Stability Analysis of Fan - Synchronizer Interconnected Power System Based on Shapelet Algorithm

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***Abstract*—With the increasing proportion of wind power, the transient behavior of power system has changed, and new instability phenomenon with unknown mechanism has occurred in some high proportion areas. In order to deeply understand the dynamic characteristics of double-fed fans and the mechanism of their interaction with the power grid, and then analyze the influence of large-scale double-fed wind power access on the stability of the power system, this paper adopts TRI co-simulation technology to conduct electromagnetic transient simulation of double-fed wind units in the RTDS system, and obtains detailed transient process data. shapelet algorithm based on mutual information method is used to select the key time series data in stable samples, and the interaction mechanism between fan and power grid is revealed by analyzing these data. This research method is of great significance to explore the transient characteristics of fan - synchronizer interconnected power systems.**

Keywords—TRI co-simulation, shapelet algorithm, Fan - synchronizer interconnection system

I. INTRODUCTION

Under the double pressure of energy shortage and environmental pollution, the world energy is undergoing a new round of great changes. To vigorously develop wind power, solar power and other renewable energy sources and realize green transformation of energy production is the only way to achieve sustainable development in the world. In China, the growth in renewable energy is even more pronounced. By the end of 2022, China's installed wind power capacity has exceeded 350 million kW, accounting for more than 10% of the country's total installed power capacity. In 2030, the total installed wind/photovoltaic capacity will reach 1.2 billion kW, and wind power will become an important power source in the power system[1]. However, with the increasing proportion of wind power, the transient behavior of the power system has changed, and new instability phenomenon with unknown mechanism has occurred in some high proportion areas.

In wind power generation technology, doubly-fed fan has been widely used. Unlike conventional synchronizers, doubly-fed fans are usually synchronized with the AC grid using phase locked loop (PLL) components and operating in Maximum Power Point Tracing (MPPT) mode. The supporting effect on the inertia of the system is almost zero. The large-scale replacement of the traditional synchronous machine will reduce the inertia of the system on a large scale and seriously threaten the stability of the system. At the same time, the interaction between the dynamics of doubler fan and the dynamics of traditional synchronous machine will affect the dynamic characteristics of the system synchronous machine after disturbance, and then cause changes in the damping characteristics and transient stability characteristics of the system[2-3]. Furthermore, doubly-fed wind power is connected to the main network of the system in a large scale, which increases the transmission pressure in the outgoing channel of the local grid and easily leads to weak damping, negative damping and even transient instability between regions. Therefore, an in-depth understanding of the dynamic characteristics of double-fed fans and the mechanism of interaction with power network is given to analyze the influence of large-scale double-fed wind power integration on the stability of electric power system, which has important theoretical and practical implications for the large-scale efficient utilization of wind power generation in our country[4].

The difference of transient characteristics of power generation equipment is an important reason for the change of transient synchronous stability mechanism of fan - synchronous interconnection system compared with traditional power system. For the fan, its transient characteristics are determined by its own energy storage element state and phase response control strategy, which has the characteristics of control strategy. After the fault disturbance, the fan phase-locked control passively tracks the phase change of the power network, providing coordinate reference for its own active/reactive power branch control, so as to achieve different control objectives. Therefore, the synchronization problem of fan-synchronizer interconnection system is no longer a problem of rotor synchronization, but is decided by the state and control of fan energy storage components, synchronization control strategy and rotor movement of synchronizer[5]. The process of system synchronization is still unclear, and the problems of transient synchronization mechanism and stability are more complex. The traditional transient stability analysis theory based on the rotor motion equation of synchronous machine faces the risk of failure.

In this paper, through the analysis of multi-scale control of double-fed fan, TRI co-simulation of fan access system in Tsat and RTDS simulation platform is carried out. Shapelet algorithm was used to extract the key time series from the transient simulation data, and through analyzing the key time series, the dynamic characteristics of doufeeders and the mechanism of their interaction with the power grid were further understood.

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II. MULTI-TIME SCALE DOUBLY-FED FAN

A. The Working Principle of Doubly-fed Fan

The basic function of the mechanical part of the doubler fan is to convert the kinetic energy of the wind into mechanical energy and transfer it to the induction generator, including the wind turbine, transmission shaft, transmission box, etc. The basic function of the electrical part is to convert mechanical energy into electric energy that meets the requirements of grid-connection guidelines. The basic structure is shown in Figure 2.1.

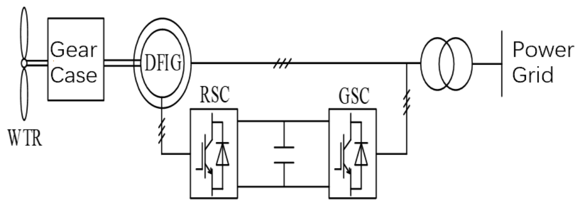

Fig. 1 DFIG schematic diagram

In normal operation, the grid voltage is applied to the stator windings, and a rotating magnetic field with a rotational speed of n_1 is formed in the air gap. The following relations exist:

$$n_1 = \frac{60 f_1}{p} \qquad (1)$$

Where, n_1 is synchronous speed, f_1 is grid voltage frequency, and p is motor pole number.

When three-phase symmetrical current passes through the rotor winding, a rotating magnetic field with a rotational speed of n_2 is generated in the air gap, and the following relation exists:

$$n_2 = \frac{60 f_2}{p} \qquad (2)$$

Where, f_2 is the voltage frequency of the grid.

If n is the rotor speed, the frequency of the induced potential in the stator windings can always be maintained as the voltage frequency of the power grid only by maintaining $n \pm n_2 = n_1 =$ a constant.

At this time, the slip rate of the doubly-fed fan is $s = (n_1 - n)/n_1$, and the frequency of the current passing through the rotor winding is:

$$f_2 = \frac{pn_2}{60} = \frac{p(n_1 - n)}{60} = \frac{pn_1}{60} \times \frac{n_1 - n}{n_1} = f_1 s \qquad (3)$$

B. Multi-time Scale Control Characteristics of Doubly-fed Fans

Professor Yuan Xiaoming and his team from Huazhong University of Science and Technology studied the multi-time-scale cascade and sequential switching characteristics of doubly-fed fan control and protection. According to different carrier forms and capacities of energy storage components in doubly-fed fans, the control and protection of doubly-fed fans were divided into rotor speed time scale, DC voltage time scale and AC current time scale.

Among them, the control of AC current time scale (0.01s) includes rotor current control and network side current control. The control goal is to track the command value provided by the upper level control. The control of DC voltage time scale (0.1s) includes power control and DC bus voltage control. The control goal is to make the output power track the power instruction value provided by the upper control and maintain the DC bus voltage constant. The time scale of rotor speed (s class) mainly includes the related control of wind turbines. The control objective is mainly to capture the wind energy to the maximum extent, while the speed is controlled within a reasonable range.

Figure 2-2 shows the multi-time scale cascaded control features of a double-fed fan.

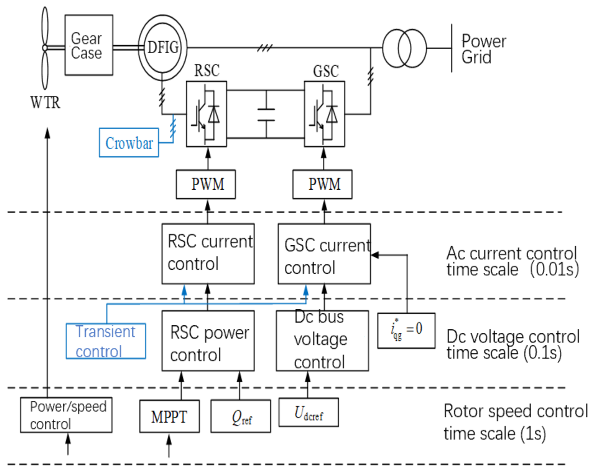

Fig. 2 Multi-time scale cascade control characteristics of DFIG

III. SHAPELET Algorithm Based on Mutual Information

Shapelet refers to a subsequence in a time series, which can be used as a partition point to divide the time series into two subsequences. The choice of Shapelet is critical because choosing the right Shapelet can better distinguish different time series categories.

A. mutual information

Mutual Information is a method used to measure the correlation or dependence between two random variables in probability theory and information theory. It is a non-negative real number that reflects the amount of information shared between two random variables.

Let's say we have two random variables, X and Y, and I(X,Y) tells us how much information we can get about Y when we know that X happens, or vice versa, how much information we can get about X when we know that Y happens. The value of mutual information can be calculated by the following formula:

$$I(X,Y) = H(X) - H(X|Y) = H(Y) - H(Y|X) = H(X) + H(Y) - H(X,Y)$$

Among them, the H (X) and H (Y) respectively entropy of X and Y, H (X | Y) and H (Y | X) respectively under the condition of a given Y or X and X or Y entropy, H (X, Y) said the entropy of X and Y.

The larger the value of mutual information, the stronger the correlation between X and Y; The smaller the value, the weaker or no correlation between them.

In machine learning, mutual information is widely used in feature selection, clustering, classification, dimension reduction and other fields. For example, in feature selection, mutual information can be used to assess the correlation between each feature and the target variable, and then features with high mutual information values can be selected as input features. In clustering, mutual information can be used to measure the correlation between different clusters, and then the data points with high correlation can be clustered into the same category.

B. *Implements*

The shapelet algorithm based on mutual information calculates the mutual information between all possible shapelets and classification tags, selects the shapelet with the largest mutual information value as the partition point, and then classifies the time series.

In the concrete implementation, firstly, some candidate shapelets are selected from the training set, then the mutual information values of each candidate Shapelet and all time series in the training set are calculated, and finally the candidate Shapelet with the maximum mutual information value is selected as the feature. The specific calculation process is as follows:

- For each candidate Shapelet, it is compared with all possible subsequences of all time series in the training set to obtain the subsequence most similar to the candidate Shapelet in each time series.
- For each time series, the subsequence that is most similar to the candidate Shapelet is taken as the new sequence to obtain a new sequence with the length of Shapelet, and then the mutual information value of the new sequence and the original sequence is calculated.
- Summed the mutual information values of all the subsequences most similar to the candidate Shapelet to get the mutual information values of the candidate Shapelet and all the time series in the training set.

By calculating the mutual information value of each candidate Shapelet, the candidate Shapelet with the largest mutual information value can be selected as the feature, and then the feature is used for classification. Since mutual information can capture the correlation between features and target variables, choosing Shapelet with the largest mutual information value as the feature can improve the accuracy of classification.

IV. Simulation Example Analysis

A. *Sample Construction*

The simulation system used in this paper adopts the IEEE 10 computer 39-node system, and its topology is shown in Figure 3. In order to establish the grid-connected hybrid simulation model of DFIG wind farm, RTDS and Tsat simulation software were used to build the simulation model and conduct TRI co-simulation. In order to consider the characteristics of DFIG wind farm, synchronous motors on bus 35 and 37 are replaced with DFIG wind farms of the same capacity according to the standard algorithm. 37 nodes are replaced with WT1 and 35 nodes are replaced with WT2. According to the base load of the system, for 30 transmission lines in the network, the three-phase earth short circuit fault is applied at 10%, 50% and 90% of the distance from the first end of the line, and the fault is removed after 2, 4, 6 and 8 cycles after the fault occurs. A total of 360 samples were generated, of which 189 were stable and 171 were unstable.

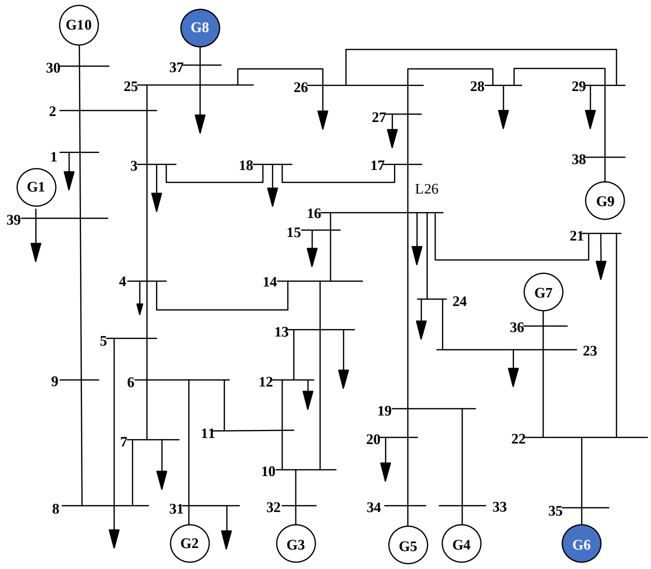

Fig.3 IEEE 39 node system wiring diagram

B. *External characteristics analysis of DFIG unit*

By using the interpretability of Shapelet to understand and analyze the key sequences, the instability law of the system hidden in the data set can be further mined. Analyze the simulation data of 2.4.6.8 cycles after the fault occurs when the load level is 100% and the three-phase short-circuit fault occurs at 90% of the line. Key timing segments, including 100 data points, were extracted from all stable and unstable samples, with a time length of 0.04s. The time series of active power output of wind units extracted by Shapelet algorithm is shown in Figure 4.

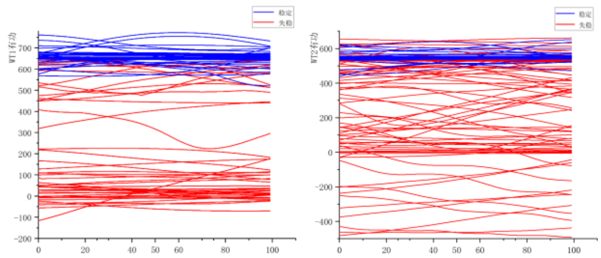

Fig.4 Active power of wind turbine

It can be found from the figure that the active power of the stable sample is concentrated near the active power of the steady state, while the variable range of the unstable sample is large, reflecting the adjustment of the active power of the stroke unit during the transient process. It is further demonstrated that the time series data extracted by Shapelet can represent the stable state of the original data.

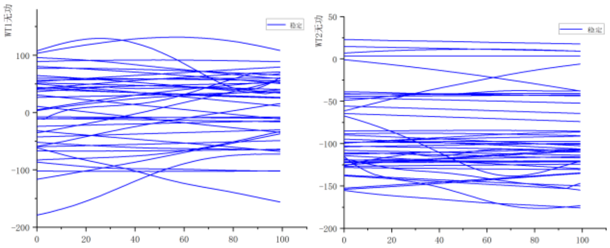

Fig.5 Reactive power of wind turbine

In the same way, the analysis of the extracted reactive power time series of wind units shows that even for stable samples, the variation range of reactive power of wind units is large, indicating that the reactive power output of wind units is adjusted to maintain the stability of node voltage during the transient process.

C. Transient characteristics analysis of DFIG unit control link

Since the transient characteristics of DFIG are jointly determined by its conventional multi-time scale control and a variety of additional controls, the interpretability of Shapelet is used to further explore the influence of internal control links on the external characteristics of DFIG.

In this section, the wind unit WT1 is analyzed. The system load running level is 100%, the fault location is 90% of the line, and the fault removal time is the data of 2, 4, 6, and 8 cycles after the fault occurs for analysis. Among them, the direct axis current component, alternating axis current component and DC voltage of the network-side converter are shown in FIG. 6, 7, and 8.

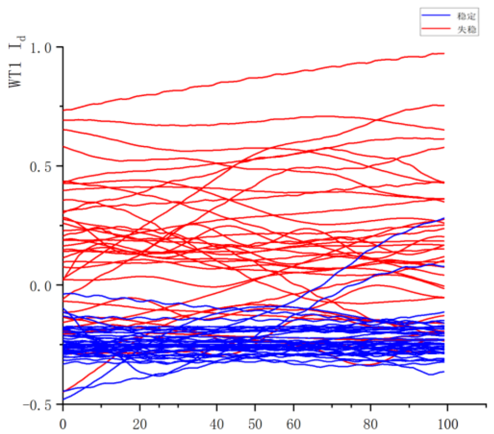

Fig.6 Direct axis current component of the converter at the net-work side of wind turbine WT1

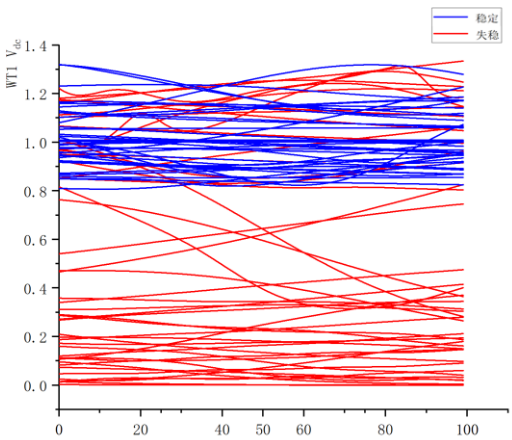

Fig.7 DC voltage of wind turbine WT1

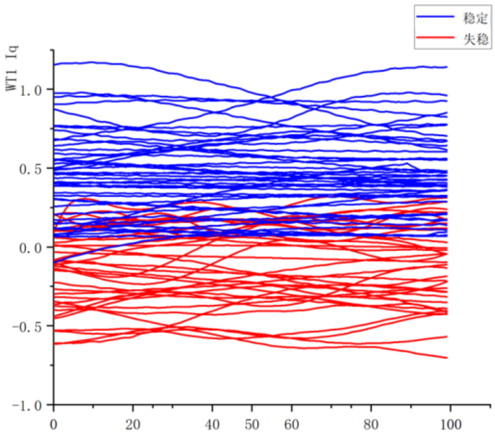

Fig.8 Quadrature axis current component of the converter at the network side of wind turbine WT1

As can be seen from the figure, due to the control characteristics of the doubly-fed fan, the DC voltage is basically negatively correlated with the direct-axis current component of the grid-side converter. Compared with the stable sample, the unstable sample has a larger variation range in the transient process.

In addition, since the D-axis direction of the two-phase rotation dq coordinate system of the grid-side converter is usually consistent with the direction of the grid voltage vector, that is, the grid voltage orientation is adopted, and the Q-axis current component is 0. Therefore, the Q-axis current component of the grid-side converter in FIG. 10 is basically distributed on both sides of 0. In the transient process, the stable samples all vary in the range greater than 0, while the unstable samples are basically distributed in the range less than 0.

Through the analysis of Shapelet critical time series, the change of fan internal data in the transient process can be intuitively understood, which is of great significance for further analysis of the interaction mechanism between fan and power grid in the fan access power supply system, and provides a reference for the transient stability control of the fan access power supply system.

V. Conclusion

In this paper, the electromagnetic transient simulation of doubly-fed air unit is realized by TRI co-simulation and RTDS, and the detailed data of the transient process of air unit is obtained. Shapelet algorithm based on mutual information method is used to obtain the key time series data of stable samples, and the interaction mechanism between fan and power grid can be understood through the analysis of the key data, which is of positive significance for the transient research of fan-synchronous interconnected power system, and provides method guidance for the analysis of transient stability control after large-scale fan access to the system.

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