) threshold. Both GFL and GFM converters switch to LVRT mode during the fault and enter LVRT recovery mode after fault clearance. Due to the fact that the control strategy change process belongs to the electromagnetic transient process, it can be ignored when studying the overvoltage at the electromechanical transient scale.
- (2) To ensure rapid response, the current control loop bandwidth of GFL converters typically ranges from tens to hundreds of hertz. Conversely, the PLL bandwidth is usually set between a few and several tens of hertz to suppress harmonics and noise. Because the current-loop bandwidth is several times that of the PLL, when studying the characteristics of the PLL, the current loop regulation process can be ignored, and

it is considered that the current loop has reached a steady state, that is, $I_d = I_{d,ref}$, $I_q = I_{q,ref}$.

- (3) The GFM converters are assumed to have a high overcurrent capability, ensuring that U_{GFM} remains essentially constant. Moreover, their large inertia constant keeps the power angle δ_M almost unchanged during faults. It can be considered that the δ_M during the fault period is equal to the steady value δ_{M0} before the fault.

2.3. Transient Overvoltage Analysis and Assessment of Hybrid GFL and GFM System

2.3.1. Pre-Fault

By representing the GFL converter as a current source and the GFM converter as a voltage source, their nonlinear characteristics are effectively linearized. Consequently, the superposition theorem can be used to first analyze each component's individual influence and then to assess their combined coupling effect.

Before the fault occurs, the system is in a steady state. As shown in Figure 4, according to the circuit superposition theorem, the voltage at the PCC is the sum of various power components at the station, as expressed below:

$$U_1 \angle \theta_1 = U_L \angle (\varphi + \theta_{PLL} + 90^\circ) + U_M \angle \delta_M + U_g \angle 0^\circ \quad (2)$$

where U_L , U_M , and U_g are the amplitudes of the voltage phasors generated by the GFL converter, the GFM converter, and the power grid at the PCC, respectively. Their values are $U_L = X_M X_g I_L / (X_M + X_g)$, $U_M = X_g U_{GFM} / (X_M + X_g)$, and $U_g = X_M U_{grid} / (X_M + X_g)$.

The phasor diagram of the system during steady state before the fault can be derived from Equation (2) and is shown in Figure 5, where d_{GFL} and q_{GFL} represent the d-axis and q-axis of the GFL converter, respectively, with the directions of $I_d > 0$ and $I_q > 0$ defined as the positive directions of the d-axis and q-axis. It can be deduced from the dq transformation that, under the GFL converter output condition, $I_d > 0$, $I_q < 0$, and $j < 0$.

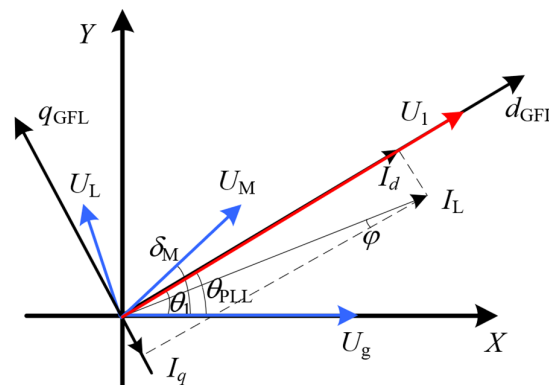


Figure 5. Pre-fault phasor diagram.

Based on the phasor relationship shown in Figure 5, the phase angle and amplitude of the voltage at the PCC can be derived as expressed in Equations (3) and (4):

$$\theta_1 = \arctan \left[\frac{U_L \sin(\varphi + \theta_{PLL} + 90^\circ) + U_M \sin \delta_M}{U_g + U_M \cos \delta_M + U_L \cos(\varphi + \theta_{PLL} + 90^\circ)} \right] \quad (3)$$

$$U_1 = U_L \cos(\varphi + \theta_{PLL} + 90^\circ - \theta_1) + U_M \cos(\delta_M - \theta_1) + U_g \cos \theta_1 \quad (4)$$

Equation (2) is derived solely from the circuit superposition theorem, while Equations (3) and (4) are obtained from Equation (2) through phasor analysis. Therefore, they are still applicable during the transient processes both during and after the fault clearance. However, it should be noted that, in different transient processes, some variables in Equations (3) and (4)

will continuously change, but they may not be directly obtained. To evaluate transient overvoltage and explore the influence of various parameters, the transient variation processes of each quantity are analyzed below.

2.3.2. Mid-Fault

As shown in Figure 3, when a short-circuit fault occurs in a certain part of the system, the Thevenin impedance changes to X'_i and the voltage drops to U'_{grid} . At the same time, X_g becomes $X'_g = (X_L + X'_i)$, and the unit enters LVRT. At this time, the voltage $U'_g = X_M U'_{grid} / (X_M + X'_g)$. From Equation (3), it can be seen that θ increases. Due to the fact that θ_{PLL} is a state variable and cannot undergo sudden changes, at this point $\theta_1 > \theta_{PLL}$, the relationship between the phasors is shown in Figure 6.

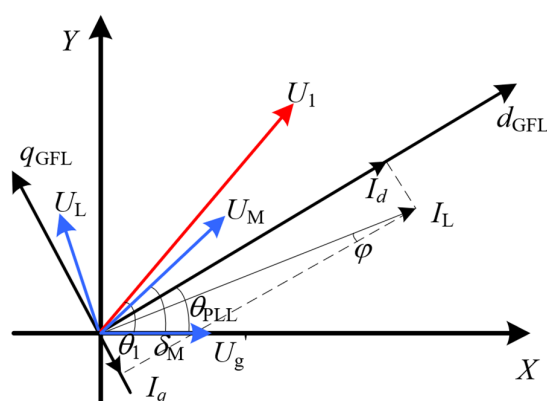


Figure 6. Phasor diagram at the instant of fault.

The existence of a PLL balance point during faults is conditional [27]. Under low-voltage conditions, the PLL may not accurately track the phase of the power grid, posing a risk of instability. Therefore, the following will determine whether the PLL can maintain stability during the fault period:

The tracking target of the PLL is $\theta_{PLL} = \theta_1$. When this equation holds during the fault period, it can be considered that the PLL has a balance point and can maintain stability. Firstly, we can assume that the PLL remains stable during the fault, which means $\theta_1 = \theta_{PLL}$; substituting this into Equation (4) and simplifying it yields

$$\sin \theta_{PLL} (U'_g + U_M \cos \delta_M) - \cos \theta_{PLL} U_M \sin \delta_M = \cos \theta_{PLL} U_L \cos(\theta_{PLL} + \varphi) + \sin \theta_{PLL} U_L \sin(\theta_{PLL} + \varphi) \quad (5)$$

Using the identity $\cos \varphi = \cos \theta_{PLL} \cos(\theta_{PLL} + \varphi) + \sin \theta_{PLL} \sin(\theta_{PLL} + \varphi)$ and collecting the terms containing U_L , we obtain

$$(U'_g + U_M \cos \delta_M) \sin \theta_{PLL} - U_M \sin \delta_M \cos \theta_{PLL} = U_L \cos \varphi \quad (6)$$

Equation (6) is of the form $A \sin x - B \cos x = C$. By introducing the magnitude R and phase φ , it can be rewritten as follows:

$$\begin{cases} R = \sqrt{(U'_g + U_M \cos \delta_M)^2 + (U_M \sin \delta_M)^2} \\ \varphi = \arctan\left(\frac{U_M \sin \delta_M}{U'_g + U_M \cos \delta_M}\right) \end{cases} \quad (7)$$

The equation simplifies to

$$R \sin(\theta_{PLL} - \varphi) = U_L \cos \varphi \quad (8)$$

To make Equation (8) solvable, the following condition must be satisfied:

$$|\sin(\theta_{PLL} - \phi)| = \left| \frac{U_L \cos \varphi}{R} \right| \leq 1 \quad (9)$$

$$U_L \cos \varphi \leq \sqrt{U_g'^2 + 2U_g'U_M \cos \delta_M + U_M^2} \quad (10)$$

By substituting U_g , U_M , and U_L into Equation (10), the condition for the PLL to maintain stability is simplified as follows:

$$I_{d,ref} \leq \sqrt{\left(\frac{U'_{grid}}{X'_g}\right)^2 + \frac{2U'_{grid}U_{GFM} \cos \delta_M}{X_M X'_g} + \left(\frac{U_{GFM}}{X_M}\right)^2} \quad (11)$$

The satisfaction of Equation (11) divides into two cases: (a) Satisfied: the PLL reaches a stable state; (b) Unsatisfied: the PLL loses stability. As Equations (3) and (4) show, the transient overvoltage magnitude U_1 can only be obtained after θ_{PLL} is known. Therefore, θ_{PLL} is solved below according to whether the PLL remains stable.

(1) When the PLL is Stable:

As shown in Figure 6, there is a difference between θ_{PLL} and θ_1 at the moment of fault. When the PLL can remain stable, as the PLL tracks θ_1 , the difference between the two gradually decreases. It can be considered that there is $\theta_{PLL} = \theta_1$ before the fault is cleared. At this time, the phasor diagram is shown in Figure 7.

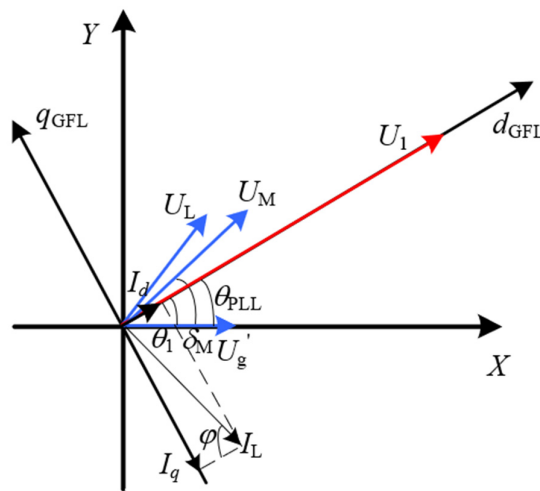


Figure 7. Phasor diagram at the instant before fault clearance under stable PLL.

When Equation (11) is satisfied, the PLL remains stable, and the solution of Equation (8) is

$$\theta_{PLL} = \phi + \arcsin\left(\frac{U_L \cos \varphi}{R}\right) + 2k \times 180^\circ \quad (k \in \mathbb{Z}) \quad (12)$$

or

$$\theta_{PLL} = \phi - \arcsin\left(\frac{U_L \cos \varphi}{R}\right) + (2k + 1) \times 180^\circ \quad (k \in \mathbb{Z}) \quad (13)$$

During the fault, the PLL is stable and satisfies $0^\circ < \theta < 90^\circ$ and $0^\circ < \varphi < \delta_M = \delta_{M0} < 90^\circ$. We can derive $-90^\circ < (\theta_{PLL} - \varphi) < 90^\circ$. Therefore, $k = 0$, and Equation (13) can be discarded. Substituting φ into Equation (12) yields

$$\theta_{PLL} = \arctan\left(\frac{U_M \sin \delta_{M0}}{U_g' + U_M \cos \delta_{M0}}\right) + \arcsin\left(\frac{U_L \cos \varphi}{\sqrt{U_g'^2 + 2U_g'U_M \cos \delta_{M0} + U_M^2}}\right) \quad (14)$$

(2) When the PLL is Unstable:

In the PLL diagram of Figure 1, the input voltage $U_1 \angle d_1$ is transformed by inverse dq to output $U_{1,q}$, and then the w_{PLL} is obtained. Finally, the phase angle q_{PLL} is obtained through the integration process.

As can be seen from the PLL control block diagram in Figure 1,

$$\dot{\theta}_{PLL} = k_p U_{1,q} + k_i \int U_{1,q} \quad (15)$$

By decomposing Equation (2) into d-axis and q-axis components, $U_{1,q}$ can be obtained:

$$U_{1,q} = I_{d,ref} \frac{X_M X'_g}{X_M + X'_g} - U_{GFM} \sin(\delta_M - \theta_{PLL}) \frac{X'_g}{X_M + X'_g} - U'_{grid} \sin \theta_{PLL} \frac{X_M}{X_M + X'_g} \quad (16)$$

Substitute U_M , U'_g , and Equation (16) into Equation (15) to obtain

$$\begin{aligned} \ddot{\theta}_{PLL} = & -k_p (U_M \cos(\theta_{PLL} - \delta_M) \dot{\theta}_{PLL} + U'_g \cos \theta_{PLL} \dot{\theta}_{PLL}) \\ & + k_i (I_{d,ref} \frac{X_M X'_g}{X_M + X'_g} - U_M \sin(\theta_{PLL} - \delta_M) - U'_g \sin \theta_{PLL}) \end{aligned} \quad (17)$$

When the balance point does not exist, the phase of the PLL approximately exhibits a power-function-level monotonic change and diverges. According to the assumption analysis in the previous section, the bandwidth of the PLL is generally between a few hertz and several tens of hertz. Therefore, the phase angle q_{PLL} output by the PLL does not change significantly in a short period of time. Therefore, in Equation (17), the θ_{PLL} can be replaced by its initial value θ_{PLL0} before the fault. The current loop regulation speed is fast, and it can be considered as $I_d = I_{d,ref}$. Therefore, a differential equation with variable coefficients can be transformed into a second-order linear differential equation with constant coefficients. Simplifying Equation (17) into Equations (18) and (19), we can obtain

$$\ddot{\theta}_{PLL} + C_1 \dot{\theta}_{PLL} = C_2 \quad (18)$$

$$\begin{cases} C_1 = k_p (U_M \cos(\theta_{PLL0} - \delta_{M0}) + U'_g \cos \theta_{PLL0}) \\ C_2 = k_i (I_{d,ref} \frac{X_M X'_g}{X_M + X'_g} - U_M \sin(\theta_{PLL0} - \delta_{M0}) - U'_g \sin \theta_{PLL0}) \end{cases} \quad (19)$$

By substituting the initial values and derivative initial values, we can obtain:

$$\begin{cases} K_1 = \theta_{PLL0} - \frac{C_2 / C_1 - \dot{\theta}_{PLL0}}{C_1} \\ K_2 = \frac{C_2 / C_1 - \dot{\theta}_{PLL0}}{C_1} \end{cases} \quad (20)$$

The complete solution of Equation (18) is:

$$\theta_{PLL}(t) = K_1 + K_2 e^{-C_1 t} + \frac{C_2}{C_1} t \quad (21)$$

Assuming that $\theta_{PLL} > \theta_1$ before the fault is cleared, the phasor diagram is shown in Figure 8.

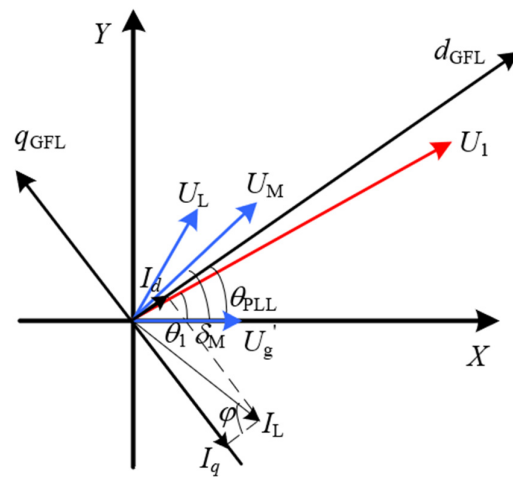


Figure 8. Phasor diagram at the instant before fault clearance when PLL is unstable.

2.3.3. Post-Fault

After the fault is cleared, the grid voltage support is restored. When the GFL converter enters LVRT recovery mode, the output I_q is still greater than the steady-state value, which has a significant supporting effect on the voltage and causes transient overvoltage. Figure 9 shows the phasor diagram at the moment of fault clearance when the PLL is stable.

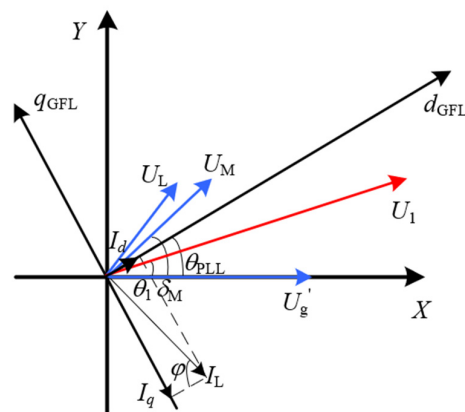


Figure 9. Phasor diagram at the instant before fault clearance when PLL is stable.

At the moment of fault clearance, U'_g returns to U_g . According to Equation (3), θ_1 decreases instantly, while θ_{PLL} cannot suddenly change. This causes PLL deviation and results in inaccurate output current of the GFL converter, which may worsen or alleviate transient overvoltage [15]. Let $\theta = \theta_{PLL} - \theta_1$, $-180^\circ \leq \theta \leq 180^\circ$. At the moment of fault clearance, Equation (4) shows the relationship between the voltage support effect of the GFL converter and θ .

When the PLL is stable, $\theta > 0$ during the fault clearance period is beneficial for alleviating overvoltage. When the PLL is unstable, it may lead to $-2\varphi - 180^\circ < \theta < 0$, further worsening overvoltage. Therefore, when evaluating overvoltage, it is necessary to correct the PLL deviation. The transient overvoltage assessment process, taking into account PLL stability and deviation, is shown in Figure 10.

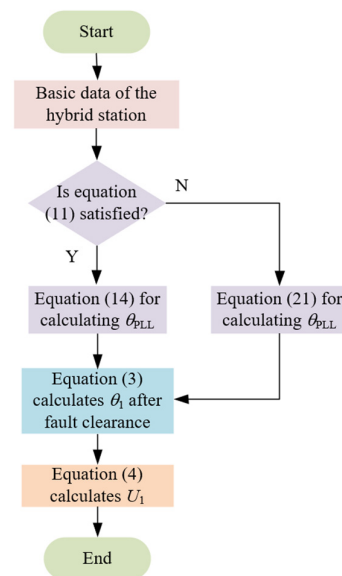


Figure 10. Transient overvoltage assessment process.

2.4. Analysis of Overvoltage's Influencing Factors

From the analysis in the previous section, it can be seen that the parameters and characteristics of GFL and GFM converters have a significant influence on transient overvoltage. Therefore, this section explores the specific effects of each factor and proposes measures to reduce transient overvoltage.

2.4.1. The Parameters of Converters

(1) The GFL Converters:

After the fault is cleared, the reactive current I_q output by GFL converters cannot quickly retract, resulting in reactive surplus, which is the fundamental cause of transient overvoltage. The amplitude and retraction speed of I_q are directly related to the magnitude and duration of overvoltage. Therefore, analysis will be conducted from two perspectives: reducing the amplitude of I_q , and accelerating the speed of I_q retraction.

The amplitude of I_q depends on the control parameters during LVRT, as shown in Equation (22):

$$I_{q,\text{ref}} = k_1 \cdot (U_{\text{in}} - U_1) + k_2 \cdot I_{q,0} + I_{q,\text{set}} \quad (22)$$

where k_1 , k_2 , and k_3 are all reactive current coefficients; U_{in} is the threshold value for LVRT; $I_{q,0}$ is the initial value of reactive current; and $I_{q,\text{set}}$ is the set value of reactive current.

Reducing both the reactive current coefficient and the initial set values can reduce I_q . However, a low I_q means that the voltage support capability of the GFL converter is also low, which is not conducive to the voltage recovery and may lead to unit disconnection [28]. Taking wind units as an example, according to the technical regulations, when a short-circuit fault occurs and the voltage is between 20% and 90% of the nominal voltage, the reactive current per unit provided by the unit should satisfy Equation (23). Therefore, the amplitude of I_q needs to be comprehensively considered in conjunction with the voltage support capability during the fault period and the transient overvoltage level.

$$I_{q,\text{ref}} \geq 1.5 \times (0.9 - U'_g) \quad (23)$$

The retraction speed of I_q depends on the parameters during the LVRT recovery mode. The T_q determines the time required for the reactive current to retract to normal levels. Therefore, reducing T_q can increase the rate of change in I_q , thereby shortening the duration

of transient overvoltage. However, rapid changes in I_q may cause voltage oscillations, affecting the normal operation. Therefore, when setting parameters, it is necessary to comprehensively consider transient overvoltage and the stability of the converter.

(2) The GFM Converters:

In actual operation, the GFM converters may experience overcurrent, affecting U_{GFM} and its voltage support capability. Therefore, the next step is to explore the influence of overload current on U_{GFM} .

Common technical specification requires the GFM converter to operate for at least 2 s under 2 times the overload current. Currently, mainstream GFM converters can achieve 10 s of operation under 3 times the overload current. When the current exceeds the threshold, it will switch to the current-limiting control mode, and the U_{GFM} will not be able to remain constant, resulting in significant changes in voltage support capability. The current overload parameter of GFM converters is commonly represented by I_{max} . During fault periods, when I_{max} is not limited, the output current is I_m . When the current limit is I_{max} ($I_{max} < I_m$), the internal potential can no longer be maintained at U_{GFM} , but at $(I_{max}/I_m)U_{GFM}$. When $I_{max} < I_m$, as I_{max} increases, the GFM converter can be regarded as a voltage source with an internal potential approaching U_{GFM} . When $I_{max} \geq I_m$, the converter can be considered to be an ideal voltage source. The control modes are shown in Figure 11.

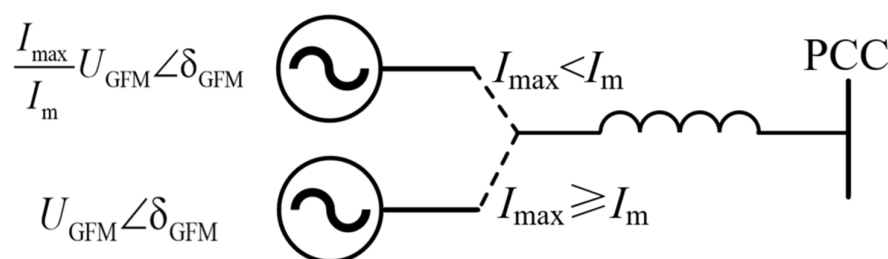


Figure 11. The control modes of the GFM converter at different I_{max} .

During the fault period, the GFM converter has two modes (current-limiting and non-current-limiting), which depend on the parameter I_{max} . Raising the I_{max} of the GFM converter strengthens its voltage support during faults and alleviates post-fault overvoltage. However, as I_{max} increases, the costs also rise. Therefore, in actual configuration, it is necessary to consider both the voltage support benefits and economic investment.

2.4.2. The Capacity Ratio of GFL and GFM Converters

As the capacity of GFM converters increases, they can provide stronger voltage support and reduce transient overvoltage. Therefore, the following will calculate the capacity ratios of GFL and GFM converters that can meet the transient overvoltage constraints.

Assuming that the voltage safety threshold at the PCC is U_{safe} , the total capacity of the system is nS_{base} , the capacity of the GFL converters is S_{GFL} , and the capacity of the GFM converters is S_{GFM} . Substituting $S_{GFL} + S_{GFM} = nS_{base}$, $I_L = I_{Terminal}(S_{GFL}/S_{base})$ and $X_M = X_{GFM}(S_{base}/S_{GFM})$ into Equation (4), we can assess the transient overvoltage that takes into account the capacity ratio of GFL and GFM converters.

The capacity ratio of GFM converters is assumed to be η . The cost of GFM converters is relatively high, so it is necessary to minimize η while meeting the requirements of transient overvoltage. Therefore, the following analysis shows the minimum value of η when the most severe metallic short-circuit fault occurs; that is, $U'_g = 0$. At this capacity ratio, when other short-circuit faults occur, the PCC voltage can meet the requirements of transient overvoltage.

When $U'_g = 0$, it can be considered that GFM converters only output reactive current I_q and the amplitude of I_q reaches its maximum: $I_{q,ref} = I_{Terminal} = I_{q,max}$, $I_{d,ref} = 0$, $\varphi \approx -90^\circ$. From Equation (11), it is evident that the PLL can maintain stability. Then, we substitute $U'_g = 0$ into Equation (14) to obtain the pre-fault-clearance $\theta_{PLL} = \theta_1 = \delta_M$. According to the cosine theorem, we can derive

$$U_1 = \sqrt{U_g^2 + (U_M + U_L)^2 + 2U_g(U_M + U_L)\cos\delta_M} \quad (24)$$

Since $0^\circ \leq \delta_M \leq 90^\circ$ and $0 \leq \cos\delta_M \leq 1$, then there is:

$$U_1 \leq U_g + U_M + U_L \quad (25)$$

By substituting U_g , U_M , U_L , $S_{GFL} + S_{GFM} = nS_{base}$, and their respective quantities into Equation (4), we can obtain the capacity ratio of GFM converters under voltage transient constraints, as follows:

$$\eta_1 = \frac{X_{GFM}(nX_g I_{q,max} + U_{grid} - U_{safe})}{nX_g(U_{safe} + X_{GFM}I_{q,max} - U_{GFM})} \quad (26)$$

In addition to transient overvoltage constraints, renewable energy units should also meet the constraint of not disconnecting from the grid after encountering short-circuit faults. When the fault occurs, $U_{grid} = 0$, $X_i = 0$, and the GFL converter has no voltage support capability ($U_L = 0$). The minimum voltage at the PCC for renewable energy units that are not disconnected from the grid is U_{min} . Substituting each quantity into Equations (3) and (4), it can be calculated that the minimum capacity ratio of GFM converter h_2 is

$$\eta_2 = \frac{X_{GFM}U_{min}}{nX_L(U_{GFM} - U_{min})} \quad (27)$$

Taking into account the transient overvoltage constraint and the constraint of the unit not disconnecting from the grid, the capacity ratio of GFM converters of station i should be η_i . Meanwhile, the ratio of GFL converters is $(1-\eta_i)$.

$$\eta_i = \max(\eta_1, \eta_2) \quad (28)$$

2.4.3. The Influence of External System

Here, $1/X_g$ denotes the external voltage support strength of station i ; the larger $1/X_g$ is, the stronger the grid's support to the station. The grid component of the voltage at the PCC is $U_g = X_M U_{grid} / (X_M + X_g)$. As the grid's support gradually weakens, the station's transient voltage characteristics become increasingly dominated by the GFL and GFM converters. For station i , X_g is determined by the outgoing transmission-line reactance X_{Line} and the external system's Thevenin reactance X_i . The roles of these two components are analyzed separately below.

(1) X_{Line} :

A larger external transmission-line reactance X_{Line} of hybrid GFL and GFM station i leads to a larger X_g and, thus, reduces the grid's voltage support strength, weakening the coupling between the station and the grid. Moreover, a higher X_{Line} causes a larger power-angle difference across the line, severely affecting the system's synchronizing stability. The most effective way to reduce X_{Line} is to shorten the distance between the station and the grid. However, when long transmission lines are unavoidable—to maximize wind and solar resource utilization— X_{Line} can still be lowered by decreasing the line's reactance per unit length, employing bundled conductors, or using expanded-diameter conductors.

(2) X_i :

The system topology and the capacity of GFM converters both influence the external Thevenin reactance X_i of station i . The influence of GFM capacity has been analyzed in Section 2.4.2, so this section focuses solely on the influence of system topology. Common topologies for renewable energy transmission systems include radial and long-chain configurations, as illustrated in the following Figure 12:

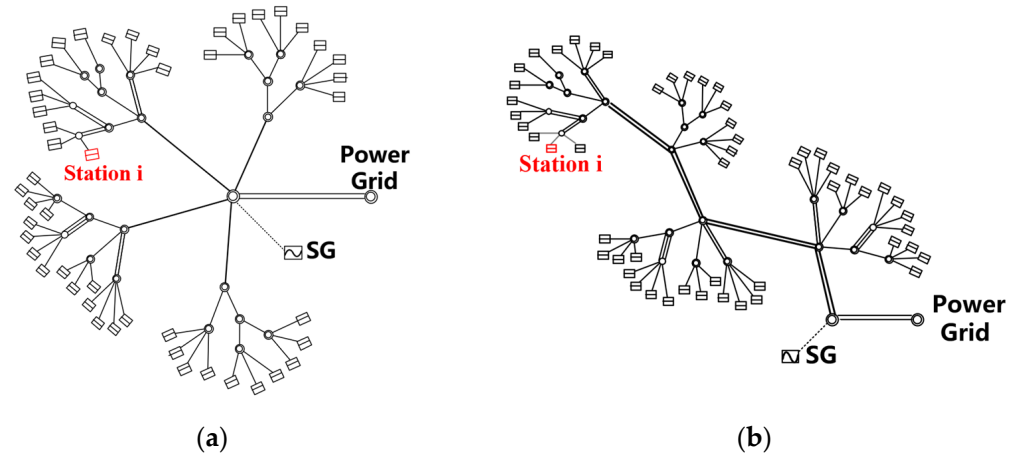


Figure 12. Radiant and long-chain transmission topologies: (a) radiant; (b) long-chain.

In a radial transmission system, stations are closely connected, with short electrical distances. This results in lower external Thevenin impedance compared to a long-chain system, providing stronger grid support. Conversely, in a long-chain system where stations are connected one after another, the longer electrical distance to the main grid leads to higher Thevenin impedance and weaker voltage support. Faults at the end of a long chain can lead to weak voltage support and potential unit disconnection. However, geographical factors limit the application of radial topology to open plains and renewable-energy-rich areas, while long-chain topology suits narrow terrain.

In conclusion, according to Equation (4), when the PLL is stable, the maximum external system reactance that ensures that the voltage at the PCC is lower than U_{safe} can be calculated. However, the PLL stability analysis of the hybrid system in Equation (11) shows that, as X_g increases, the PLL of the internal GFL converters becomes increasingly prone to instability. As discussed in Section 2.3.3, once the PLL loses stability, a PLL deviation within $-2\varphi - 180^\circ < \theta < 0$ can further worsen transient overvoltage. Therefore, in practical station construction, the line reactance should be chosen even smaller than the value obtained from the above equation to account for PLL stability constraints.

3. Results

To verify the correctness of the theoretical analysis mentioned above, an example for the electromechanical simulation was constructed based on STEPS v2.2.0 [29], as shown in Figure 4. The parameters of the station and converters are shown in Table 1. At 1 s, a three-phase short-circuit fault is set, with $X'_g = 0.5$ and $U'_{\text{grid}} = 0.33$. The fault is cleared after 0.2 s.

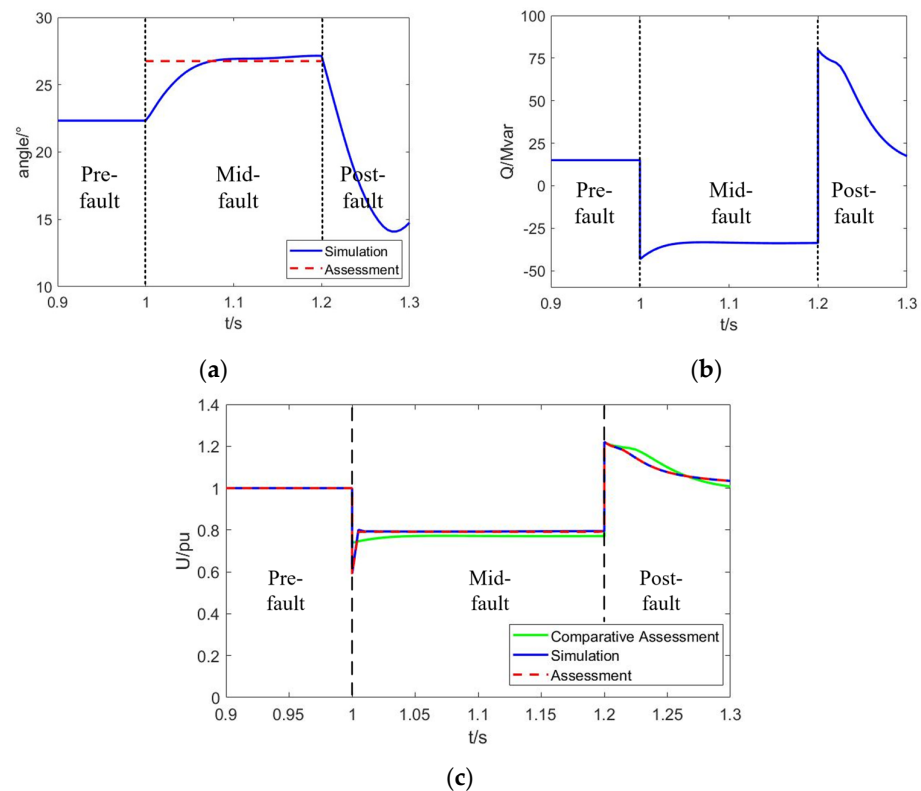
Table 1. The parameters of the station and converters.

Station Parameters		GFL Parameters				GFM Parameters			
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
S_{base}	100 MVA	P_{GFL}^*	70 MW	k_p	20	P_{GFM}^*	6 MW	I_{max}	99.99
S_{GFL}	90 MVA	Q_{GFL}^*	12 MVar	P_{rated}	2 MW	Q_{GFM}^*	1 MVar	P_{rated}	2 MW
S_{GFM}	10 MVA	T_q	0.02 s	U_{in}	0.9	J	30.0	U_{in}	0.9
X_{GFM}	0.1	T_p	0.02 s			D	5.0		
X_g	0.6	k_i	40			K_q	0.2		

3.1. Transient Overvoltage Assessment Under Different PLL Stability

(1) Verification of Assessment Method when the PLL is Stable:

The basic parameters satisfy Equation (11), and the PLL is stable. Calculate θ_{PLL} using Equation (14) and obtain Figure 13a. According to Equation (3), at the instant the fault occurs, θ_1 jumps abruptly. However, θ_{PLL} is a state variable that cannot change instantaneously. It gradually tracks θ_1 , and once θ_{PLL} converges to θ_1 , the two angles settle at the assessed value, thereby validating Equation (14).

**Figure 13.** Comparison of quantities when PLL is stable: (a) θ_{PLL} ; (b) reactive power; (c) voltage.

Using the method described in Section 2.3.3 to evaluate transient overvoltage, substitute various quantities into Equation (11) at other times to directly calculate the voltage, and obtain the voltage assessment value in Figure 13c. At every instant, the assessed voltages match the simulated values closely, confirming the accuracy of the assessment method.

Meanwhile, in order to further verify the correctness of the voltage assessment method, we compared it with the voltage assessment method in [19]. The reactive power at the PCC is shown in Figure 13b. The short-circuit capacity S_c at the PCC is 300 MVA. According

to [19], the voltage based on reactive power and short-circuit capacity can be obtained as follows:

$$U_1 = 1 + \frac{\Delta Q}{S_c} \quad (29)$$

As shown in Figure 13c, the result of the comparative assessment matches the value obtained by the proposed voltage assessment method, confirming the accuracy of the latter. However, in hybrid renewable systems, the post-fault reactive power change at the PCC cannot be predetermined. Therefore, the comparative assessment is applicable only to simulation studies and cannot account for PLL instability effects. The assessment method presented here allows planners to assess the transient overvoltage level under different PLL stability conditions during the planning stage, offering broader applicability.

(2) Verification of Assessment Method when the PLL is Unstable:

Let $I_{d,ref} = 0.85$ and $S_{GFM} = 2.0$ MW, so that Equation (11) is not satisfied and the PLL is unstable. At this point, the simulation values and assessed values are shown in Figure 14.

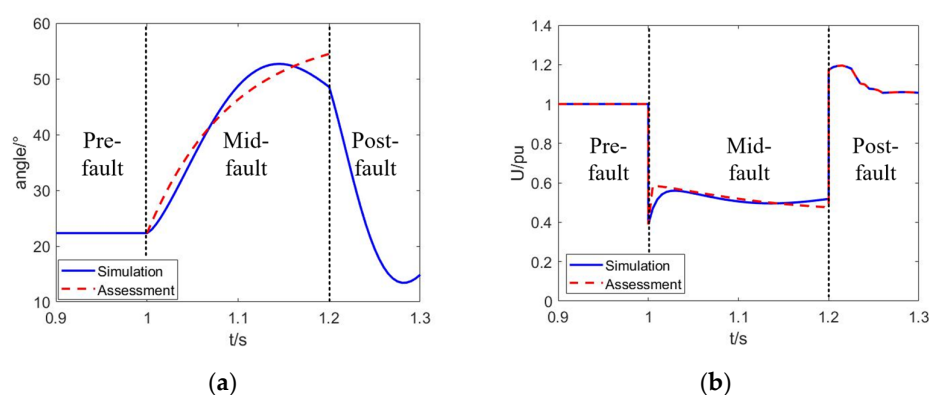


Figure 14. Comparison between simulated and assessed values when PLL is unstable: (a) angle; (b) voltage.

From Figure 14a, it can be seen that the phase angle shows a divergent and increasing trend when the PLL is unstable, and there is a deviation between the simulation value and the assessed value. The reasons may include the following: (1) The full-order model of the PLL is simplified to a second-order model, ignoring the influence of other control links. (2) Assuming that the coefficients of the second-order differential equation are constants, the influence of phase changes on the equation is ignored, but the above deviation is relatively small and does not affect the assessment of transient overvoltage. As shown in Figure 14b, the assessed value is essentially equal to the simulation value, which verifies the correctness of the voltage assessment method when the PLL is unstable.

3.2. Verification of the Influence of Converter Parameters

(1) The influence of GFL Converter Parameters:

In the example, by changing the reactive current coefficient to alter the output I_q , the PCC voltage at different I_q values is simulated, as shown in Figure 15. It should be noted that, for the convenience of analysis, the following I_q only represents the amplitude of the reactive current output of the GFM, and it does not focus on its direction.

As I_q increases, the voltage support capability of the GFL converter improves, and the PCC voltage increases before fault clearance. The transient overvoltage after fault clearance also increases accordingly. The voltage magnitude is proportional to the I_q , consistent with theoretical analysis.

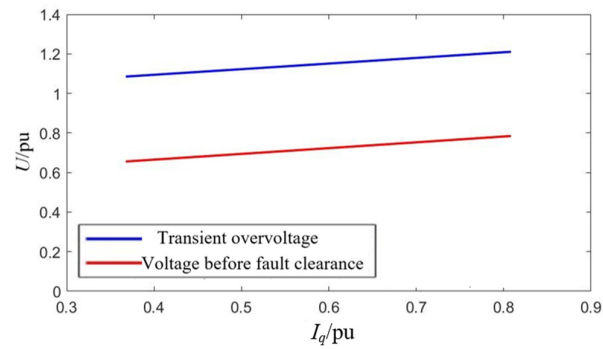


Figure 15. The influence of I_q .

By changing T_q , Figure 16 was simulated. From Figure 16a, it can be seen that as T_q decreases, the duration of I_q retraction becomes significantly shorter and the current retraction speed increases. Therefore, from Figure 16b, it can be seen that the reduction in T_q can significantly shorten the duration of transient overvoltage, which is also consistent with the theoretical analysis results.

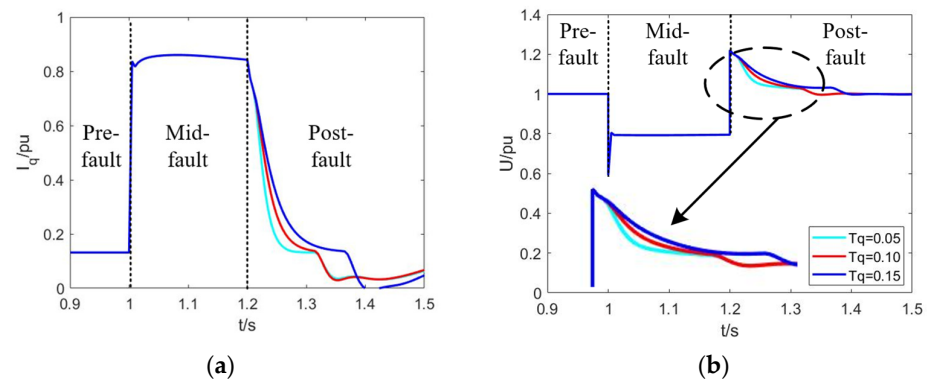


Figure 16. The influence of T_q : (a) I_q ; (b) voltage.

(2) The Influence of GFM Converter Parameters:

When the current overload multiple is not limited in the example, the maximum output current I_m is 3.5 pu. By changing I_{max} , Figure 17 was obtained. When $I_{max} < 3.5$ pu, the GFM converter is in current-limiting mode. Increasing I_{max} can improve its voltage support capability and suppress transient overvoltage. However, when $I_{max} > 3.5$ pu, the GFM converter is in an unrestricted current mode, and its voltage support capability reaches its maximum value, no longer changing with the increase in I_{max} . The simulation results are consistent with the theoretical analysis.

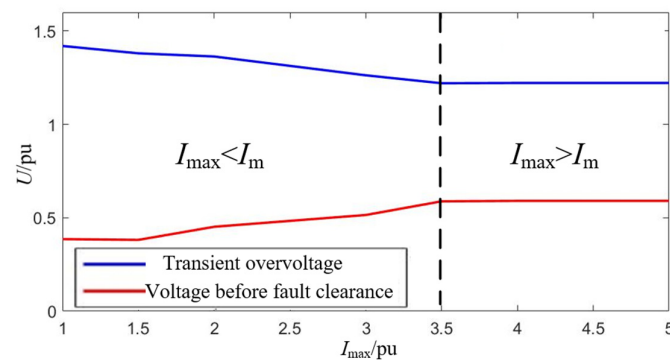


Figure 17. The influence of I_{max} .

3.3. Influence of the Capacity Ratio of GFL and GFM Converters

By changing the capacity ratio of S_{GFL} and S_{GFM} while keeping the total capacity nS_{base} constant, the voltage at the PCC under different GFM converter capacity ratios can be obtained, as shown in Figure 18. As h_i increases, the PCC voltage at the moment of the fault significantly increases, and the transient overvoltage significantly decreases, consistent with theoretical analysis.

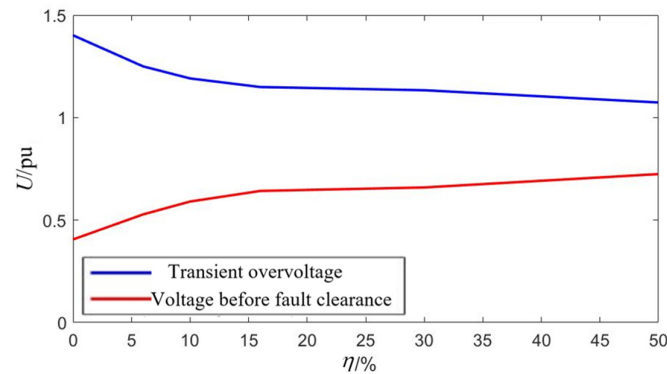


Figure 18. The influence of capacity ratio of GFM converters.

Taking the maximum output reactive current $I_{q,max}$ as 1.2 pu, the basic parameters remain unchanged. Substituting each quantity into Equations (26)–(28), we can calculate that the capacity ratio of the GFM converters should be more than 14.4%. We constructed a hybrid station example with $h_i = 14.4\%$. When the short-circuit fault occurs and $U_{grid} = 0$, the simulated voltage at the PCC is as shown in Figure 19. The transient overvoltage is 1.17 pu, which is lower than 1.3 pu, verifying the correctness of Equation (28).

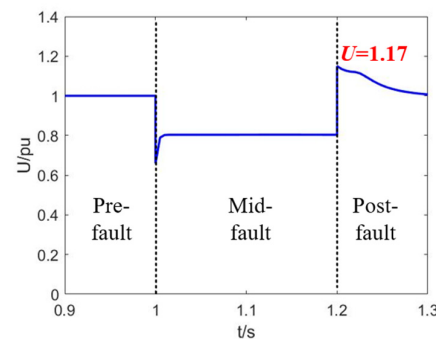


Figure 19. Verification of minimum capacity ratio of GFM converters.

3.4. Verification of the Influence of External Systems

Because $X_g = X_{Line} + X_i$, X_{Line} and X_i are equivalent to X_g in the system simulation. By changing the size of the parameter X_g , the influence of the length and topology of the transmission line outside station i can be reflected. In order to investigate only the influence of external reactance, it is assumed that a three-phase short-circuit fault occurs at the PCC with a grounding reactance of 0.5, and that the other parameter conditions are the same as in Table 1. By changing the parameter X_g , Figure 20 can be obtained through simulation.

As can be clearly seen from the above figure, with the increase in X_g , the voltage support capacity of the power grid for the station is significantly weakened. As X_g increases, the specific changes in the terminal voltage are as follows: during the fault period, the voltage support provided by the power grid decreases, and the terminal voltage drops significantly; after the fault is cleared, the transient overvoltage at the PCC significantly increases.

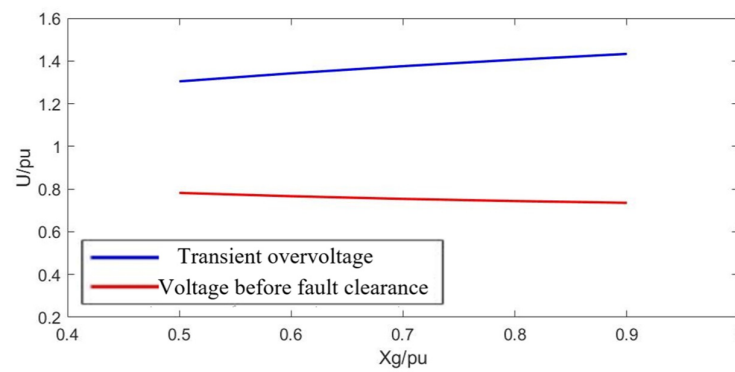


Figure 20. The influence of X_g .

The above simulation results are consistent with the theoretical analysis, further verifying the influence of the external topology parameter X_g on the terminal voltage in Section 2.4.3. Based on theoretical analysis and practical simulation, strengthening the connection between the station and the power grid is an effective means to ensure voltage stability.

4. Conclusions

This paper proposes a transient overvoltage assessment method for hybrid GFL and GFM systems, and it analyzes the influence of different factors on transient overvoltage. The conclusions were verified through electromechanical transient simulation. The main conclusions drawn are as follows:

1. Simplify the complex transmission system based on Thevenin's theorem and the control characteristics of the converter, and obtain the hybrid GFL and GFM converter station model. This can reflect system characteristics while reducing complexity.
2. Based on simplified models and assumptions, a transient overvoltage assessment method for the PCC in hybrid stations with different PLL stability is proposed using circuit theorems and phasor diagrams.
3. In terms of converter parameters, changing the reactive current coefficient and time constant of the GFL converters can reduce the magnitude and duration of overvoltage, respectively. The influence of the current overload multiple of GFM converters on overvoltage depends on its current-limiting mode.
4. In terms of system parameters, we derived a formula for the capacity ratio of GFL and GFM converters under the constraints of unit non-disconnection and transient overvoltage, which can be used to guide the planning and operation of hybrid stations. Increasing external system reactance will weaken the connection between the station and the system and worsen the transient overvoltage of the PCC.

The proposed transient overvoltage assessment method can be used to quantitatively evaluate the overvoltage level of hybrid GFL and GFM systems, and to guide the parameter configuration and capacity ratio. In terms of limitations, the transient overvoltage assessment method proposed in this paper may not be applicable when the scale of the external transmission system is too large. In addition, further research is needed to investigate the effects of other GFM control models and electromagnetic transient parameters on overvoltage in the future.

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