Fast estimation method of renewable energy carrying capacity of power grid based on nadir frequency constraint

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Abstract. With more and more renewable energy connected to the power system, the power system gradually presents the characteristics of low inertia and the risk of frequency instability gradually becomes prominent. Therefore, nadir frequency has become one of the limiting factors of renewable energy carrying capacity. In this paper, firstly, based on the swing equation, frequency dynamic response after power loss was analysed. Secondly, quantitative analysis on system inertia time with renewable resources was carried out, with higher penetration rate k and the replacement rate a, the inertia time is relative lower. Thirdly, fast estimation method of renewable energy carrying capacity of power grid based on nadir frequency constraint was proposed. Finally, taking a regional power grid as an example, the effectiveness of the proposed estimation method is verified.

1. Introduction

Frequency is one of the key indicators to measure whether the system is safe and stable. With the continuous increase of renewable energy connected to power system, the inertia level and dynamic frequency response of the power system are bound to be affected[1-4]. The "9·28" blackout in Australia in 2016[5] and the "8·9" blackout in the UK in 2019[6,7] all revealed that the low inertia was one of the causes of the above accidents. With more and more renewable energy connected to power system, the risk of frequency instability of power system is becoming prominent. Frequency stability, especially the nadir frequency after disturbance, has become one of the key factors constraining the renewable energy carrying capacity of power grid.

Reference [8] revealed the impact of renewable energy on system frequency and proposed generalized inertia level of power system with high penetration electronics. Reference [9] revealed that the main factors affecting the stability of power system in China is the proportion of new energy generation and analysed the maximum proportion of new energy generation restricted by frequency stability. Reference [10] revealed the trend of frequency characteristics of future power systems and proposed estimation method for upper limit of renewable energy permeability.

In this paper, first, frequency dynamic response after power loss was analysed. Second, quantitative analysis on system inertia time with renewable resources was carried out. Third, fast estimation method of renewable energy carrying capacity of power grid based on nadir frequency constraint was proposed. Finally, the effectiveness of the proposed method is verified based on dynamic simulation.

2. Frequency dynamic response after power loss

The swing equation in per unit form for unit i is
2H_i \frac{df_i}{dt} = T_{mi} - T_{ei} \approx P_{mi} - P_{ei} \tag{1}

where $H_i$ is the inertia constant of unit $i$, $f_i$ is the frequency of unit $i$, $t$ is time, $T_{mi}$ is mechanical torque of unit $i$, $T_{ei}$ is electromagnetic torque of unit $i$, $P_{mi}$ is mechanical power of unit $i$, $P_{ei}$ is electromagnetic power of unit $i$.

If there are $N$ units in the power system, noting that in large power system, the frequency of different units are almost the same as system frequency $f_s$, then

$$2H_s \frac{df_s}{dt} = \sum_{i}^{N} (P_{mi} - P_{ei}) = \Delta P_s$$ \tag{2}

where $H_s$ is the total inertia constant of the system, $DP_s$ is the power unbalance of the system.

A typical frequency response after power loss at $t_1$ is shown in figure 1. From $t_1$ to $t_2$, the $DP_s$ is negative because of power loss, $\frac{df_s}{dt}$ is negative and $f_s$ decreases. When $f_s$ decreases, the system load also decreases because of load frequency effect and the output of generator increases because of governor primary frequency modulation. Then, the magnitude of $\frac{df_s}{dt}$ decreases and $f_s$ drop slows down. At nadir point($t_2$), $\frac{df_s}{dt}$ is zero which indicates that $DP_s$ is zero. From $t_2$ to $t_3$, with the response of the governor primary frequency, $DP_s$ turned into positive and system frequency increase. Finally, the system frequency recovery to steady state at $t_4$.

![Figure 1. A typical frequency response after power loss.](image)

3. Quantitative analysis on system inertia time with renewable resources

Although the demand for renewable resources (wind power and photovoltaic power) to provide inertia response is increasingly prominent, however, most of the renewable resources in operation cannot provide inertia response. Considering conservatively, the inertia response characteristics of the renewable resources will not be considered in the following analysis.

As shown in figure 2, there are $N$ generators in the power system, when some renewable resources with total capacity $S_R$ are connected to the power system, some conventional generators (assuming generator $M+1$ to $N$) are out of operation and the output of other generators has to be adjusted to meet the total load. The capacity of out-of-operation conventional generators is $S_i$ and the replacement rate $a$ can be defined as...
\[ \alpha = S_i / S_R = \sum_{i=M+1}^{N} S_i / S_R \]  

(3)

If the penetration rate \( k \) is defined as

\[ k = S_R / \sum_{i=1}^{N} S_i = S_R / S_{total} \]  

(4)

Then the system capacity with renewable resources \( S'_{total} \) is

\[ S'_{total} = S_{total} - S_i + S_{ve} = \left[ 1 + \left( 1 - \alpha \right) k \right] \cdot S_{total} \]  

(5)

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**Figure 2. Power system with renewable resources**

Before the renewable resources are connected to the power system, the total inertia constant is

\[ H_s = \frac{\sum_{i=1}^{N} H_i S_i}{S_{total}} \]  

(6)

With the renewable resources are connected to the power system, the total inertia constant is

\[ H'_s = \frac{\sum_{i=1}^{N} H_i S_i - \sum_{j=M+1}^{N} H_j S_j}{S_{total}} \]  

(7)

Noting that \( H_s \) and \( H'_s \) are corresponding to different VA base. In order to compare, \( H'_s \) can be changed to \( H''_s \) at the same VA base with \( H_s \).
Where \( H_{sr} \) means the inertia constant of generators that are out of operation. It can be inferred that with renewable resources connected to power system, the corresponding system inertia constant will decrease. Lower system inertia constant indicates higher frequency rate with power disturbance. Therefore, with the same power disturbance, it can be inferred that the system frequency nadir point is lower with renewable resources connected to power system.

4. Fast estimation method of renewable energy carrying capacity of power grid based on nadir frequency constraint

As shown in figure 1, at nadir point, \( \frac{df}{dt} \) is zero, then

\[
P_{loss} = P_{load-f} + P_{load-cut} + \eta P_{g-r}
\]

(9)

Where \( P_{loss} \) is the power loss of the system and is determined by the scenario and presupposed contingencies; \( P_{load-f} \) is the load response to frequency change from nominal frequency to nadir; \( P_{load-cut} \) is load shedding (if configured) amount and normally is triggered by certain presupposed contingency; \( P_{g-r} \) is the generator spinning reserve; \( \eta \) is response rate of generator governor at nadir point.

Normally, the generator spinning reserve can be calculated as

\[
P_{g-r} = \lambda P_{g-r}
\]

(10)

Where \( P_{g-r} \) is the total active output of traditional generators; \( \lambda \) is the spinning reserve ratio.

From equation (9) and equation (10), the total active output of traditional generators can be determined as

\[
P_{g-r} = \frac{P_{loss} - P_{load-f} - P_{load-cut}}{\lambda \eta}
\]

(11)

Noting that the total power generation should be approximately the same before and after renewable resources are connected to the power system, then

\[
P_{g-new} = P_{g-r0} - \frac{P_{loss} - P_{load-f} - P_{load-cut}}{\lambda \eta}
\]

(12)
Where $P_{g-new}$ is the renewable energy carrying capacity of power system; $P_{g-t0}$ is the initial total power generation of traditional generators before the renewable resources are connected to power system.

5. Simulation verification

Taking a regional power grid as an example, in the dry-season off-peak scenario, the total load $P_{LOAD}$ is 130000MW and the initial total power generation $P_{g-t0}$ is 100000MW. There are 4 EHVDC transmission lines connected to this regional power grid and the biggest power loss $P_{loss}$ is 7500MW. The trigger value of under frequency load shedding (UFLS) in this regional power grid is 49.00Hz, therefore, the frequency nadir can be set as 49Hz in order not to trigger UFLS in case of bipole block of EHVDC and loss of 7500MW power. The load response caused by frequency $P_{load-f}$ is 1500MW and the load shedding amount is 4500MW which will be triggered by bipole EHVDC bipole block. Normally, the spinning reserve ratio $\lambda$ is 6% and response rate of generator governor at nadir point $\eta$ is approximately 50%.

Therefore, based on nadir frequency(49.00Hz) constraint, the renewable energy carrying capacity of this regional power grid $P_{g-new}$ can be calculated as

$$P_{g-new} = P_{g-t0} - \frac{P_{loss} - P_{load-f} - P_{load-cut}}{\lambda \eta}$$

$$= 100000 - \frac{7500 - 1500 - 4500}{50\% \times 6\%}$$

$$= 50000MW$$

After 50000MW renewable energy resources are connected to this regional power grid, the system frequency is shown in figure 3 with EHVDC bipole block and 4500MW load shedding. It can be concluded from figure 3 that, after 50000MW renewable energy resources are connected to this regional power grid, when EHVDC bipole block occurs and 4500MW load was shed, the frequency nadir is over 49.00Hz.

![Figure 3. System frequency with EHVDC bipole block and 4500MW load shedding](image-url)
6. Conclusion
In this paper, the frequency dynamic response after power loss was analysed, the system inertia time with renewable resource was quantitatively analysed and fast estimation method of renewable energy carrying capacity of power grid based on nadir frequency constraint was proposed. Based on the above analysis, it can be concluded as follows:

1. The system frequency is driven by the power balance between the generation and the load. At frequency nadir point, the frequency rate is zero which means the generation and the load are balanced.
2. With more renewable resources connected to power system, the inertia time will decrease. The higher penetration rate $k$ and the replacement rate $a$ is, the lower the inertia time is.
3. The effectiveness of the fast estimation method of renewable energy carrying capacity of power grid based on nadir frequency constraint was verified.

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