Energy Function Based Transient Stability Analysis of Power System Integrated with DFIG

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Abstract. The access of large-scale wind power seriously threatens the safe and stable operation of the power system. In this paper, a novel energy function based transient stability analysis approach is proposed for the power system integrated with Double Fed Induction Generator (DFIG). First, the network structure-preserving model of power system integrated with DFIG is established, where generators adopt 3th order electromechanical model, and its energy function is deduced. Next, the energy function of post-fault system is approximately calculated by trapezoidal integral path, and energy function based transient stability criteria are put forward to access the stability of the post-fault system. Finally, the New England-39 bus system integrated with DFIG is used as test system to investigate the validity of the proposed approach.

1. Introduction

With the continuous increase of world energy consumption, the global energy crisis has become more and more obvious. As an important category of renewable energy, wind energy is one of the oldest and most important energy sources on the earth. The characteristics of huge reserves, renewable, wide distribution and no pollution make wind power generation an important direction for the development of renewable energy [1]. However, after the access of large-scale wind power generation, whether the power system can maintain safe and stable operation is crucial, especially the transient stability.

In the field of transient stability analysis and control of power system integrated with wind power generation, scholars have carried out a lot of research. In reference [2, 3], the impact of wind power integration on the transient stability of the power system under different access locations, different access modes, different access ratios and different control modes, is investigated by time domain simulation, respectively. The influence mechanism of DFIG on the transient stability of power system is analyzed in [4]. However, there are few research about the direct transient stability method considering wind power, such as energy function method. Reference [5, 6] constructed an energy function considering nonlinear load on the basis of the first integration approach and the structure-preserving model, where the active power and reactive power of the load model can be arbitrary nonlinear functions of the bus voltage amplitude and phase angle. Reference [7] proposed a systematic approach to construct the energy function considering various components, where the energy function considering the detailed model of generator and governor and other components was deduced. In conclusion, this paper presents a novel energy function based transient stability analysis approach for the power system integrated with DFIG.
The rest of paper is organized as follows. In Section 2, the network structure-preserving model of the power system integrated with DFIG is established, where generators adopt 3th order model. Next, the energy function is derived and energy function based stability criteria are put forward for the transient stability analysis of post-fault system. In Section 3 the New England-39 bus system integrated with DFIG is used as test system to investigate the effectiveness of the proposed approach. Section 4 concludes this paper.

2. Energy Function Based Transient Stability Analysis

2.1. Model of Power System Integrated with DFIG

The structural topology of DFIG is given in Fig.1, and suppose that the power injected to the grid by DFIG is $P_W + jQ_W$.

![Figure 1. Structural topology of DFIG.](image1)

For the power system integrated with DFIG, there are $m$ generator buses, $n$ load buses, $k$ DFIGs and synchronous generators adopt 3th order model. Then the network structure-preserving model of the power system integrated with DFIG is established [8], as shown in Fig. 2.

![Figure 2. Structure-preserving model of power system integrated with DFIG.](image2)
The following 3th order synchronous generator model is adopted for \( i \)-th generator:

\[
\dot{\theta}_i = \omega_i \quad (1)
\]

\[
M_i \dot{\omega}_i + D_i \omega_i = P_{mi} - P_{ei} - \frac{M_i}{M_T} P_{COI} \quad (2)
\]

\[
T''_{di} E'_{qi} = -E'_{qi} + I_{di} (x_{di} - x'_{di}) + E''_{di} \quad (3)
\]

\[
U_{di} = I_{dq} x_{di} \quad (4)
\]

\[
U_{qi} = E''_{qi} - I_{dq} x_{di} \quad (5)
\]

\[
M_T = \sum_{i=1}^{m} M_i, P_{COI} = \sum_{i=1}^{m} (P_{mi} - P_{ei}) \quad (6)
\]

\[
P_{ei} = \frac{E''_{qi} U_{i} \sin(\theta_i - \phi_i)}{x'_{di}} + \frac{U_{i}^2 (x_{di}'' - x_{qi})}{2 x_{di}'} \sin(2 \theta_i - 2 \phi_i) \quad (7)
\]

\[
Q_{ei} = \frac{U_{i}^2}{x'_{di}} - \frac{E''_{qi} U_{i} \cos(\theta_i - \phi_i)}{x'_{di}} - \frac{U_{i}^2 (x_{di}'' - x_{di})}{2 x_{di}'} (\cos(2 \theta_i - 2 \phi_i) - 1) \quad (8)
\]

Where \( i=1, 2, \ldots, m \), \( \theta_i \) and \( \omega_i \) are rotor angle and rotor speed in Center Of Inertia (COI), respectively. \( P_{mi} \) is mechanical power. \( P_{ei} \) is active power. \( Q_{ei} \) is reactive power. \( M_i \) is inertia constant? \( D_i \) is damping coefficient. \( E_{f,di} \) is excitation EMF. \( x_{di} \) and \( x_{qi} \) are d-axis and q-axis synchronous reactance, respectively. \( x_{di}' \) is d-axis transient reactance. \( E''_{qi} \) is transient EMF of q-axis winding. \( T''_{di} \) is open-circuit d-axis transient time constant? \( \phi_i \) and \( U_i \) are phase angle in COI and voltage amplitude of generator bus, respectively.

Next, the power balance equations at \( i \)-th bus are given by:

\[
\begin{align*}
-P_{ei} + \sum_{j=1}^{n} U_i U_j B_{ij} \sin \phi_j + P_{Li} + \alpha P_{wi} &= 0, \quad i = 1, 2, \ldots, m \\
\sum_{j=1}^{i} U_i U_j B_{ij} \sin \phi_j + P_{Li} + \alpha P_{wi} &= 0, \quad i = m+1, m+2, \ldots, n
\end{align*}
\]

\[
-\sum_{j=1}^{n} U_i U_j B_{ij} \cos \phi_j + Q_{Li} + \alpha Q_{wi} = 0, \quad i = 1, 2, \ldots, m \\
-\sum_{j=1}^{n} U_i U_j B_{ij} \cos \phi_j + Q_{Li} + \alpha Q_{wi} = 0, \quad i = m+1, m+2, \ldots, n
\]

Where \( i=1, 2, n \). If \( i \)-th bus has DFIG accessed, \( \alpha=1 \), otherwise \( \alpha = 0 \).
2.2. Construction of Energy Function

Wind power generation has the characteristics of type diversity, high order, and complex dynamic behavior. There are two technical routes to construct the energy function of wind power generation: 1) Construct the energy functions of various types of wind power generation respectively, which is accurate but tedious; 2) Seek an approximate processing method, which can adapt to different types of wind power generation. Therefore, on the precondition of that dynamic behaviors of DFIG are fully considered, DFIG could be modeled as additional loads at buses when the energy function is derived [9], which will greatly reduce the difficulty of constructing energy function of power system integrated with DFIG. The energy function of DFIG can be expressed by

\[ V_{wi} = \int_{\phi_i}^{\phi_f} P_{wi} d\phi_i + \int_{U_a}^{U_f} \frac{Q_{wi}}{U_j} dU_j \]  

(11)

Where \( V_{wi} \) is treated as part of potential energy.

Next, the energy function of power system integrated with DFIG is deduced based on (1)-(11) [10], and \( x_s \) is defined as the post-fault stable equilibrium point. The energy function \( V \) is obtained below.

\[ V = V_p + V_{pe} = V_{pk} + V_b + V_{dc} \]  

(12)

\[ V_{pk} = \frac{1}{2} \sum_{i=1}^{m} M_i \omega_i^2 \]  

(13)

\[ V_b = \sum_{i=1}^{6} (V_{bi} - V_{bi0}) \]  

(14)

\[ \begin{align*}
V_w &= \sum_{i=1}^{k} \left[ \int_{\phi_i}^{\phi_f} P_{wi} d\phi_i + \int_{U_a}^{U_f} \frac{Q_{wi}}{U_j} dU_j \right] \\
&= V_{b1} + V_{b2} + V_{b3} + V_{b4} + V_{b5} + V_{b6} + V_{b7}
\end{align*} \]  

(15)

Where \( V_{pk} \) kinetic energy is \( V_{pe} \) is potential energy. \( V_b \) is potential energy of AC system \( V_w \) is potential energy of DFIG? Besides,

\[ V_{b1} = -\sum_{i=1}^{m} P_{mi} \theta_i \]  

(16)

\[ V_{b2} = \sum_{i=1}^{n} \int_{\phi_i}^{\phi_f} P_{i} d\phi_i + \int_{U_a}^{U_f} \frac{Q_{i}}{U_j} dU_j \]  

(17)

\[ V_{b3} = \sum_{i=1}^{m} \frac{E_{qi}^2 + U_i^2 - 2 U_i E_{qi} \cos(\theta_i - \phi_i)}{2 x_i} \]  

(18)

\[ V_{b4} = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} B_{ij} U_i U_j \cos(\phi_i - \phi_j) \]  

(19)

\[ V_{b5} = -\sum_{i=1}^{m} \int_{x_{qi}}^{x_{qi}} E_{pi} x_i \frac{dE_{qi}}{x_i} \]  

(20)

\[ V_{b6} = \sum_{i=1}^{m} \frac{E_{qi}'}{2} \]  

(21)

\[ V_{b7} = -\sum_{i=1}^{m} \frac{U_i^2 (2 \theta_i - 2 \phi_i) - 1 (x_i' - x_i)}{4 x_i' x_i} \]  

2.3. Energy Function Based Stability Criteria

When the novel energy function is deduced, the energy function curve of post-fault power system integrated with DFIG is approximately calculated by trapezoidal integration path. Moreover, the times of that the sign of \( \frac{dV_{pe}}{dt} \) changes is defined as \( \beta \).

It is known that the proposed energy function must satisfy certain conditions which requires that the derivative of the energy function is non-negative on any trajectory and be zero only on trivial trajectories, and the energy function is bounded when the post-fault system trajectory is bounded. Next, according
to the characteristics of energy function, the energy function based transient stability analysis criteria are proposed in the following manners.

Criterion 1: If (16) is satisfied, then it is determined that post-fault system will be unstable.

\[ \beta = 2, V < 0 \]  \hspace{1cm} (16)

Criterion 2: If (17) is satisfied, then it is determined that post-fault system will be stable.

\[ \beta = 2, V > 0 \]  \hspace{1cm} (17)

3. Results and Analysis

3.1. Test system

The New England-39 bus system integrated with DFIG is built to investigate the validity of the proposed approach in this paper, where the network topology is shown in Fig. 3. The synchronous generator at Bus-30 is replaced by DFIG. Moreover, generators adopt 3th order model. The simulation step and total simulation time are \( h=0.01 \text{s} \) and \( T=5 \text{s} \), respectively.

![Figure 3. New England-39 bus system integrated with DFIG.](image)

The trapezoidal integration path is used to approximately calculate the energy function curve of post-fault system, where fault cleared time \( x_c \) is chosen as the starting point of integration. Next, the energy function based criteria are adopted to assess the transient stability of post-fault power system integrated with DFIG under following scenarios.
3.1.1. Scenario I: A three-phase short circuit fault occurs at Bus-14. The fault starts at \( t=0 \)s and the fault duration is 0.21s. It can be seen from Fig. 4(a) that relative rotor angle of generators are gradually convergent, which indicates that post-fault power system integrated with DFIG is stable. It is known from Fig. 4(b) that the derivative of energy function \( V \) of post-fault system is constantly non-positive, and energy function \( V \) has a lower bound on condition that post-fault system is stable, which demonstrates the correctness of proposed energy function. In addition, it is determined at \( t=2.11 \)s that post-fault system is stable according to the energy function based transient stability criteria.

![Figure 4. Critical stable scenario.](image)

3.1.2. Scenario II: A three-phase short circuit fault occurs at Bus-14. The fault starts at \( t=0 \)s and the fault duration is 0.20s. It can be seen from Fig. 5(a) that relative rotor angle of generators are gradually divergent, which indicates that post-fault power system integrated with DFIG will be unstable. It is known from Fig. 5(b) that the derivative of energy function \( V \) of post-fault system is constantly non-positive, and energy function \( V \) is unbounded on condition that post-fault system is unstable, which demonstrates the correctness of proposed energy function. In addition, it is determined at \( t=1.83 \)s that post-fault system is unstable according to the energy function based transient stability criteria.

![Figure 5. Unstable scenario.](image)
3.2. Comparative analysis

The different fault is set at different locations in New England-39 bus system integrated with DFIG. The CCT of the power system integrated with DFIG is obtained by proposed approach and time domain simulation, respectively, and the results are obtained in Table 1.

| Fault Type | Fault Location | Proposed Approach | Time Domain Simulation |
|------------|----------------|-------------------|------------------------|
| $f^{(1)}(1)$ | Bus-14 | 0.29 | 0.29 |
|             | Bus-15 | 0.26 | 0.26 |
|             | Bus-16 | 0.20 | 0.20 |
| $f^{(2)}$   | Bus-14 | 0.31 | 0.31 |
|             | Bus-15 | 0.28 | 0.28 |
|             | Bus-16 | 0.21 | 0.21 |
| $f^{(3)}$   | Bus-14 | 0.21 | 0.21 |
|             | Bus-15 | 0.20 | 0.20 |
|             | Bus-16 | 0.16 | 0.16 |

According to Table 1, the analysis results of the proposed approach are basically consistent with the results of time domain simulation in different fault type and different fault location, respectively, which demonstrates the effectiveness of the approach proposed. In addition, it is inconvenient to assess the stability of post-fault system based on relative rotor angle of generators, while the proposed transient stability criteria can avoid this problem.

4. Conclusions

This paper proposes a novel transient stability analysis approach for the power system integrated with DFIG. The validity of proposed approach are verified by simulation results of New England-39 bus system integrated with DFIG. The following conclusions are obtained.

1) A novel energy function of the power system integrated with DFIG is derived, where generators adopt 3th order model;
2) The energy function based criteria are put forward for the transient stability analysis of power system integrated with DFIG, where the results are consistent with time domain simulation.

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