Analysis of disturbance source location of direct drive wind turbine based on energy function

Zijie Zhang¹,* Na Cao¹b
¹College of Electrical Engineering and Automation, Shandong University of Science and Technology, Qingdao, Shandong, 266590, China
*a*zhangzijie_1996@163.com, bcaona_2006@163.com,

Abstract—In order to locate the disturbance source quickly and accurately in the wind farm, taking the direct drive wind turbine as an example, using the transient energy method, firstly, the transient energy flow formula is derived according to the mathematical model of each part of the direct drive wind turbine, the energy flow power is obtained by linear fitting, and the position of the disturbance source is judged by the positive and negative energy flow power; then a single machine infinite bus system model with forced oscillation source is built on PSCAD/EMTDC simulation platform for simulation. The results show that the transient energy method can accurately locate the disturbance source of direct drive wind turbine unit.

1. Introduction
With the increasingly prominent environmental problems in today's society, the use of new energy has gradually become a trend, in which wind power generation has developed rapidly. However, with the gradual increase of wind power installed capacity and the continuous expansion of wind power development scale, wind turbine grid connection has brought new challenges to the stable operation of power system [1]. The access of various power electronic equipment and the interaction between fan and power grid may cause the subsynchronous oscillation of the system. Therefore, the research on the timely location of subsynchronous oscillation source and accurately locate the specific location of disturbance source plays a key role in the suppression and elimination of subsynchronous oscillation.

Transient energy method is an oscillation analysis method proposed in recent years, which has been well applied in doubly fed wind turbine [2~5]. In [2], the phasor measurement data at the generator terminal are collected and selected to calculate the dissipative energy flow into the generator, estimate the damping of the generator through the change rate of the dissipative energy flow, and then judge the position of the disturbance element. In [3], the transient energy flow is applied to Subsynchronous Oscillation for the first time, and the oscillation source location of subsynchronous forced oscillation is realized. In [4~5], the transient energy flow of doubly fed wind turbine is derived by using the transient energy flow method and applied to doubly fed wind farm.

In view of this, this paper mainly considers the application of transient energy method to the disturbance source location of direct drive wind turbine. The main work is as follows: firstly, the mathematical modeling of each part of direct drive wind turbine is carried out; then the transient energy flow formula of direct drive fan is deduced according to the mathematical model formula; finally, a single machine infinite bus system with forced oscillation source is constructed in PSCAD/EMTDC electromagnetic transient simulation software to verify the correctness of the application of transient energy method in direct drive fan.
2. Transient energy structure of direct-driven wind turbine

2.1 Mathematical model of direct drive wind turbine

2.1.1 Permanent magnet synchronous generator model

In order to simplify the calculation, the assumption in reference[6] specifies the positive direction according to the generator convention. The model of permanent magnet synchronous motor is:

\[
\begin{align*}
    u_{id} &= L_{sd}\frac{di_{d}}{dt} + R_{s}i_{d} - w_{s}L_{sd}i_{q} \\
    u_{iq} &= L_{sq}\frac{di_{q}}{dt} + R_{s}i_{q} + w_{s}L_{sq}i_{d} + w_{q}\psi_{f}
\end{align*}
\]

(1)

Where: \(u_{id}, u_{iq}, i_{d}, i_{q}\) are DQ axis components of stator voltage and current respectively; \(R_{s}\) is the stator resistance of permanent magnet synchronous generator; \(L_{sd}\) and \(L_{sq}\) are DQ axis components of stator inductance respectively, making \(L_{sd} = L_{sq} = L_{s}\); \(w_{s}\) is the electrical angular velocity of the generator; \(\psi_{f}\) is permanent magnet flux linkage.

2.1.2 Mathematical model of grid side converter

Grid side converter adopts grid voltage vector oriented control technology (i.e. \(e_{d} = 0\)), and the control equation is shown in equation (2):

\[
\begin{align*}
    u_{2d} &= -K_{p2}\int (i_{2d}^{*} - i_{2d})dt - K_{i2}\left(i_{2d}^{*} - i_{2d}\right) + w_{2}L_{2}i_{2q} + e_{2d} \\
    u_{2q} &= -K_{p2}\int (i_{2q}^{*} - i_{2q})dt - K_{i2}\left(i_{2q}^{*} - i_{2q}\right) + w_{2}L_{2}i_{2d} + e_{2q} \\
    i_{2d} &= K_{p2}\left(u_{2d}^{*} - u_{2d}\right) + K_{i2}\left(u_{2d}^{*} - u_{2d}\right)dt
\end{align*}
\]

(2)

Where: \(u_{2d}, u_{2q}, i_{2d}, i_{2q}\) are DQ axis components of grid side converter voltage and current respectively; \(L_{2}\) is the equivalent inductance of the incoming reactor of the grid side converter; \(e_{2d}\) is the d-axis component of grid voltage; \(w_{2}\) is the synchronous power angle of the power grid; \(i_{2d}^{*}, i_{2q}^{*}\) are the current reference values of d-axis and q-axis of grid side converter respectively; \(u_{2d}^{*}, u_{2q}^{*}\) are DC bus voltage and its reference value; \(K_{p1}, K_{i1}, K_{p2}, K_{i2}\) are control parameter of grid side converter.

The transfer function block diagram of grid side converter can be obtained from equation (2):

![Fig.1 Grid side converter control](image_url)

2.2 Energy function of direct drive wind turbine

The formula for defining the transient energy flow from the node \(i\) through the branch \(L_{i}\) is:
\[ W = \int \left( P_i d\theta + \frac{Q_i}{U_i} dU_i \right) = \int \text{Im}(i_{d,q}^* dU_i) = \int \text{Im}(i_{d,q}^* - j i_{d,q}^*) (dU_i + j dU_i) = \int (i_{d,q}^* dU_i - j i_{d,q}^* dU_i) \]  

(3)

Where: \( P_i, Q_i \) are active power and reactive power of branch \( L_i \); \( u_i \) is the instantaneous voltage value of the node \( i \); \( U_i, \theta_i \) are the amplitude and phase angle of node \( i \) voltage respectively; \( i_j \) is the current of the branch \( L_j \).

The energy flow direction of direct drive wind turbine is shown in Fig. 2.

![Fig.2 Transient energy flow direction of PMSG](image)

According to equation (3) and Fig.2, the transient energy flow \( W \) from direct drive wind turbine parallel node \( A \) is:

\[ W = \int \left( P_i d\theta + \frac{Q_i}{U_i} dU_i \right) = \int (i_{d,q}^* dU_i - j i_{d,q}^* dU_i) = \int (u_{d,q} i_{d,q}^* + u_{d,q} i_{d,q}^*) d\delta_2 + \int (i_{d,q}^* dU_{d,q} - i_{d,q} dU_{d,q}) = \int P_i d\delta_2 + \int (i_{d,q}^* dU_{d,q} - i_{d,q} dU_{d,q}) = W_1 + W_2 \]  

(4)

Where: \( P_2 = u_{d,q} i_{d,q}^* + u_{d,q} i_{d,q}^* \) is the active power at the outlet of grid side converter; \( u_{d,q}, i_{d,q}, i_{d,q}, i_{d,q} \) are DQ axis components of outlet voltage and current of direct drive wind turbine; \( \delta_2 \) is the power angle at the outlet of direct drive wind turbine.

Substituting equations (2) into equation (4), the transient energy flow of direct drive wind turbine is as follows:

\[ W = W_1 + W_2 = \int P_2 w_0 d\theta + w_0 L_2 \left( i_{d,q}^* dU_{d,q} + i_{d,q} dU_{d,q} \right) + \int \left( i_{d,q}^* dU_{d,q} + i_{d,q} dU_{d,q} \right) - K_\rho \int (i_{d,q}^* dU_{d,q} - i_{d,q} dU_{d,q}) \int (i_{d,q}^* dU_{d,q} - i_{d,q} dU_{d,q}) \]  

(5)

2.3 Steps of energy function method

**Step 1**: Collect the instantaneous value of voltage and current at the port of the component to be tested for a period of time, convert it to \( xy \) axis coordinate system, and carry out fast Fourier transform on the collected variables to obtain the voltage and current at each synchronous frequency.

**Step 2**: The above variables are substituted into equation (4) to obtain the variation curve of transient energy flow with time.

**Step 3**: The energy flow curve is linearly fitted, and the positive and negative slope a reflects the damping characteristics of the element, which is defined as the energy flow power.
Step 4: At a certain frequency, the absolute value of the component energy flow power is the largest. We define this frequency as the dominant frequency. At the dominant frequency, if the element has a negative energy flow power, it means that the element absorbs energy and presents positive damping characteristics, not an oscillation source. If the element has a positive energy flow power, it indicates that the element generates energy and presents negative damping characteristics. It is considered to be an oscillation source.

3. Simulation verification

Modeling is carried out in PSCAD/EMTDC. Taking a single machine infinite bus system as an example, according to the analysis steps of transient energy flow method, the accuracy of locating the oscillation source of direct driven wind turbine under disturbance is verified by using transient energy flow method.

The parameters of direct drive wind turbine are shown in Table 1, and the input wind speed of the fan is 8m/s.

| Parameter value | Parameter value |
|-----------------|-----------------|
| 1.5             | Permanent magnet flux linkage/pu |
| 50              | Inertia time constant of wind turbine/s |
| 0.69            | Inertia time constant of generator/s |
| 0.017           | Shaft stiffness coefficient |
| 0.064           | Stator leakage inductance/pu |

3.1 Adding current source to single machine infinite bus system

Add current disturbance at 35kV side of unit transformer, and set measuring points at generator side, oscillation source side and infinite bus system side respectively, as shown in Fig.3. The outflow measuring point is specified as the positive direction of transient energy flow.

![Fig.3 System with current source disturbance](image)

The energy flow power near the complementary frequency of torsional vibration is mainly studied here, because the oscillation is more obvious when the disturbance frequency is complementary to the natural frequency of torsional vibration [3], and the natural frequency of torsional vibration of the system is 1.8Hz. Take the instantaneous values of voltage and current of three measuring points within 10–11s and substitute them into equation (4) to obtain the transient energy flow of direct drive wind turbine. The transient energy flow is linearly fitted to obtain the energy flow power of each measuring point, as shown in Fig.4.
Fig. 4 Energy flow power of measuring points when adding current source

The simulation results show that the dominant frequencies of figure (a) and figure (b) are about 48.2 Hz. At the dominant frequency, combined with Fig. 3, it can be seen that the energy flow power of measuring point 1 and measuring point 3 is negative, indicating that both measuring points consume energy, have positive damping characteristics, and are not disturbance sources. The energy flow power on the oscillation source side is positive, indicating that the measuring point generates energy and flows into measuring point 1 and measuring point 3, showing negative damping characteristics, which is the disturbance source.

3.2 Adding forced voltage source to single machine infinite bus system

Add voltage disturbance at 35kV side of unit transformer, and set measuring points at generator side and infinite bus system side respectively, as shown in Fig. 5. The outflow measuring point is specified as the positive direction of transient energy flow.

Fig. 5 System with voltage source disturbance

Take the instantaneous values of voltage and current of three measuring points within 10~11s and substitute them into equation (4) to obtain the transient energy flow of direct drive wind turbine. The transient energy flow is linearly fitted to obtain the energy flow power of each measuring point, as shown in Fig. 6.

Fig. 6 Energy flow power of measuring points when adding voltage source
The simulation results show that the dominant frequency in Fig. 6 (a) is 48.3Hz and that in Fig. 6 (b) is 48.2Hz. At the dominant frequency, the energy flow power of measuring point 1 and measuring point 2 is negative, indicating that both measuring points consume energy and are not disturbance sources. Combined with Fig. 5, it can be seen that the energy generated by the oscillation source flows into the two measuring points respectively, so it is located to the disturbance source.

4. Conclusion
This paper establishes the mathematical model of each part of the direct drive fan, and deduces the transient energy formula of the direct drive fan according to the model. The correctness of locating the disturbance source by using the transient energy method is verified by building a single machine model in PSCAD simulation software. The theoretical and simulation analysis shows that:

(1) From the derived formula of transient energy of direct drive fan, it can be seen that the energy function of direct drive fan is mainly determined by the output power and control parameters of grid side converter.

(2) The forced disturbance source is added to the single machine infinite bus system to obtain the voltage, current, power and other data of the measuring point, which are substituted into the transient energy formula to obtain that the energy flow power on the disturbance source side is positive and the energy flow power on the non disturbance side is negative. Therefore, the position of the disturbance source can be directly determined according to the positive and negative energy flow power. The correctness of the legal potential disturbance source of transient energy is verified.

In the following research, according to the analysis conclusion of this paper, the influence of grid side converter control parameters will be further studied.

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