An improved method of TEF considering the saturation of inverter under VSG strategy

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Abstract. In order to reduce influence of the total inertia of the system on the system stability, the virtual synchronous generator(VSG) technology is becoming a research hotspot for the penetration of distributed power supply with high permeability. Due to the existence of the current limiter in the inverter, the transient energy function which is constructed by first integral (TEF) derivative is not monotonous. It may make using TEF method to obtain the critical clearing time and system stability error. This paper proposes an improved TEF method using the tangent function to replace the saturation one. Firstly, the relationship between the virtual power angle and the power angle of the traditional system is analyzed after the improvement of the inverter current saturation link. Then, the first integral method is used to construct the TEF with improved saturation. Finally, it simulates to a single machine infinite bus system and IEEE three-machine-nine-bus system by MATLAB/Simulink, and the results show that the improved TEF is proposed, it can effectively evaluate the VSG strategy and the transient stability of AC system inverter current limiting.

1. Introduction

When power grid occurs large disturbance, the inverters using VSG strategy[1] will exhibit electromechanical dynamic characteristics similar to that of synchronous machine(SG). While the inverter has the current saturation characteristic, the transient stability analysis of the system will be more complex[2]. Therefore, it is necessary to study the transient stability analysis method considering the saturation characteristics of the inverter.

In present studies about the direct method of power system transient stability analysis which are based on the VSG strategy to improve the transient stability of the system, the references [3-5] change the rotary inertia of virtual synchronous generator. While the effect of the inverter’s current saturation is ignored when using the direct method. Therefore, the reference [6] points out the problem that the inverter leads to transient instability easily under the current limiting conditions, and advances the virtual impedance, which is used to replace traditional current limiting for improving the large disturbance stability, but there is a lack of in-depth analysis on its instability rationality. As far as the electromechanical transient progress which occurs when the inverter current is saturated, the reference [7] provides the mechanism of the power angle instability from the time domain, but it only analyzes
the transient power angle instability of VSG qualitatively, and the simulation verification is not provided.

As for the influence of inverter current saturation characteristics on the transient stability margin of AC system, this paper analyses the limitations of transient energy function considering the saturation of inverter, and on this basis, it proposes an improved method using the arctan function to approximate. Based on the transient stability analysis method of traditional synchronous generator, this paper deduces the relationship between the traditional power angle and the virtual power angle of the approximately improved inverter’s current saturation link, and constructs the transient energy function. Finally, it uses a single machine infinite bus (SMIB) system and the system of IEEE 3 generators and 9 nodes to simulate and it verifies the validity of this method.

2. Transient model of virtual power angle of inverter using VSG

In this chapter, the virtual power angle of the inverter under the VSG strategy is modeled, and the power angle characteristics whether the inverter is saturated or not are also respectively considered.

2.1. Definition of the virtual power angle of inverter using VSG

1) The virtual power angle characteristic when the inverter is not saturated

When the inverter is not saturated, its output power expression is shown in formula (1):

\[ P_e = \text{Re}(|\hat{U}^r|) = \frac{|E\|U|}{X_{\Sigma}} \sin \delta' \]  

(1)

Where, \( \delta' \) is virtual power angle, it can also be considered as the angle between the inverter’s output voltage and the grid voltage. From the above formula, we find that the virtual power characteristic of VSG strategy when the inverter is not saturated is similar with traditional synchronous generator, and the virtual power angle curve is shown in the Figure 1 marked by the unsaturated curve.

![Figure 1. VSG virtual power angle curve](image)

2) The virtual power angle characteristic when the inverter is saturated

In order to prevent the excessive current flowing in the inverter from damaging the equipment, it is necessary to set the current limiter to protect the inverter during operation [8]. When \( I_{\text{mag}} \leq I_{\text{max}} \), the inverter normally outputs. But when \( I_{\text{mag}} > I_{\text{max}} \), its current limiting section start up, and the current is clamped at \( I_{\text{max}} \). Therefore, it can be equivalent to the limit model shown in formula (2):

\[ I = \begin{cases} I_{\text{min}}, & I < I_{\text{min}} \\ I_{\text{max}}, & I > I_{\text{max}} \\ I_{\text{max}}, & I \geq I_{\text{max}} \end{cases} \]  

(2)

The presentation of the power angle characteristics when the inverter current saturated is shown as formula (3):

\[ P_e = \left( \frac{I_{\text{mag}} \left| \hat{U} \right|}{X_{\Sigma}} \right) \sin(\delta' + 90^\circ) \]  

\[ = (I_{\text{max}} \left| \hat{U} \right|) \sin(\delta' + 90^\circ) \]  

\[ = P_{\text{m}} \cos \delta' \]  

(3)
According to formula (3), we can obtain the virtual power angle characteristic curve when the inverter’s current is saturated shown as Figure 1. Its’ cosine characteristic is no longer consistent with the sinusoidal power angle characteristic of the traditional synchronous generator.

2.2. Transient model of virtual power angle considering the inverter current saturation

We can establish the dynamic equivalent model of the inverter with VSG control strategy, and the rest of the grid can be seen as an infinite system. Thus, this SMIB system is shown in Figure 2.

For the SMIB system as above, the relationship between electrical quantities can express as follows:

\[ E = U + jX_I \]
\[ I = \frac{\dot{E} - \dot{U}}{jX_I} = \frac{(E\cos\delta - U) + jE\sin\delta}{jX_I} = \frac{E\sin\delta - jE\cos\delta - U}{X_I} \]

Where, \( E \) is the terminal voltage of the Inverter, \( U \) is the infinity bus’s reference voltage, \( X_I \) is the line’s reactance, and \( I \) is the inverter’s output current.

Thus, the relation between current amplitude and power angle is shown in formula (5):

\[ I = \sqrt{(E\sin\delta)^2 + (E\cos\delta)^2 - 2EU\cos\delta + U^2} \]

That is,

\[ \cos\delta = \frac{E^2 - U^2 - (IX_I)^2}{2EU} \]

According to the formula (6), it can be equivalent to virtual power angle clipping to analyze the system transient stability conveniently of inverter’s current saturation link under VSG strategy. For the SMIB system, the total energy after the fault stage can be expressed as (7):

\[ V(\delta, \omega) = \frac{1}{2} M \omega^2 - P_M(\delta - \delta_s) - P_{em3}(\cos\delta - \cos\delta_s) \]

Where, \( \omega \) and \( M \) are the generator’s angular velocity and inertia constant; \( \omega_0 \) is the synchronous electrical angular velocity; \( P_M \) is the mechanical input power of prime mover; \( \delta \) is the stable work power angle of the post-fault system; \( P_{em3} \) is the generator’s maximum electromagnetic power after fault. The system energy curve of traditional TEF can be shown in the Figure 3.

![Figure 2. SMIB System Model under VSG Strategy](image)

![Figure 3. Transient Energy Curves with Inverter Current Limiting Link](image)

From the figure, we can see that, the overall trend of the total system energy \( V \) is getting smaller, but its derivative is not always less than zero, which does not meet the Lyapunov stability conditions. In this case, we can’t accurately determine the critical cut-off time of the fault system and the stability of the system if we use TEF method.
3. The influence of inverter current saturation on TEF
According to the previous formulas, we let \( \dot{x}_1 = \delta - \delta_c, \dot{x}_2 = \omega - \omega_c \) and \( f(x_1) = P_{em1} \sin(x_1 + \delta_c) - P_M \), the system equations that account for inverter saturation under the VSG strategy is as follow[9]:

\[
\begin{dcases}
\dot{x}_1 = x_1 \\
\dot{x}_2 = -\frac{D}{M} x_1 - \frac{1}{M} f(x_1)
\end{dcases}
\tag{8}
\]

When the current is unsaturated, the derivative of the system energy \( V \) is always less than zero. But the power gets saturated along with that the current becomes saturation. We can see that when \( x_1 \) is saturated, its derivative does not exist at the point A or B (shown in Figure 4). We let \( x_{10} \in [x_{10} \in \mathbb{R}^n, |x_1| = x_{1\text{max}}] \), hence the derivative of the \( x_1 \) at the point \( x_{10} \) is:

\[
\lim_{t \to 0^+} \frac{x_1(x_{10} + t\dot{x}_{10}) - x_1(x_{10})}{t} = \begin{cases} 0, & |x_1(x_{10} + t\dot{x}_{10})| > x_{1\text{max}} \\ \dot{x}_1, & |x_1(x_{10} + t\dot{x}_{10})| \leq x_{1\text{max}} \end{cases}
\]

\tag{9}

The following formula is established when the power angle is saturated:

\[
V = M\dot{x}_2 \dot{x}_2 + D\dot{x}_1 x_{1\text{max}} + \frac{D^2 \dot{x}_2^2}{2M} x_{1\text{max}}^2 - P_M x_{1\text{max}}
\]

Substitute the second equation of the formula (8) into the formula (10), we can get that:

\[
h = V = -D\dot{x}_2^2 + (P_M - P_e)\dot{x}_2 + c
\]

\tag{11}

Where, \( c = D\dot{x}_1 x_{1\text{max}} + \frac{D^2 \dot{x}_2^2}{2M} x_{1\text{max}}^2 - P_M x_{1\text{max}} \).

There will be that:

\[
h_{\text{max}} = \frac{(P_M - P_e)^2}{4D} + c
\]

\tag{12}

From the above, we can find that the analysis method of the traditional TEF is suitable when \( h_{\text{max}} \leq 0 \) because the system energy \( V \) is negative, while it is not suitable when \( h_{\text{max}} > 0 \). Thus, this paper improves the TEF method for this problem.

4. TEF considering the current saturation of VSG inverter
Due to the saturation of the inverter, the system energy function is no longer negative. Therefore, it is necessary to improve the model which express the saturation for the system energy to suitable with Lyapunov conditions.

4.1. The improved virtual power angle model of the inverter considering saturation
In order to correctly study the transient stability of the system include the inverters under the VSG strategy by the traditional TEF method, this paper improves the model which describes the inverter’s current saturation. We use arctangent function to approximate the characteristic of the inverter’s current saturation, the curve and expression of which is shown as Figure 4 and formula (13). After that, the TEF could be derivable at any point.

\[
sat(I) \approx I_M \times \tan h\left(\frac{I}{I_M}\right) = I_M e^{\frac{1}{I_M}I} - e^{-\frac{1}{I_M}I}
\]

\tag{13}

After improving the saturated link, the expression can be simplified as formula (14):
\[
\cos \delta_N = \frac{E^2 + U^2 - (IX_\Sigma)^2}{2EU} = \frac{E^2 + U^2 - \left(\frac{I_{\max}}{I_{\max}}\right)^2 X_\Sigma^2}{2EU} \\
E^2 + U^2 - 2EU \cos \delta_O - \left(\frac{I_{\max}}{I_{\max}}\right)^2 X_\Sigma^2 \right) \frac{E^2 + U^2 - 2EU \cos \delta_O}{2EU} \cdot \frac{X_\Sigma^2}{2EU}
\]

\[\text{(14)}\]

\[\cos \delta_N = \frac{E^2 + U^2 - (IX_\Sigma)^2}{2EU} = \frac{E^2 + U^2 - \left(\frac{I_{\max}}{I_{\max}}\right)^2 X_\Sigma^2}{2EU} \]

\[\text{Figure 4. Current saturation}\]

According to the formula (14), we can get the relationship between the virtual power angle \(\delta_N\) of the approximately improved inverter current saturation and the power angle \(\delta_O\) of the traditional power system without the saturation.

After substituting the formula (13) into the formula (14), we can get the system energy’s curve of the improved limiting model shown as Figure 5.

\[\text{Figure 5. The transient energy curve which the improved limiting link}\]

After approximated, we can find out that the total energy curve of the system is continuously declining from figure 5, and there is no fluctuation which satisfies the Lyapunov condition.

After we improve the model expressing the inverter saturation link, the traditional TEF constructed by the first integral method can be used to analyze the transient stability of the system when the inverter’s current saturation.

4.2. The improved TEF considering saturation link

Constructing the transient energy function by the first integral method[10], it’s shown as formula (15):

\[V(\delta, \omega) = \frac{1}{2} \sum_i M_i (\omega_i - \omega_b)_i^2 + \sum_i \sum_j V_i B_{ij} (\cos \delta_{ij} - \cos \delta_{ij_0}) + \sum_i \left[ (D_i \lambda_{ij}(\omega - \omega_b)_i)(\delta - \delta_{ij_0}) + \frac{1}{2} M_i \lambda_{ij}(\delta - \delta_{ij_0})^2 \right] \]

\[\text{Potential energy Vp}\]

\[\text{Total energy V}\]

\[\text{Time/s}\]

\[\text{System energy V}\]

\[\text{Potential energy Vp}\]

\[\text{Total energy V}\]

\[\text{Elastic energy V}\]

\[\text{Potential energy Vp}\]

\[\text{Total energy V}\]

\[\text{Time/s}\]

\[\text{System energy V}\]

\[\text{Potential energy Vp}\]

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\[\text{Elastic energy V}\]

\[\text{Potential energy Vp}\]

\[\text{Total energy V}\]
Where, $M_i$ and $\omega_i$ are inertia constant and rotor angular velocity of the $i$-th generator; $\omega_k$ is the synchronous electrical angular velocity; $V_i$, $B_i$, $D_i$, $\lambda_i$ and $P_{mi}$ are electric potential, susceptance, damping coefficient, weighting factor and mechanical power of the $i$-th generator. The value of $\lambda_i$ is between 0 and 1; and $\delta_i$ is the stable power angle of system after fault[11].

The specific procedure using this method to determine the system transient power angle stability is as follows:

1) Input data: Main parameters of electrical part, they include network parameters such as VSG, line, transformer, fault location and maximum and minimum current of limiting device.
2) Get fault trajectory: Integrate rotor equation of motion with R-K method, namely the $\delta(t)$ and $\delta_i(t)$ of the VSG rotor. This procedure considers the equivalent power angle limit of the formula (14).
3) Get the transient energy $V_{cl}$ and critical energy $V_{cr}$ of system at the time of fault removal: they are obtained separately according to formula (12) and the critical energy formula of reference [12].
4) Determines the system stability: Compare the system transient energy $V_{cl}$ with the system critical energy $V_{cr}$ obtained by procedure 3) at the time of fault removal. The system will be stable if $V_{cl} \leq V_{cr}$, it’s unstable otherwise.
5) Calculate the critical cut-off time: Command $V_{cl}=V_{cr}$ and there will be $t_c=t_{cr}$ according to system energy trajectory.

5. Simulation verification and analysis

5.1. Simulation environment
This paper uses SMIB and IEEE 3 machines 9 nodes system to validate the effectiveness of this method. The basic data of the two systems are refer to references [11] and [13]. And $D=0.1, \lambda=0.5, P_{M}=0.9, x_{1\text{max}}=0.6$. The topology of these two systems are shown in figure 6:

5.2. Simulation analysis
1) Comparison of system stability domains
Taking all the points on the boundary of the stable point’s small neighborhoods as the integration initial points, have an inverse integral to the system, and the stability region of the system before and after the current saturation model’s improvement is obtained, as shown in Figure 7.
From figure 7, we can see that the stability region after the inverter current saturation improvement of the system become larger than the region before improvement, this is because the arctangent function in the improvement is smooth continuous, and there won’t be saturation in the stability region.

2) Comparison of transient energy changes after fault removal

After calculating, we can get $h_{max} = 0.4549 > 0$ according to formula (11), and the total system energy $V$ is not monotonically decreasing. Substituting the SMIB system’s parameters into the formula (15), we can obtain the system energy curve of the unmodified saturation model shown in figure 5.

3) Comparison of system’s critical cut-off time (CCT)

We use time domain method, unimproved and improved TEF method to compare CCT in both SMIB and IEEE 3 machines 9 nodes system. Simulating results are shown as Table I to IV. Where, Distance_M stands for the distance from the fault point to the head (close to the generator) of the double circuit line.

Table 1 and 2 show CCT’s comparison and its error between improved and unimproved model of the saturation link in the SMIB and 3 machine 9 nodes systems. We can find that the improved method proposed increases the CCT and all the relative errors is less than 5%. Therefore, it is feasible and meets the actual requirements in the time domain simulation.

Respectively use both time domain simulation method and TEF method to analyze the system before and after the improvement of the inverter’s current saturation model, the CCTs are shown in Table 3. It can be found that the CCT’s value obtained by the TEF method is consistent in the fault 2, 3, 4, 5 and 6, and conservatism occurs only in fault 1. So we can get that the conservativeness of the TEF is improved when the inverter current saturation has been improved.

Table 4 shows the CCT of the three-machine system obtained respectively by time domain simulation method and TEF method. The assessment for the network faults 4 and 7 is conservative. We can find out that, for the system which inverter current saturation has been improved, the conservatism obtained by TEF has been improve.

| Fault position Distance M | Unmodified | Modified | Error (%) |
|---------------------------|------------|----------|-----------|
| 0.65                      | 1.78-1.79  | 1.86-1.87| 4.49      |
| 0.6                       | 1.62-1.63  | 1.69-1.70| 4.32      |
| 0.55                      | 1.48-1.49  | 1.54-1.55| 4.05      |
| 0.5                       | 1.32-1.33  | 1.37-1.38| 3.78      |
| 0.4                       | 1.04-1.05  | 1.07-1.08| 2.76      |
| 0.3                       | 0.74-0.75  | 0.75-0.76| 1.35      |
### Table 2. The CCT of the IEEE 3 machine 9 nodes system

| number | Fault line | CCT(s) | Error (%) |
|--------|------------|--------|-----------|
| 1      | 4*-5       | 0.31-0.32 | 0.32-0.33 | 3.23 |
| 2      | 5*-4       | 0.40-0.41 | 0.41-0.42 | 2.5  |
| 3      | 4*-6       | 0.30-0.31 | 0.31-0.32 | 3.33 |
| 4      | 6*-4       | 0.43-0.44 | 0.45-0.46 | 4.55 |
| 5      | 5*-7       | 0.31-0.32 | 0.32-0.33 | 3.26 |
| 6      | 7*-5       | 0.16-0.17 | 0.16-0.17 | 0    |
| 7      | 6*-9       | 0.38-0.39 | 0.39-0.40 | 2.63 |
| 8      | 9*-6       | 0.21-0.22 | 0.21-0.22 | 0    |
| 9      | 7*-8       | 0.18-0.19 | 0.18-0.19 | 0    |
| 10     | 8*-7       | 0.26-0.27 | 0.27-0.28 | 3.85 |
| 11     | 8*-9       | 0.29-0.30 | 0.30-0.31 | 3.45 |
| 12     | 9*-8       | 0.21-0.22 | 0.22-0.23 | 4.76 |

### Table 3. The CCT’s comparison of the SMIB system

| Distance_M | Time domain method | TEF |
|------------|--------------------|-----|
|            | Before improve     | After improve | Before improve | After improve |
| 0.65       | 1.78-1.79          | 1.86-1.87     | 1.746         | 1.851         |
| 0.6        | 1.62-1.63          | 1.69-1.70     | 1.605         | 1.692         |
| 0.55       | 1.48-1.49          | 1.54-1.55     | 1.482         | 1.542         |
| 0.5        | 1.32-1.33          | 1.37-1.38     | 1.320         | 1.371         |
| 0.4        | 1.04-1.05          | 1.07-1.08     | 1.041         | 1.071         |
| 0.3        | 0.74-0.75          | 0.75-0.76     | 0.741         | 0.753         |

### Table 4. The CCT’s comparison of three-machine system

| Fault line | Time domain method | TEF |
|------------|--------------------|-----|
|            | Before improve     | After improve | Before improve | After improve |
| 4*-5       | 0.31-0.32          | 0.32-0.33     | 0.322         | 0.313         |
| 5*-4       | 0.40-0.41          | 0.41-0.42     | 0.413         | 0.403         |
| 4*-6       | 0.30-0.31          | 0.31-0.32     | 0.311         | 0.302         |
| 6*-4       | 0.43-0.44          | 0.45-0.46     | 0.443         | 0.419         |
| 5*-7       | 0.31-0.32          | 0.32-0.33     | 0.324         | 0.313         |
| 7*-5       | 0.16-0.17          | 0.16-0.17     | 0.164         | 0.163         |
| 6*-9       | 0.38-0.39          | 0.39-0.40     | 0.382         | 0.369         |
| 9*-6       | 0.21-0.22          | 0.21-0.22     | 0.217         | 0.213         |
| 7*-8       | 0.18-0.19          | 0.18-0.19     | 0.183         | 0.182         |
| 8*-7       | 0.26-0.27          | 0.26-0.28     | 0.273         | 0.253         |
| 8*-9       | 0.29-0.30          | 0.30-0.31     | 0.305         | 0.284         |
| 9*-8       | 0.21-0.22          | 0.22-0.23     | 0.226         | 0.226         |

### 6. Conclusion
Considering the influence that the inverter’s current saturation characteristic to the system’s transient stability margin, this paper proposes the improved method that approximating the current saturation link model as an arctangent function, and constructs the TEF based on the first integral method. It verifies the effectiveness of the TEF constructed by the simulation in SMIB and 3-machines systems.
with the inverter using the VSG strategy which considering its current saturation, and gets the following conclusions:

1) Comparing the change of the stability margin the system, kinetic energy, potential energy and total energy when the fault has been removed before and after the improvement, we can get that the improved method proposed can quantitatively assess the transient stability of the system with the inverter current saturation based on the VSG strategy.

2) Comparing the CCT of system before and after the improvement, we can get that the improved method proposed can improve the conservatism of traditional TEF method.

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