Research on identifying parameter of DFIG-based wind farm based on mathematical mechanization analysis

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Abstract. In order to obtain precise running parameters which are the intrinsic cause resulting in sub-synchronous resonance (SSR) in transmission line with series compensation capacitor, an approach that can be used to identify the dynamic equivalent parameters of DFIG (doubly-fed induction generator) -based wind farm has been proposed based on the mechanized mathematics theory. Core work is to derive the analytical expressions of the stator resistance, inductance and the rotor resistance, inductance and the mutual inductance which are expressed by the sampling voltage, current and active power based on polynomial modelling and characteristic set of the mathematical mechanization. Simulation results which are associates with the actual sampled data of a wind farm show that, the equivalent parameters consist of 32 DFIGs have been given and verified by proposed approach. Also, the maximum identifying error of corresponding resistance and inductance of the stator and rotor was lower than 5% based on sampling an actual DFIG farm. This work can provide a reference for analysing and suppressing SSR which is a bottleneck for a wind farm stable running.

1. Introduction

In order to analyze and suppress the SSR which is affecting the stable operation of a DFIG wind farm, it is necessary to modelling and identify the parameters of equivalent DFIG in real time [1-3]. Above mentioned reasons are as follows: ① For a DFIG, its stator and rotor parameters have some perturbations and uncertain items due to the influence of unstable wind speed and operation temperature [4]. ② For whole wind farm, due to the limitation of the model dimension of the simulation software and the capacity of the calculation platform, it is urgent to derive an equivalent DFIG model that can represent the work state of the wind farm [5]. ③ The stator and rotor parameters of the equivalent DFIG are one of the main reasons for SSR of a wind farm with series compensation capacitance [6-8]. ④ It puts forward some new requirements for evaluating equivalent parameters due to the complexity and variety if the DFIG in a wind farm [9]. Above discussion shows that it is necessary to research on an approach for equivalent modeling and identifying parameter of a DFIG wind farm [10-12].

At present, researchers often prone to adopt the relevant transmission line parameters of the wind farm or the third-order to fifth-order modeling analysis to obtain an equivalent model of a wind farm.
which have characteristics of high order and high dimension. However, due to the demands of real-time and rapidity for analyzing and suppressing SSR, a simplified algorithm that has the advantages of less computing and data-communicating amount should be given [13]. The mathematical mechanization method presented by Wu may be considered to be a high efficiency approach to modelling an equivalent wind farm and identifying its corresponding parameters. As one of the main supporting theories of AI (artificial intelligence), this method is mainly characterized by quasi division and characteristic sequence. It can obtain analytic solutions of characteristic sets that can reflect the regularity of a class of research objects [14]. Due to above characteristics, this method may give a solution to identify the accurate parameters of equivalent wind farm which can be used to analyze and control the on-line SSR.

A modelling and solving framework for the DFIG wind farm has been given based on the mathematical mechanization method in this paper. Taking a wind farm with 32 DFIGs for example, its equivalent model which were described by sampled voltage and current of the stator and rotor has been derived firstly. Secondly, the differential equations that used to image the characteristics of the equivalent model of the wind farm have been solved and expressions of the resistance, self-inductance of the stator and rotor, and their mutual inductance have been given and verified by proposed modelling and solving framework. Thirdly, the identifying accuracy has been verified by comparing the measured active power and reactive power to corresponding simulation results which maximum identifying error was lower than 5%. It denotes that the proposed approach can satisfy the demands of real-time equivalent modelling and high-efficiency identification for an actual DFIG wind farm [15-18].

2. Mathematical mechanization method

Definition of mathematical mechanization method: For two polynomial rings \((u_1,u_2,\ldots,u_m)\) and \((x_1,x_2,\ldots,x_n)\), there variables \(m\) and \(n\) is any integer and \(m < n\); \(u_i (i = 1, 2, \ldots, m)\) and \(x_i (i = 1, 2, \ldots, n)\) is real number. Let \(k\) be a field with zero characteristics, define variables \((u_1,u_2,\ldots,u_m)\) be the constituent parameters of the ring \(k[u_1,\ldots,u_m,x_1,\ldots,x_n]\).

For ring \(P(u_1,\ldots,u_m,x_1,\ldots,x_n) \in k[u_1,\ldots,u_m,x_1,\ldots,x_n]\), the variable with the largest subscript in \((x_1,x_2,\ldots,x_n)\) which appears in \(P(u_1,\ldots,u_m,x_1,\ldots,x_n)\) is called the main variable of ring \(P(u_1,\ldots,u_m,x_1,\ldots,x_n)\), it can be recorded as \(CLS(P)\). If the polynomial \(P(u_1,\ldots,u_m,x_1,\ldots,x_n)\) variables \((x_1,x_2,\ldots,x_n)\) does not appear, there is not any main variable and its class is \(CLS(P) = 0\).

Assuming \(\varepsilon\) is a monomial order on ring \(T\), for a non-zero polynomial \(f \in k[x_1,x_2,\ldots,x_n]\), the largest power in \((T(f),\varepsilon)\) is called the first term which can be expressed by \(HT(f)\). The largest power in \((M(f),\varepsilon)\) is called the first monomial of \(f\), which is represented by \(HM(f)\). The coefficient of the first monomial \(HM(f)\) is called the first coefficient, expressed in \(HC(f)\), which can be written as,

\[
HM(f) = HC(f) \cdot HT(f)
\]  

(1)

Compared with classical numerical methods, the advantage of the mathematical mechanization method is that it can give an analytical solution of the problem in a short time. For any polynomial ring, each independent polynomial equation is called the characteristic set. The essence of mathematical mechanization method is to obtain the expression of any \(x_j, j \in [1,n]\) by eliminating high-order characteristic set. It is the mathematical basis for modelling and solving the equivalent DFIG wind farm.
3. Modelling and solving a DFIG wind farm
The research object is a wind farm with 32 DFIGs in north China which capacity of every DFIG is 1.5MW. Topology of a DFIG with transformer (0.69 kV / 10kV) and power line is shown in Figure 1.

![Diagram of a wind farm with DFIGs](image)

**Figure 1.** An actual wind farm: where (a) is topology of the farm, (b) is a DFIG connected to the grid.

In Figure 1, considering the changes of wind farm load and input wind speed, dynamic equivalent model of the DFIG wind farm in the dq coordinate system can be written as.

\[
\begin{align*}
\frac{d}{dt} i_d &= \left( -R_s L_m i_d + \omega_d L_m i_q + \omega_d \left( L_s i_q - L_s i_d \right) \right) i_d + R_L i_d + \omega_L L_m i_q + L_m v_{ds} - L_m v_{dq} \\
\frac{d}{dt} i_q &= \left( -\omega_s L_m i_q + \omega_d \left( L_s i_d - L_s i_q \right) \right) i_q - R_L i_q - \omega_L L_m i_d - R_L i_d + L_m v_{ds} + L_m v_{dq} \\
\frac{d}{dt} i_d &= \left( R_L i_d - \omega_s L_m i_d - \omega_d \left( L_s i_d - L_s i_q \right) \right) idr - R_L i_d - L_m v_{ds} + L_m v_{dq} \\
\frac{d}{dt} i_q &= \left( \omega_s i_q - \omega_d \left( L_s i_d - L_s i_q \right) \right) idr - R_L i_d - L_m v_{ds} + L_m v_{dq} \\
\end{align*}
\]

(2)

Where, \( R_s, R_r, L_s, L_r, \) and \( L_m \) are DFIG stator resistance, rotor resistance, stator inductance, rotor inductance and mutual inductance respectively; \( s \) is the slip rate; \( v_{ds}, v_{dq} \) is the stator voltage; \( v_{ds}, v_{dq} \) is the rotor voltage; \( i_{sd}, i_{sq} \) is the stator current; \( i_{rd}, i_{rq} \) is rotor current; \( \psi_{sd}, \psi_{sq} \) is stator flux; \( \psi_{rd}, \psi_{rq} \) is rotor flux linkage; \( \omega_r, \omega_d \) is the synchronous velocity and angular velocity of equivalent DFIG.

Moreover, the active power and reactive power corresponding to the sampled voltage and sampled current of the stator and rotor of the equivalent DFIG can be given by following equations which consists of \( P_s = v_{ds} i_{ds} + v_{dq} i_{dq}, P_r = v_{rd} i_{rd} + v_{rq} i_{rq}, Q_s = v_{ds} i_{ds} - v_{dq} i_{dq} \) and \( Q_r = v_{rd} i_{rd} - v_{rq} i_{rq} \). Where, \( P_s \) and \( Q_s \) are the active power and the reactive power of the stator, and \( P_r \) and \( Q_r \) are the active power and the reactive power of the rotor of the equivalent DFIG.

Considering the relationship of the active power of rotor current to other parameters of the DFIG, such as the electromagnetic torque, an initial characteristic set \( \{f_1, f_2, f_3, f_4\} \) can be given as.

\[
\begin{align*}
\frac{df_1}{dt} &= T_e - L_m (i_{rd} i_{dq} - i_{rd} i_{dq}) = 0 \\
\frac{df_2}{dt} &= i_{dq} - (i_{sd} R_r - i_{dq} L_{rs} - u_{sd}) / L_m = 0 \\
\frac{df_3}{dt} &= i_{rd} - (u_{dq} - i_{rd} R_s - i_{rd} L_{rs}) / L_m = 0 \\
\frac{df_4}{dt} &= P_r - (u_{rd} i_{rd} + u_{rq} i_{rq}) = 0 \\
\end{align*}
\]

(3)

Based on above analysis, due to the voltage \( v_{ds}, v_{dq}, v_{rs}, v_{rq} \) and current \( i_{sd}, i_{sq}, i_{rd}, i_{rq} \) were sampled from the actual DFIG wind farm, i.e. above mentioned variables can be understood as the constant at every fundamental period. And then, the expressions of parameters \( R_s, L_s, R_r, L_r \) and \( L_m \) of the equivalent DFIG can be obtained by elimination procedure which shown in Figure 2 and Figure 3.
Figure 2. Solution and elimination process.  Figure 3. Identification flowchart of DFIG parameters.

Above analysis shows that, the time series data of the stator and rotor parameters of the equivalent DFIG can be identified at every fundamental period of sampled voltage, sampled current and electromagnetic torque of the actual wind farm. Therefore, a whole DFIG wind farm can be modelled and identified by proposed approach based on mathematical mechanization method.

4. Parameter identification of equivalent DFIG
The measured voltage, current and active power of 0.69kV side of Figure 1 are shown in Figure 4. Corresponding to Equation (2) all tested data have been transformed into format of dq coordinate system.

Figure 4. Measured data of an actual DFIG in in dq coordinate system: where (a) is stator voltage, (b) is the stator current, (c) is the rotor voltage, (d) is the rotor current, (e) is the rotor active power.

Figure 5. Identification parameters of an actual DFIG: where (a) is stator inductance $L_s$, (b) is the stator resistance $R_s$, (c) is the rotor inductance $L_r$, (d) is the rotor resistance $R_r$, (e) is the mutual inductance $L_{mr}$. 

\[ R_s = (i_d u_{sd} + i_q u_{sq}) / (i_d^2 + i_q^2) \]
\[ L_r = (i_d u_{rd} - i_q u_{rq}) / (i_d^2 + i_q^2) \]
\[ R_r = (i_d u_{rd} + i_q u_{rq}) / (i_d^2 + i_q^2) \]
\[ L_o = (P_i i_d - i_q u_{rd} - i_q^2 u_{rd}) / i_d (i_d^2 + i_q^2) \]
\[ L_n = (y_1 + y_2) / \left[ s (i_d^2 + i_q^2) (i_d^2 + i_q^2) \right] i_d^2 u_{rd} \]

Where, $y_1 = i_d^2 i_d^2 + R_r - i_q^2 i_q^2 u_{rd} - i_d^2 u_{rd} i_d$, $y_2 = -i_q^2 i_q^2 u_{rd} i_d - i_d^2 i_d^2 P_i i_d - i_q^2 i_q^2 u_{rd}$. 

\[ \begin{align*}
L_{ls} &= \frac{(i_d u_{sd} + i_q u_{sq})}{(i_d^2 + i_q^2)} \\
L_{re} &= \frac{(i_d u_{rd} - i_q u_{rq})}{(i_d^2 + i_q^2)} \\
L_{rs} &= \frac{(i_d u_{rd} + i_q u_{rq})}{(i_d^2 + i_q^2)} \\
L_{ro} &= \frac{(P_i i_d - i_q u_{rd} - i_q^2 u_{rd})}{i_d (i_d^2 + i_q^2)} \]
\]
Substituting above tested voltage, current and active power to Equation (4), the inductance and resistance of the stator and rotor of the equivalent DFIG have been obtained and shown by Figure 5 and Table 1.

| order | DFIG parameters | identification value | actual value | error (%) |
|-------|-----------------|----------------------|-------------|-----------|
| 1     | stator resistance \( r_s \) (\( \Omega \)) | 0.83798 | 0.8000 | 4.75 |
| 2     | self inductance of stator \( L_s \) (mH) | 0.51341 | 0.5000 | 2.68 |
| 3     | rotor resistance \( r_r \) (\( \Omega \)) | 0.9859 | 1.0000 | 1.41 |
| 4     | self inductance of rotor \( L_r \) (mH) | 4.1052 | 4.0000 | 2.63 |
| 5     | stator and rotor mutual inductance \( L_{sr} \) (mH) | 4.5451 | 4.5000 | 1.00 |

In order to validate correctness and accuracy of identification parameters of proposed approach, the arithmetic average for the \( L_s, r_s, L_r, r_r \) and \( L_{sr} \) are shown in Table 1. It indicates that, the maximum relative identification error is less than 5%. Figure 5 and Table 1 show that, this work can lay an algorithm foundation for the equivalent modelling and identifying its parameter of the whole wind farm.

5. Simulation and verification

Taking a wind farm with 32 DFIGs for example, we should identify its equivalent parameters for suppressing the SSR which influenced on stable running of this farm of Northern China. As Figure 6(a) shows, in order to validate the effect of proposed approach further, we checked it with a simulation model by the PSCAD software. There, instead of 32 DFIG which rated power is 1.5MW, an equivalent DFIG which total power is 48MW has been connected to an infinite power grid. Due to the Table 1, corresponding conversion parameters were used to set the simulation values of the inductance and the resistance of the equivalent DFIG of the wind farm with 32 DFIGs.

The active power and reactive power of the equivalent DFIG of the wind farm are shown in Figure 6(b) and Figure 6(c). There dash-dotted line and solid line denotes the simulation data and measured data respectively. Detail comparison errors of both measured and simulated were shown in Table 2. In order to make the simulation more closely to the practical wind farm, the tested wind speed was used to be the input excitation which is one of the main characteristics of this simulation.
Figure 6. Simulink model and results: where (a) is the simulation topology, (b) is simulation active power and measured active of equivalent DFIG, (c) is simulation reactive power and measured reactive of equivalent DFIG.

Table 2. Error analysis of parameter identification results.

| order          | simulation value | measured value | absolute error | relative error (%) |
|----------------|------------------|----------------|----------------|--------------------|
| active power (MW) | 20.691           | 19.832         | 0.858          | 4.326              |
| reactive power (MVar) | 9.959            | 10.438         | 0.479          | 4.589              |

As Table 2 shows, the relative error of simulation value to measured one of the active powers and reactive powers is 4.326% and 4.589%, respectively. It means that the proposed approach is not only suitable to identify the parameters of a DFIG, but also suitable to evaluate the corresponding parameters of the equivalent DFIG of the actual wind farm. The correctness and feasibility of proposed equivalent modelling and analysis solving approach can be illustrated with this simulation instance.

6. Conclusions
Aiming at the urgent demand for predicting and suppressing SSR of a DFIG wind farm, an equivalent modelling parameter identifying approach has been proposed based on mathematical mechanization method. By the characteristic set and eliminating of mathematical mechanization method, the whole wind farm can be equivalent to be a DFIG and its inductance and resistance of the stator and the rotor can be described by sampling voltage, current and active power. Due to the analytical expressions of the inductance and resistance of the equivalent DFIG have been derived, this work is convenient for on-line identifying the equivalent parameter in embedded system such as DSP28335 especially. Therefore, this work can provide an algorithm and control foundation for predicting, analyzing and controlling the SSR of a DFIG wind farm with series compensation capacitor.

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References
[1] Kui Luo, Wenhui Shi and Jian Qu 2017 Multi-machine equivalent model parameter identification method for double-fed induction generator (DFIG)-based wind power plant based on measurement data[C]. The 6th International Conference on Renewable Power Generation 2017(13) 1550-1554
[2] Zhou Y, Zhao L, Hsieh T Y, et al. 2019 A multistage dynamic equivalent modeling of a wind farm for the smart grid development[J]. IEEE Transactions on Industry Applications 55(5) 4451-4461
[3] M Soos, L Wang, R O Fox, et al. 2007 Population balance modeling of aggregation and breakage in turbulent Taylor–Couette flow[J]. Journal of Colloid and Interface Science 307(2) 433-446
Xie Xiaorong, Liu Huakun, He Jingbo, et al. 2018 On new oscillation issues of power system[J]. Proceedings of the CSEE 38(10) 2821-2828
Sun Kun, Yao Wei and Wen Jingyu 2018 Mechanism and characteristics analysis of sub-synchronous oscillation caused by DFIG-based wind farm integrated into grid through VSC-HVDC system[J]. Proceedings of the CSEE 38(22) 6520-6532
Zaker B, Gharehpetian G B and Karrari M 2019 Small signal equivalent model of synchronous generator-based grid-connected microgrid using improved Heffron-Phillips model[J]. International Journal of Electrical Power & Energy Systems 108(JUN.) 263-270
Abdulrahman I, R Belkacemi and Radman G 2021 Power oscillations damping using wide-area-based solar plant considering adaptive time-delay compensation[J]. Energy Systems 12(2) 459-489
Wei C, Benosman M and Kim T 2019 Online Parameter Identification for State of Power Prediction of Lithium-ion Batteries in Electric Vehicles Using Extremum Seeking[J]. International Journal of Control, Automation and Systems 17(11) 2906-2916
Garmat A, Azzouzi M and Bouchechima B 2021 Comparison between Improved PID and LQ Multimodel Optimal Controllers for Variable-Speed Wind Turbines[J]. Electric Power Components and Systems 48(18) 1875-1887
Chen Wuhui, Xie Xiaorong, Wang Danhui, et al. 2018 Probabilistic stability analysis of subsynchronous resonance for series-compensated DFIG-based wind farms[J]. IEEE Transactions on Sustainable Energy 9(1) 400-409
Wang Y, Lu C, Zhu L, et al. 2016 Comprehensive modeling and parameter identification of wind farms based on wide-area measurement systems[J]. Journal of Modern Power Systems & Clean Energy 4(3) 383-393
Wang P, Zhang Z, Huang Q, et al. 2018 Improved Wind Farm Aggregated Modeling Method for Large-scale Power System Stability Studies[J]. IEEE Transactions on Power Systems 33(6) 6332-6342
Yasmine I, Chakib E B and Badre B 2018 Improved Performance of DFIG-generators for Wind Turbines Variable-speed[J]. International Journal of Power Electronics and Drive Systems 9(4) 1875-1890
Cao Jianchun, Xiang Zutao, et al. 2019 Research on mitigating DFIG wind farm SSR with STATCOM[J]. Power System Technology 43(3) 902-9099
Tajdinian Mohsen, Ali Reza Seifi and Mehdi Allahbakhshi 2019 Transient stability of power grids comprising wind turbines: new formulation, implementation, and application in real-time assessment IEEE Systems Journal 13(1) 894-905