



An approach to estimate the equivalent parameters of a wind farm with DFIGs during wind gusts based on data-driven analysis

Jianhua Chen¹, Ligu Wang^{2✉}, Alena Dreglea³, Elena Chistyakova⁴, Chunlai Yu⁵

^{1,2}Harbin Institute of Technology, Harbin, China

^{3,4}Irkutsk National Research Technical University, Irkutsk, Russia

⁴Matrosov Institute for System Dynamics and Control Theory of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

⁵Dalian Maritime University, Dalian, China

Abstract. The purpose of the study is to develop an approach based on online measurements and the theory of Ritt–Wu characteristic sets from the field of algebraic geometry and computer algebra to solve one of the main tasks of wind energy studies such “abandon wind” caused by wind gusts. The Ritt–Wu theory is effective in studying polynomial systems and their solutions. To obtain an equivalent double-fed induction generator, the following basic steps are used: build the characteristic sets by modeling a wind farm; establish the polynomial rings based on the real-time aggregation data; derive analytical expressions of a model of an equivalent double-fed induction generator; validate of the developed approach to modeling an double-fed induction generator using mathematical modeling in the PSCAD software environment and analysis of a combination of model data and telemetry data. A general solution procedure is used, which can be applied to obtain the analytical expressions of the inductance and impedance of an equivalent wind farm. The expediency and effectiveness of the developed approach is illustrated by the example of a real wind farm with a capacity of 50 MW with 34 double-fed induction generators. The simulation results demonstrate that the obtained parameters of an equivalent double-fed induction generator can accurately follow wind speed fluctuations with a lower error. Thus, this study presents a new effective method for estimating the exact equivalent parameters of a wind farm during wind gusts. The developed method is suitable for obtaining the analytical solutions of equivalent wind farm parameters in real time. Validation of the accuracy and speed of the author’s method has been carried out. Moreover, this study can be applied to any wind farms equipped with double-fed induction generators.

Keywords: equivalent parameter, data-driven approach, characteristic set, analytical solution, wind farm

Funding. The study was partially supported by the Beijing Science and Technology Project of China (MH20210194) and the Ministry of Science and Higher Education of the Russian Federation, project FZZS- 2024-0003.

For citation: Chen Jianhua, Wang Ligu, Dreglea A., Chistyakova E., Yu Chunlai. An approach to estimate the equivalent parameters of a wind farm with DFIGs during wind gusts based on data-driven analysis. *iPolytech Journal*. 2024;28(4):597-611. <https://doi.org/10.21285/1814-3520-2024-4-597-611>. EDN: SIYCGX.

ЭНЕРГЕТИКА

Научная статья

УДК 621.548

Оценка эквивалентных параметров ветроэлектростанций с асинхронными генераторами во время порывов ветра: подход на основе анализа данных

Ц. Чэнь¹, Л. Ван^{2✉}, А. Дрегля³, Е. Чистякова⁴, Ч. Юй⁵

^{1,2}Харбинский технологический институт, Харбин, Китай

^{3,4}Иркутский национальный исследовательский технический университет, Иркутск, Россия

⁴Институт динамики систем и теории управления им. В.Ф. Матросова СО РАН, Иркутск, Россия

⁵Даляньский морской университет, Далянь, Китай

Резюме. Цель исследования – для решения одной из основных задач ветроэнергетики, связанной с порывами ветра, разработать подход, основанный на онлайн измерениях и теории характеристических множеств

Ритта-Ву из области алгебраической геометрии и компьютерной алгебры. Теория Ритта-Ву эффективна при изучении полиномиальных систем и их решений. Для получения эквивалентного асинхронного генератора с двойным питанием применяются основные шаги: построение характеристических множеств путем моделирования ветропарка; создание полиномиальных колец на основе регистрации и обработки данных в режиме реального времени; вывод аналитических выражений модели эквивалентного асинхронного генератора с двойным питанием; валидация разработанного подхода к моделированию асинхронного генератора с двойным питанием с помощью математического моделирования в программной среде PSCAD и анализа комбинации модельных данных и данных телеметрии. Использована общая процедура решения, которая может быть применена для получения аналитических выражений индуктивности и импеданса эквивалентной ветряной электростанции. Целесообразность и эффективность разработанного подхода проиллюстрирована на примере реального ветропарка мощностью 50 МВт с 34 асинхронными генераторами с двойным питанием. Результаты моделирования демонстрируют, что полученные параметры эквивалентного асинхронного генератора с двойным питанием могут точно следовать колебаниям скорости ветра с меньшей погрешностью. Таким образом, в данном исследовании представлен новый эффективный метод оценки точных эквивалентных параметров ветропарка во время порывов ветра. Разработанный метод подходит для получения аналитических решений эквивалентных параметров ветропарка в реальном времени. Проведена валидация точности и быстродействия авторского метода. Более того, данное исследование может быть применено к любой ветроэлектростанции, использующей асинхронные генераторы с двойным питанием.

Ключевые слова: эквивалентный параметр, подход, основанный на данных, характеристическое множество, аналитическое решение, ветроэлектростанция

Финансирование. Исследование было частично поддержано Пекинским научно-техническим проектом Китая (MH20210194) и Министерством науки и высшего образования Российской Федерации, проект FZZS-2024-0003.

Для цитирования: Чэнь Ц., Ван Л., Дрегла А., Чистякова Е., Юй Ч. Оценка эквивалентных параметров ветроэлектростанций с асинхронными генераторами во время порывов ветра: подход на основе анализа данных. *iPolytech Journal*. 2024. Т. 28. № 4. (In Eng.). С. 597–611. <https://doi.org/10.21285/1814-3520-2024-4-597-611>. EDN: SIYCGX.

INTRODUCTION

The wind gusts can disrupt the operation of wind farms and cause “wind abandonment” due to sub-synchronous resonance (SSR) occurring between the feeder line and the wind farm, which has become a major obstacle to further development of wind power in Northeastern China [1, 2]. To analyze the occurrence mechanism of SSR, wind farms with double-fed induction generators (DFIGs) can be modeled as a single DFIG using an equivalence method based on the output data of the wind farm [3]. For this purpose, two issues should be addressed: (1) Accuracy: the parameters of DFIG are constantly change due to dynamic changes in stator and rotor temperatures. (2) Efficiency: the equivalent parameters of the wind farm under wind gusts need to be quickly evaluated as they are the basis for assessing wind farm instability. As discussed above, it is necessary to develop an approach that can accurately and efficiently estimate the equivalent parameters of a wind farm when wind gusts occur.

In order to meet the demand for accurate and efficient suppression of SSR, the entire wind farm should be aggregated into a single DFIG with online changing parameters. Investigation shows that, as shown in Table

1, there are many suitable equivalent algorithms for aggregating a wind farm which including modeling type and structure of DFIG, power load flow calculations, aggregation of wind farm system, clustering algorithm, Prony algorithm, dynamic equivalence of hybrid farms and aggregation by frequency domain impedance, etc. These methods have been successfully applied and achieved corresponding effects in practical examples. However, in order to overcome perturbed equivalent parameters of the wind farm online. The emergence of the data-driven approach provides a solution to the negative effects of the wind gusts.

Currently, data-driven approaches have been seen as promising solutions for optimizing controlled plants under external perturbations. As shown in Table 2, the data-driven approach can take different forms depending on a particular application. It consists of model-free adaptive control, model-free sliding control, virtual reference feedback tuning, iterative feedback tuning and, adaptive leaning control etc. These methods have demonstrated excellent performance and functionality in analyzing complex control system. However, considering the computation demand for the online estimation of equivalent parameters

Table 1. Wind farm aggregation algorithm

Таблица 1. Алгоритм агрегации ветроэлектростанции

Order	Algorithm		Ref	Note
1	Modeling type and structure of DFIG		[3]	On-line?
2	Load flow calculation	Conventional load flow	[4]	×
		Equivalent wind load	[5]	×
		Probabilistic load flow	[6]	×
3	Aggregation of wind farm system	Aggregation of wind speed	[7]	×
		Dynamic equivalent modeling	[8]	×
		Multi-machine equivalent model	[9]	×
		Layout design and yaw control	[10]	×
4	Clustering algorithm	Custer power prediction	[11]	×
		Optimization of clustered wind	[12]	×
		Probabilistic clustering algorithms	[13]	×
5	Prony algorithm	Combined MEEMD-Prony	[14]	×
6	Time-frequency-domain equivalent modeling		[15]	
7	Wind speed point-interval fuzzy forecasting		[16]	×
8	Decoupled impedance modeling		[17]	×

Table 2. Data-driven approach methods

Таблица 2. Методы, связанные с подходом, основанным на данных

Order	Algorithm	Accuracy	Rapidity
1	Model-free adaptive control	Restrict and influence each other, it is hard to reconcile performance parameters	
2	Model free sliding mode		
3	Iterative feedback tuning		
4	Adaptive learning control		
5	Fuzzy neural networks		
6	Virtual reference feedback tuning		

during wind gusts, there is still a trade-off between accuracy and efficiency that needs to be addressed to fully utilize the potential of data-driven methods.

Here we propose a data-driven approach to estimate the online equivalent parameters of a wind farm, which corresponds to the real-time sampling data. The main contribution of this study is the development of a faster and more efficient algorithm for identifying changing parameters of the equivalent DFIG. We suggest the following algorithm: (1) Construct a characteristic set consisting of unknown equivalent parameters by modeling the wind farm; (2) Establish polynomial rings associated with real-time aggregation current, voltage and slip ratio; (3) Derive analytical expressions for the inductance and impedance of the equivalent DFIG via zero decomposition of the characteristic set [18–25]; (4) Validate the equivalent DFIG using pseudo-residual analysis and simulation based on Power System Computer Aided Design (PSCAD). These

steps are integrated into a general data-driven procedure that can be used to obtain the equivalent parameters of a wind farm online. The feasibility and validity of the proposed approach are illustrated with a 50 MW wind farm that comprises 34 DFIGs connected to a 35 kV distribution system. Simulation results show that the errors in the active power and reactive power between the equivalent DFIG model and the actual wind farm are less than 5 and 10% respectively.

MODELING AND SOLVING WIND FARM PROBIEMS

In this paper, we use a wind farm with DFIGs as the research background to validate the proposed approach. As shown in Fig. 1, a 50 MW wind farm consisting of 34 DFIGs has been considered. The capacity, frequency and pole pair number of each DFIG is 1.5 MW, 50 Hz and 2 respectively. The detailed parameters of a DFIG associated with Eq. (1) to (7) are given in Table 3.

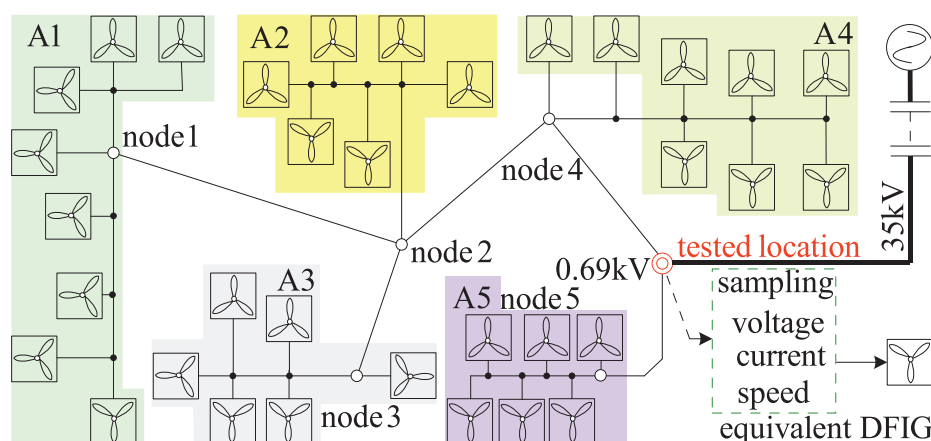


Fig. 1. Transmission system topology of the wind farm with 34 DFIGs

Рис. 1. Топология системы передачи данных ветроэлектростанции с 34 асинхронными генераторами

Table 3. Detailed DFIG parameters

Таблица 3. Подробные параметры DFIG

Order	Parameter	Unit	Note	Order	Parameter	Unit	Note
1	R_s	Ω	Stator resistance	10	Q_s	kVar	Stator reactive power
2	R_r	Ω	Rotor resistance	11	U_G	V	Terminal voltage
3	L_s	mH	Stator inductance	12	ψ_{ds}	Wb	d-axis component of stator flux linkage
4	L_r	mH	Rotor inductance	13	ψ_{qs}	Wb	q-axis component of stator flux linkage
5	L_m	mH	Mutual inductance	14	ψ_{dr}	Wb	d-axis component of rotor flux linkage
6	s	–	Slip ratio	15	ψ_{qr}	Wb	q-axis component of rotor flux linkage
7	i_{sd} / i_{sq}	A	Stator active/Reactive current	16	ω_s	rad/s	Synchronous angular velocity of DFIG
8	i_{rd} / i_{rq}	A	Rotor active/Reactive current	17	ω_r	rad/s	Rotor angular velocity of DFIG
9	P_s / P_r	kW	Active power of stator/rotor	18	T_e	kNm	Rotor torque of DFIG

A. Analysis of characteristic set method

Accurate modeling and efficient solving of a wind farm are the basis for estimating its equivalent parameters. To this end, the Ritt-Wu's characteristic set method [24] has been used to derive an analytical solution for the equivalent DFIG, which can serve as a foundation for the proposed general data-driven approach.

The characteristic set method was developed for ordinary difference polynomial systems [25]. This method includes fields, polynomials, ascending chains, and Pseudo-remainders analysis based on zero decomposition for difference polynomial systems.

In order to use the characteristic set method to estimate the equivalent parameters of a wind farm, we need to check whether a coherent difference chain is proper irreducible. For this purpose, the following issues should be addressed:

tems [25]. This method includes fields, polynomials, ascending chains, and Pseudo-remainders analysis based on zero decomposition for difference polynomial systems.

1) determine the difference chain from the wind farm;

2) extract the characteristic set based on modeling of the equivalent DFIG;

3) construct polynomial ring $R = K\{x_1, x_2, \dots, x_n\}$ over K by modeling the wind farm;

4) obtain the analytical expressions of unknown parameters by eliminating coupled variables of the characteristic set based on zero decomposition.

B. Data-driven approach based on characteristic set

To increase the system stability and extract maximum energy associated with the wind speed during wind gusts, the entire wind farm need to be aggregated as a DFIG. Fig. 2 shows the equivalent model of the wind farm corresponding to Fig. 1.

Fig. 2 shows that the calculation efficiency will be improved rapidly due to the fact that the calculating nodes of the equivalent model have been significantly decreased.

The equivalent DFIG consists of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter.

Neglecting the electromagnetic transient, the steady-voltage equation for the equivalent DFIG can be represented as:

$$u_{sd} = i_{sd}R_s - i_{sq}L_s - i_{rq}L_m; \quad (1a)$$

$$u_{sq} = i_{sq}R_s + i_{sd}L_s + i_{rd}L_m; \quad (1b)$$

$$u_{rd} = -si_{sq}L_m + i_{rd}R_r - si_{rq}L_r; \quad (1c)$$

$$u_{rq} = si_{sd}L_m + i_{rq}R_r + si_{rd}L_r. \quad (1d)$$

Usually, there are following relationships in the framework of stator voltage reference:

$$u_{sq} = U_G; \quad (2a)$$

$$u_{sd} = 0; \quad (2b)$$

$$P_s = u_{sd}i_{sd} + u_{sq}i_{sq} = U_G i_{sq}; \quad (2c)$$

$$Q_s = u_{sd}i_{sq} - u_{sq}i_{sd} = -U_G i_{sd}. \quad (2d)$$

Also, the d-q axis components of rotor current can be represented as:

$$i_{rq} = (i_{sd}R_s - i_{sq}L_s - u_{sd})/L_m; \quad (3a)$$

$$i_{rd} = (u_{sq} - i_{sq}R_s - i_{sd}L_s)/L_m. \quad (3b)$$

Based on above formulas, the rotor active power can be written as:

$$P_r = u_{rd}i_{rd} + u_{rq}i_{rq} = (-si_{sq}L_m + i_{rd}R_r - si_{rq}L_r) \times \\ \times (u_{sq} - i_{sq}R_s - i_{sd}L_s)/L_m + \\ = (si_{sd}L_m + i_{rq}R_r + si_{rd}L_r)(i_{sd}R_s - i_{sq}L_s - u_{sd})/L_m. \quad (4)$$

We select $\mathbb{X} = \{\mathbb{P}, \mathbb{W}\}$ as the chain, where $\mathbb{P} = \{u_{sd}, i_{sd}, u_{sq}, i_{sq}, u_{rd}, i_{rd}, u_{rq}, i_{rq}, s\}$ and $\mathbb{W} = \{R_s, L_s, R_r, L_r, L_m\}$.

Define the Eq. (1) and (4) as the characteristic set. Corresponding polynomial rings can be written as following expressions:

$$f_1 = u_{sd} - i_{sd}R_s + i_{sq}L_s + i_{rq}L_m = 0; \quad (5a)$$

$$f_2 = u_{sq} - i_{sq}R_s - i_{sd}L_s - i_{rd}L_m = 0; \quad (5b)$$

$$f_3 = u_{rd} + si_{sq}L_m - i_{rd}R_r + si_{rq}L_r = 0; \quad (5c)$$

$$f_4 = u_{rq} - si_{sd}L_m - i_{rq}R_r - si_{rd}L_r = 0; \quad (5d)$$

$$f_5 = P_r - u_{rd}i_{rd} - u_{rq}i_{rq} = 0. \quad (5e)$$

And then by zero decomposing the polynomial rings, based on eliminating the coupling variables, the equivalent parameters of the wind farm have been derived:

$$R_s = (i_{ds}u_{ds} + i_{qs}u_{qs})/(i_{qs}^2 + i_{ds}^2); \quad (6a)$$

$$L_s = (i_{ds}u_{qs} - i_{qs}u_{ds})/(i_{qs}^2 + i_{ds}^2); \quad (6b)$$

$$R_r = (i_{dr}u_{dr} + i_{qr}u_{qr})/(i_{qr}^2 + i_{dr}^2); \quad (6c)$$

$$L_r = (P_r i_{dr} - i_{dr}^2 u_{dr} - i_{qr}^2 u_{qr})/[i_{qr} s (i_{qr}^2 + i_{dr}^2)]; \quad (6d)$$

$$L_m = (y_1 + y_2)/[s(i_{qs}^2 + i_{ds}^2)(i_{qr}^2 + i_{dr}^2)i_{ds}i_{qs}]. \quad (6e)$$

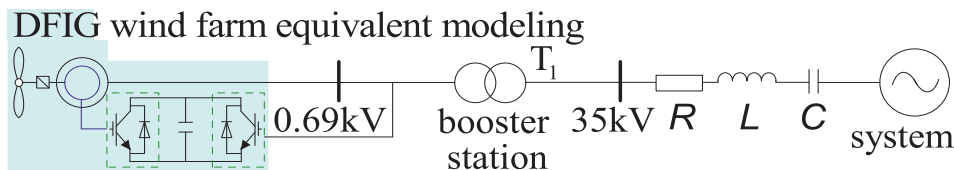


Fig. 2. Equivalent model of the wind farm with DFIG

Рис. 2. Эквивалентная модель ветроэлектростанции с асинхронными генераторами

Where, the intermediate variable y_1 and y_2 have the form:

$$y_1 = i_{qr}^2 i_{ds}^2 P_r - i_{qr}^3 i_{ds}^2 u_{qr} - i_{qr}^2 i_{ds}^2 u_{dr} i_{dr}; \quad (7a)$$

$$y_2 = -i_{qr}^2 i_{qs}^2 u_{dr} i_{dr} - i_{dr}^2 i_{ds}^2 P_r - i_{qr}^3 i_{qs}^2 u_{qr}. \quad (7b)$$

Since $\mathbb{P} = \{u_{sd}, i_{sd}, u_{sq}, i_{sq}, u_{rd}, i_{rd}, u_{rq}, i_{rq}, s\}$ can be seen as known variables at every sampling period, the unknown variables $\mathbb{X} = \{R_s, L_s, R_r, L_r, L_m\}$ can be calculated online according to Eq. (6) and (7). Table 4 provides a summary of the results given above.

In Table 4, parameter $\mathbb{P}$ is a set of r-pols under descending chain; $A = A_1, A_2, \dots, A_p$ is a finite sequence of nonzero r-pols; $\text{Zero}(\mathbb{P})$ denotes the set of solutions of $\mathbb{P} = 0$; $\mathfrak{B}$ is characteristic set, $\mathfrak{B} = C.S(\mathbb{P})$ is a characteristic set of $\mathbb{P}$.

ANALYSIS AND VALIDATION OF PROPOSED DATA DRIVEN APPROACH

In accordance with Fig. 1, a 50 MW wind farm has been considered, which is located in the northeastern China. The farm consists of thirty-four 1.5 MW DFIGs connected to a 0.69 kV distribution system, which exports power to the 35 kV grid through a 15 km feeder line. The corresponding sampled data were measured by a phasor measurement unit (PMU).

A. Data driven approach analysis

Based on the sampled voltage, current, and wind speed from the farm the influence of wind gusts on the slip ratio, rotor current and torque is shown in Fig. 3–5.

Comparison of Fig. 3, 4 and 5 shows that there is relationship near time 0.05 s: wind

Table 4. Data-driven algorithm procedure

Таблица 4. Порядок работы алгоритма, основанного на данных

1. Input: a finite set $\mathbb{P} = \{u_{sd}, i_{sd}, u_{sq}, i_{sq}, u_{rd}, i_{rd}, u_{rq}, i_{rq}, s\}$ of r-pols
2. Output: $W = \{A_1, A_2, A_3, A_4, A_5\} = \{R_s, L_s, R_r, L_r, L_m\}$ which every element is coherent proper irreducible difference chain and $\text{Zero}(\mathbb{P}) = \bigcup_{i=1}^5 \text{Zero}(\text{sat}(A_i))$
3. Begin: Call Eq. (1) and (4) $\mathfrak{B} = C.S(\mathbb{P}), \mathfrak{B} = B_1, B_2, B_3, B_4, B_5$ If $\mathfrak{B} = 1$ then $W = \{1\}$ Else $\mathbb{R} = \{\text{prem}(f, \mathfrak{B}) \neq 0 \mid f \in (\mathbb{P} \setminus B) \cup \Delta(\mathfrak{B})\}$, If $\mathbb{R} = \emptyset$ then test $\mathbb{P}$ Construct new characteristic set Eq. (6), repeat 3
4. Validate: Calculate Eq. (6) to (7) based on sampling $\mathbb{P}$ Tested power - simulated power $< \delta$? Where δ is the error Yes, End the procedure No, repeat 3

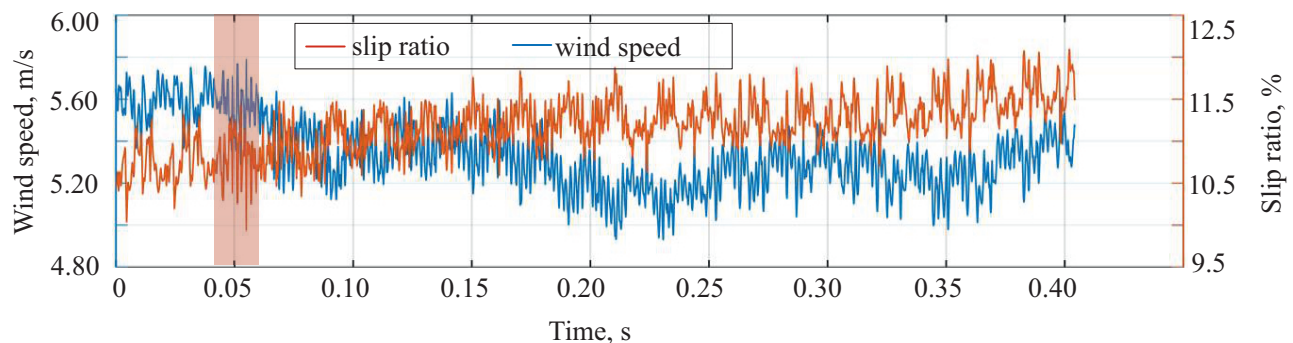


Fig. 3. Wind speed and wind farm slip

Рис. 3. Скорость ветра и скольжение ветроэлектростанции

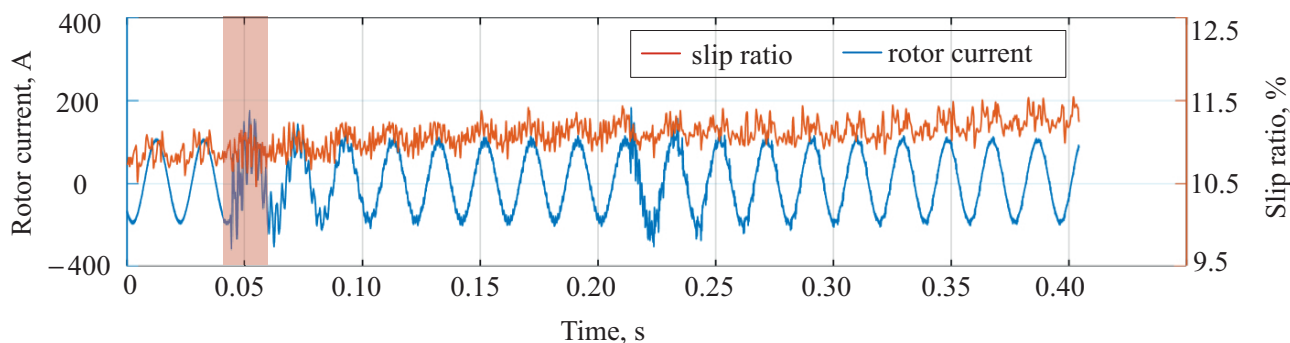


Fig. 4. Instantaneous rotor current and wind farm slip

Рис. 4. Мгновенный ток ротора и проскальзывание ветроэлектростанции

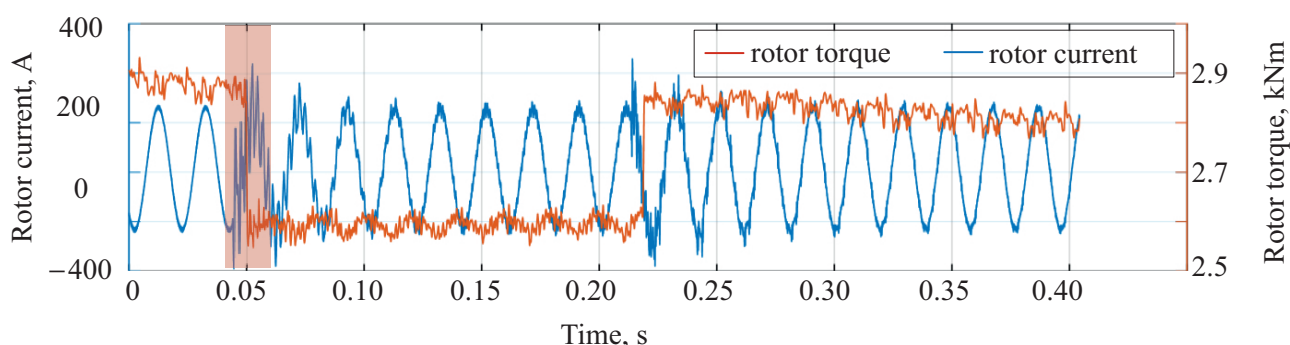


Fig. 5. Instantaneous current and torque of the wind farm rotor

Рис. 5. Мгновенный ток и крутящий момент ротора ветроэлектростанции

gusts $\rightarrow$ perturbed slip ratio $\rightarrow$ resonant current $\rightarrow$ disturbed torque which is also reflected by Eq. (1c) and (1d).

Fig. 6–10, corresponding to the set $\mathbb{P} = \{u_{sd}, i_{sd}, u_{sq}, i_{sq}, u_{rd}, i_{rd}, u_{rq}, i_{rq}, s\}$, show the sampling voltage, current and active power associated with Eq. (1) and (4).

Fig. 6–10 show that there are remarkable perturbations at time t_1 and t_2 due to the influence of wind gusts. Contrarily, we can analyze the influence of wind gusts by analyzing the voltage and current of the equivalent DFIG.

Fig. 11–15, corresponding to the set $\mathbb{X} = \{R_s, L_s, R_r, L_r, L_m\}$, show the estimation parameters of the equivalent DFIG according to Table 4. Due to Eq. (6), it makes the estimation procedure of Table 4 run with higher accuracy and higher efficiency.

Additionally, there are similar parameters perturbation near the time t_1 and t_2 which means that the equivalent parameters can be used to represent the influence of wind gusts.

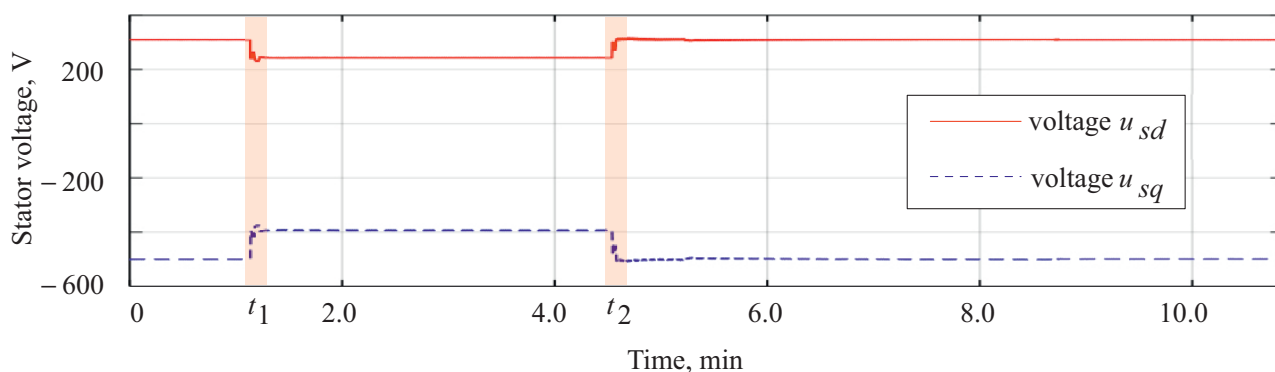


Fig. 6. Stator voltage components of the equivalent DFIG in dq coordinate system

Рис. 6. Составляющие напряжения статора эквивалентного асинхронного генератора в системе координат dq

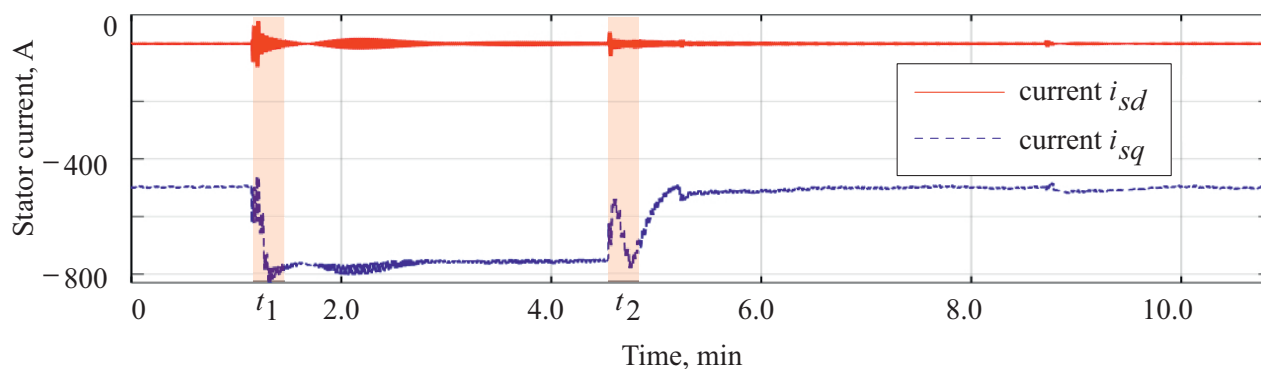


Fig. 7. Stator current components of the equivalent DFIG in dq coordinate system

Рис. 7. Составляющие тока статора эквивалентного асинхронного генератора в системе координат dq

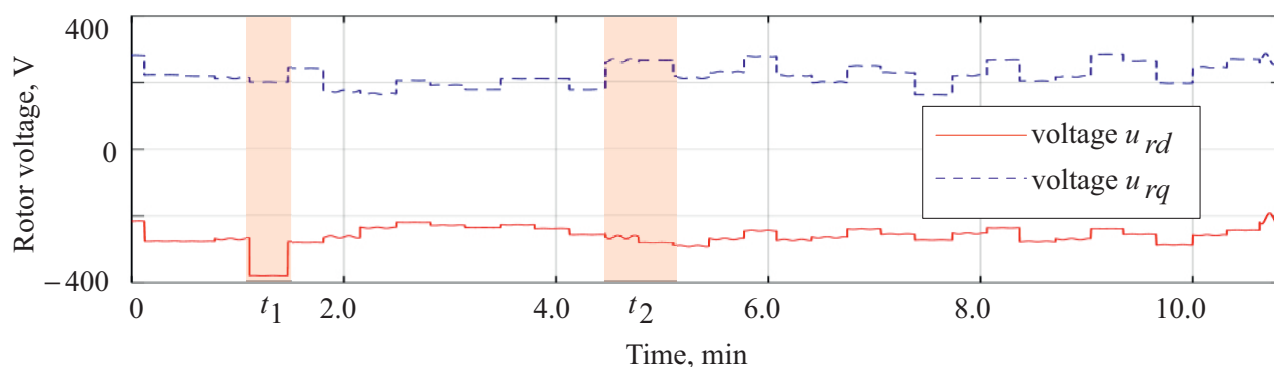


Fig. 8. Rotor voltage components of the equivalent DFIG in dq coordinate system

Рис. 8. Составляющие напряжения на роторе эквивалентного асинхронного генератора в системе координат dq

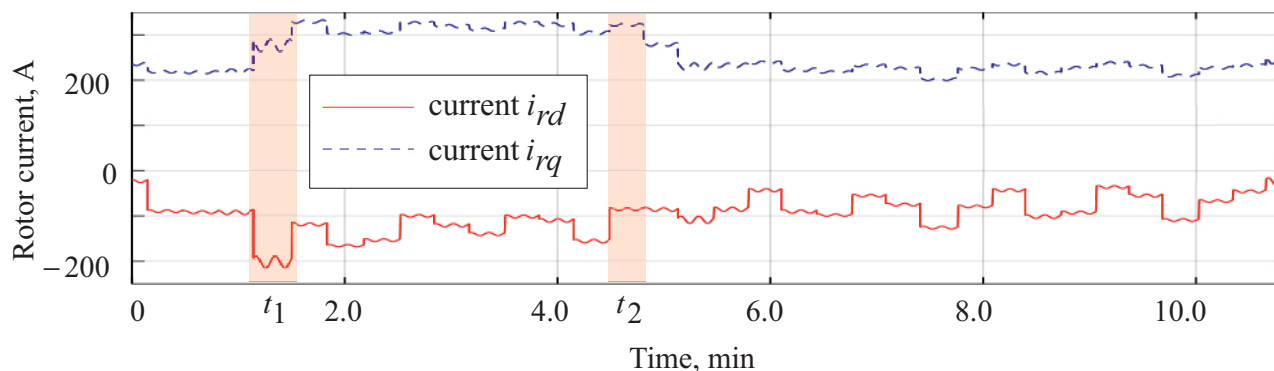


Fig. 9. Rotor current components of the equivalent DFIG in dq coordinate system

Рис. 9. Составляющие тока ротора эквивалентного асинхронного генератора в системе координат dq

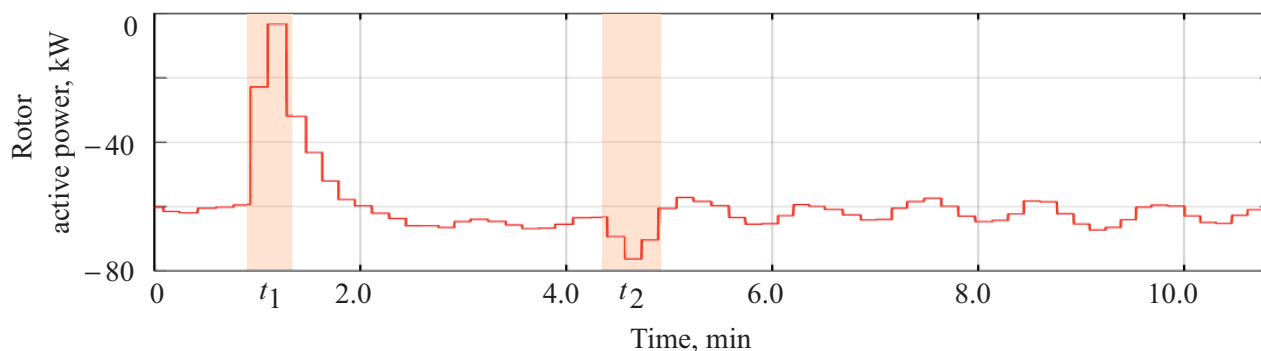


Fig. 10. Rotor active power of the equivalent DFIG

Рис. 10. Активная мощность ротора эквивалентного асинхронного генератора

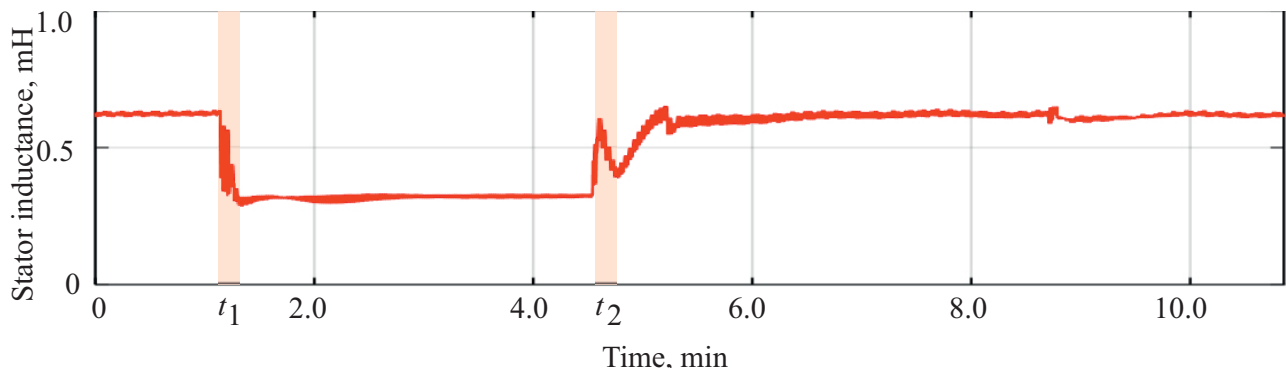


Fig. 11. Stator inductance of equivalent DFIG by proposed method

Рис. 11. Индуктивность статора эквивалентного асинхронного генератора по предлагаемому способу

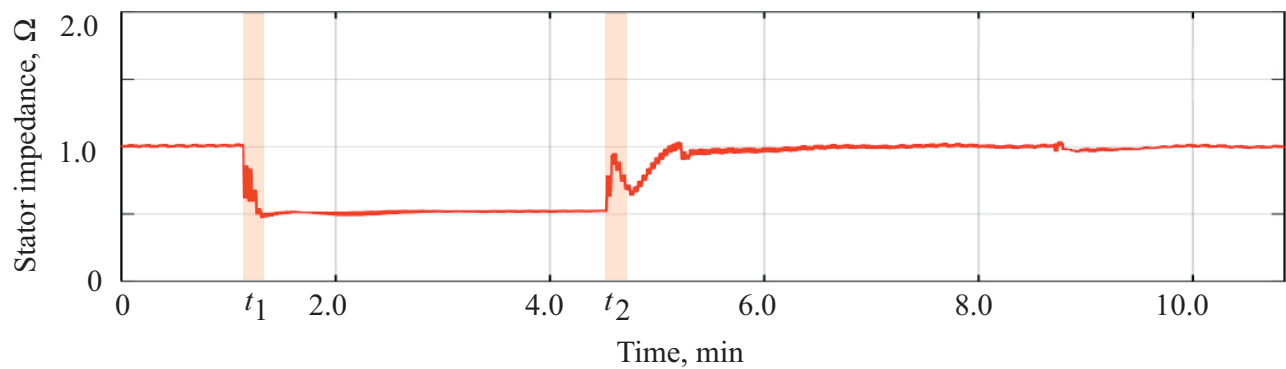


Fig. 12. Stator impedance of equivalent DFIG by proposed method

Рис. 12. Полное сопротивление статора эквивалентного асинхронного генератора по предлагаемому способу

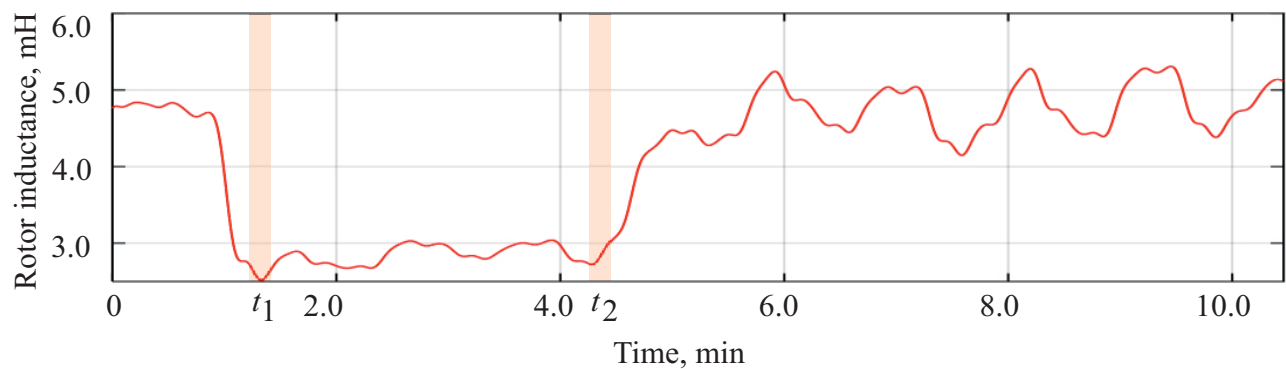


Fig. 13. Rotor inductance of equivalent DFIG by proposed method

Рис. 13. Индуктивность ротора эквивалентного асинхронного генератора по предлагаемому способу

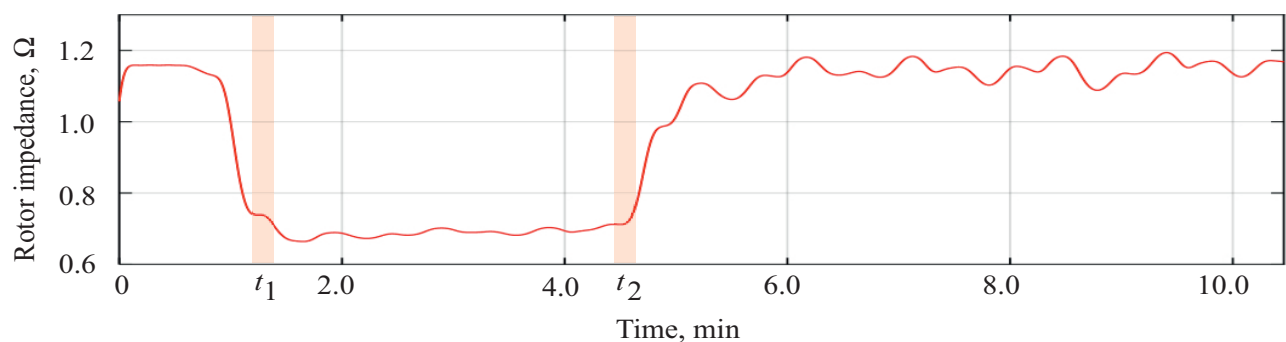


Fig. 14. Rotor impedance of equivalent DFIG by proposed method

Рис. 14. Полное сопротивление ротора эквивалентного асинхронного генератора в среде по предлагаемому способу

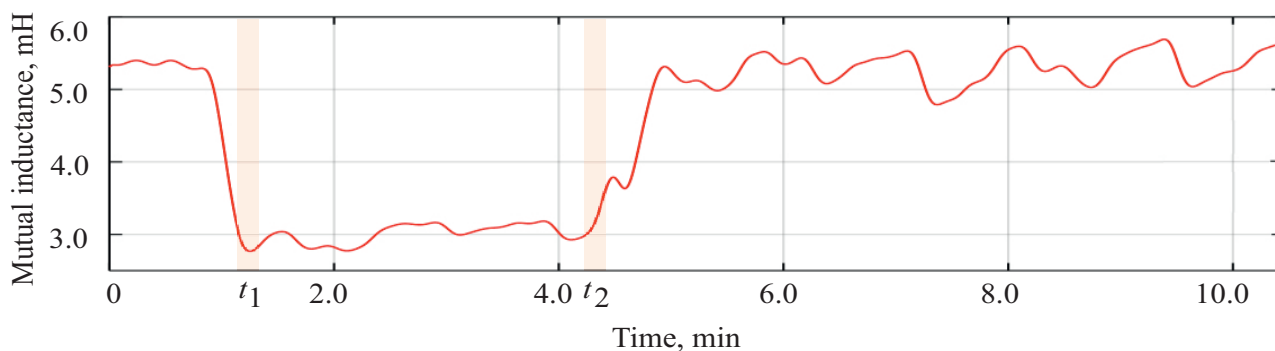


Fig. 15. Mutual impedance of equivalent DFIG by proposed method

Рис. 15. Взаимное сопротивление эквивалентного асинхронного генератора по предлагаемому способу

The estimation parameters (average value) of the equivalent DFIG within the testing time are shown in Table 5.

B. Validation of data-driven approach

In order to validate correctness of the estimation parameters of the equivalent DFIG with parameters shown in Table 5 and corresponding to Fig. 1, the topology of the simulation model and the simulation model of the equivalent DFIG has been proposed and shown in Fig. 16 and 17.

Fig. 17 shows a 50 MW equivalent DFIG connected to a 0.69 kV distribution system which parameters are exactly the same as shows in Table 5. Fig. 16 shows that this model consists of a wound rotor induction generator and an excitation converter. The stator winding is connected directly to the 50 Hz grid, while the rotor is fed at variable frequency through the AC/DC/AC converter. In this model, the wind speed is changed from 4.8 m/s to 6.0 m/s.

Table 5. Estimation parameters (average value) of equivalent DFIG

Таблица 5. Оценочные параметры (среднее значение) эквивалентного асинхронного генератора

Order	Parameter	Unit	Estimation value	Note
1	R_s	Ω	0.8380	Stator resistance
2	R_r	Ω	0.9859	Rotor resistance
3	L_s	mH	0.5134	Stator inductance
4	L_r	mH	4.1052	Rotor inductance
5	L_m	mH	4.5451	Mutual inductance

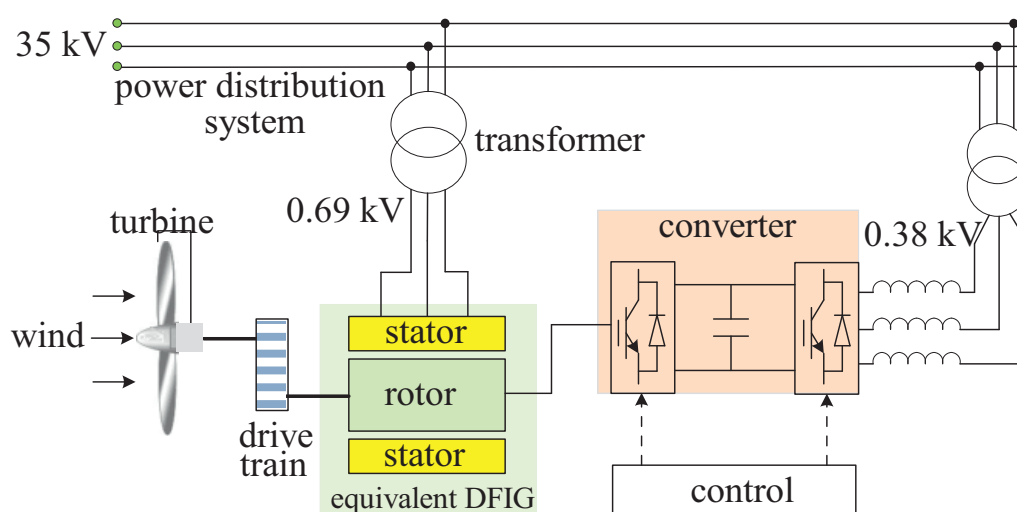


Fig. 16. Topology of the simulation model of the equivalent DFIG

Рис. 16. Топология имитационной модели эквивалентного асинхронного генератора

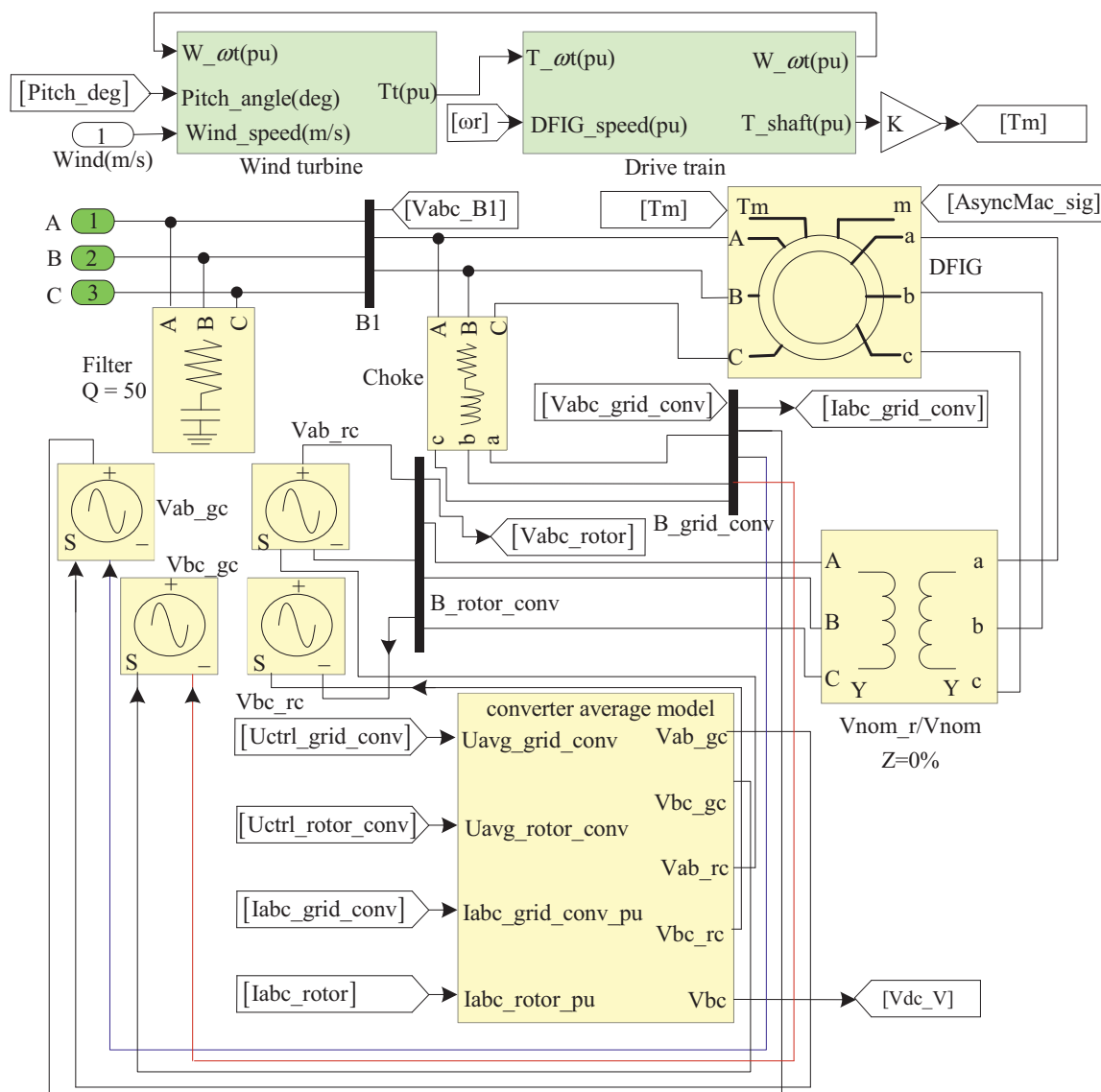


Fig. 17. Simulation model of the equivalent DFIG based on PSCAD

Рис. 17. Имитационная модель эквивалентного асинхронного генератора в среде PSCAD

One of the challenges in establishing a model for the equivalent DFIG is that the sampled data from Fig. 6 to 10 and the sampled

wind speed data which has been imported into the proposed model were not theoretical but real-world data.

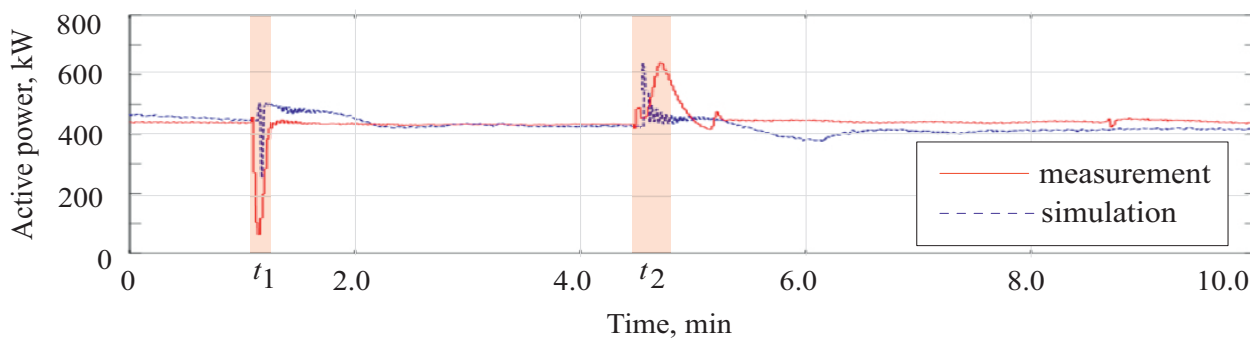


Fig. 18. Simulation of the equivalent DFIG based on PSCAD

Рис. 18. Моделирование эквивалентного асинхронного генератора в среде PSCAD

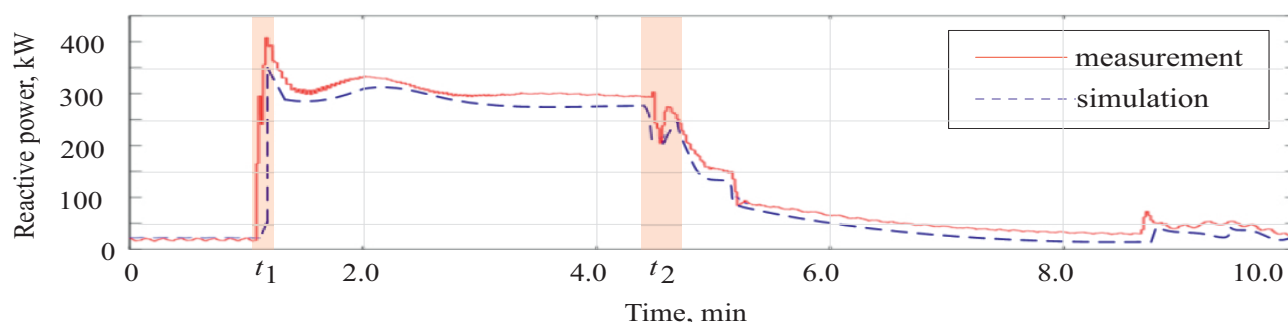


Fig. 19. Simulation of the equivalent DFIG based on PSCAD

Рис. 19. Моделирование эквивалентного асинхронного генератора в среде PSCAD

Table 6. Analysis of the maximum error between simulated and tested power of the equivalent DFIG

Таблица 6. Анализ максимальной погрешности между моделируемой и протестированной мощностью эквивалентного асинхронного генератора

Order	Parameters	Maximum error δ , %	
		absolute	relative
1	Active power, kW	28.588	4.52
2	Reactive power, kVar	48.896	9.42

The accuracy of the estimated parameters of the equivalent DFIG can be verified from two perspectives:

1. By comparing Fig. 18 to 19, it is clear that there are significant fluctuations of stator active power and reactive power of the DFIG due to wind gusts.

2. The comparison between the simulated and actual power curves shows that the trend is consistent, although there are still some noticeable errors during the simulation process.

The maximum errors between the simulated and tested power of the equivalent DFIG are shown in Table 6. It reveals that the maximum errors are less than 10% under wind gusts.

As discussed above, we have found that the accurate parameters of a wind farm can be determined using the data-driven approach. The correctness and feasibility of this method has been demonstrated through both theoretical and simulated results.

CONCLUSION

This paper proposes a data-driven approach to estimate the real-time equivalent parameters of a wind farm during wind gusts. The main contribution of this study is the aggregation of a wind farm with DFIGs into an equivalent generator. By using characteristic set analysis, analytical expressions for the parameters of the equivalent DFIG have been derived from the algebraic equations with variable coefficients. Due to our study, the derived

equivalent parameters of DFIG can accurately follow perturbations of the wind speed. The feasibility and validity of the proposed approach are illustrated with a 50 MW wind farm consisting of 34 DFIGs. This study provides an effective way for online suppression of the SSR in a real-life wind farm under wind gusts.

At the algorithm level, a data-driven procedure that is suitable for aggregating a wind farm with DFIGs has been developed. The main goal of this study has been to derive analytical solutions of the variable coefficient algebraic equations.

The procedure consists of the following steps: selecting characteristic set by modeling the irreducible chains $\rightarrow$ zero-decomposing by solving the polynomial rings $\rightarrow$ validating the correctness by analyzing pseudo-residual.

This method is suitable for obtaining analytical solutions of the online equivalent parameters of a wind farm. The accuracy and rapidity of this data-driven procedure has been verified through simulations of a wind farm using PSCAD software.

At the engineering level, in order to suppress the SSR in a wind farm during wind gusts, we have developed a data-driven approach based on constructing a modeling-solving-validating research framework. This paper provides a reference for the “abandonment of wind” caused by wind gusts. Moreover, this study can be applied to any wind farm that consists of DFIGs, based on making full use of sampled data.

References

1. Yan Weihang, Shah Shahil, Gevorgian V., Koralewicz P., Wallen R., Gao David Wenzhong. On the low risk of SSR in type III wind turbines operating with grid-forming control. *IEEE Transactions on Sustainable Energy*. 2024;15(1):443-453. <https://doi.org/10.1109/TSTE.2023.3300219>.
2. Du Chengmao, Du Xiong, Tong Chenghui. SSR stable wind speed range quantification for DFIG-based wind power conversion system considering frequency coupling. *IEEE Transactions on Sustainable Energy*. 2023;14(1):125-139. <https://doi.org/10.1109/TSTE.2022.3203317>.
3. Lin Siqi, Yao Wei, Xiong Yongxin, Shi Zhongtuo, Zhao Yifan, Ai Xiaomeng, et al. Three-stage dynamic equivalent modeling approach for wind farm using accurate crowbar status identification and voltage differences among wind turbines. *Electric Power Systems Research*. 2024;228:110091. <https://doi.org/10.1016/j.epsr.2023.110091>.
4. Yang Pengwei, Cao Yuqi, Tan Jie, Chen Junfa, Zhang Chao, Wang Yan, et al. Electric vehicle charging capacity of distribution network considering conventional load composition. *Energy Engineering*. 2023;120(3):743-762. <https://doi.org/10.32604/ee.2023.024128>.
5. Dong Xiaofeng, Jiang Qi, Lian Jijian, Miao Zhuo, Yu Tongshun, Zhou Huan. Optimized identification process of equivalent wind load calculations for offshore wind turbines under standstill conditions. *Ocean Engineering*. 2024;312(1):119043. <https://doi.org/10.1016/j.oceaneng.2024.119043>.
6. Huang Jingwen, Du Zhiye, Cai Hongwei, He Jingxuan, Yue Guohua, Li Gen, et al. Probabilistic load flow calculation and power system security analysis based on improved CGC-CM. *Electric Power Systems Research*. 2024;237:110995. <https://doi.org/10.1016/j.epsr.2024.110995>.
7. Niu Yunbo, Wang Jianzhou, Zhang Ziyuan, Yu Yannan, Liu Jingjiang. A combined interval prediction system based on fuzzy strategy and neural network for wind speed. *Applied Soft Computing*. 2024;155:111408. <https://doi.org/10.1016/j.asoc.2024.111408>.
8. Wang Peng, Zhang Zhenyuan, Chen Chenxu, Huang Qi, Dai Ningyi, Lee Wei-Jen. Multistage parameter identification featured generic wind farm dynamic equivalent modeling. *IEEE Transactions on Industry Applications*. 2023;59(6):7475-7483. <https://doi.org/10.1109/TIA.2023.3307656>.
9. Gupta A.P., Mitra A., Mohapatra A., Singh S.N. A multi-machine equivalent model of a wind farm considering LVRT characteristic and wake effect. *IEEE Transactions on Sustainable Energy*. 2022;13(3):1396-1407. <https://doi.org/10.1109/TSTE.2022.3159307>.
10. Yang Shanghui, Deng Xiaowei, Yang Kun. Machine-learning-based wind farm optimization through layout design and yaw control. *Renewable Energy*. 2024;224:120161. <https://doi.org/10.1016/j.renene.2024.120161>.
11. Hou Xinxing, Hu Wenbo, Luo Maomao. Short-term wind farm cluster power point-interval prediction based on graph spatio-temporal features and S-stacking combined reconstruction. *Heliyon*. 2024;10(14):e33945. <https://doi.org/10.1016/j.heliyon.2024.e33945>.
12. Tao Siyu, Feijóo-Lorenzo A.E. Multi-objective optimization of clustered wind farms based on potential game approach. *Ocean Engineering*. 2024;300:117291. <https://doi.org/10.1016/j.oceaneng.2024.117291>.
13. Rahman M.T., Hasan K.N., Sokolowski P. Evaluation of wind farm aggregation using probabilistic clustering algorithms for power system stability assessment. *Sustainable Energy, Grids and Networks*. 2022;30:100678. <https://doi.org/10.1016/j.segan.2022.100678>.
14. Ahmed S., Huang Yongyi, Tayyab Q., Senju T., Elkholy M.H. Identification of power grids low-frequency oscillations through a combined MEEMD-Prony method. *Energy Reports*. 2024;11:4245-4253. <https://doi.org/10.1016/j.egyr.2024.04.015>.
15. Feng Shuang, Cui Hao, Lei Jiaying, Yang Hao, Tang Yi. Data-driven time-frequency-domain equivalent modeling of wind farms for wideband oscillations analysis. *IEEE Transactions on Power Delivery*. 2023;38(6):4465-4475. <https://doi.org/10.1109/TPWRD.2023.3321592>.
16. Xia Yurui, Wang Jianzhou, Zhang Ziyuan, Wei Danxiang, Cao Zhining, Li Zhiwu. A wind speed point-interval fuzzy forecasting system based on data decomposition and multi-objective optimizer. *Applied Soft Computing*. 2024;165:112084. <https://doi.org/10.1016/j.asoc.2024.112084>.
17. Huang Liang, Wu Chao, Zhou Dao, Blaabjerg F. Two-port-network-based decoupled impedance modeling method of DFIG system and DC-link coupling analysis. *International Journal of Electrical Power & Energy Systems*. 2024;157:109878. <https://doi.org/10.1016/j.ijepes.2024.109878>.
18. Shi Xingyu, Cao Yijia, Li Yong, Ma Junjie, Shahidehpour M., Wu Xi, et al. Data-driven model-free adaptive damping control with unknown control direction for wind farms. *International Journal of Electrical Power & Energy Systems*. 2020;123:106213. <https://doi.org/10.1016/j.ijepes.2020.106213>.
19. Rajendran S., Jena D., Diaz M., Rodriguez J. Design of modified complementary terminal sliding mode controller for wind turbine at region II using a two-mass model. *Results in Engineering*. 2024;24:103026. <https://doi.org/10.1016/j.rineng.2024.103026>.
20. El Jaadi M., Haidi T., Belfqih A., Farah M., Dialmy A. Optimizing wind farm layout for enhanced electricity extraction using a new hybrid PSO-ANN method. *Global Energy Interconnection*. 2024;7(3):254-269. <https://doi.org/10.1016/j.gloi.2024.06.006>.
21. Zhang Zuan, Liang Yanchang, Zhao Xiaowei. Adaptive inter-area power oscillation damping from offshore wind farm and MMC-HVDC using deep reinforcement learning. *Renewable Energy*. 2024;224(C):120164. <https://doi.org/10.1016/j.renene.2024.120164>.

22. Treesatayapun C. Data-driven fault-tolerant control with fuzzy-rules equivalent model for a class of unknown discrete-time MIMO systems and complex coupling. *Journal of Computational Science*. 2022;63(9):101827. <https://doi.org/10.1016/j.jocs.2022.101827>.
23. Liu Zhijian, Luo Jun, Han Jiangbei, Yu Chengjun, Fang Qian, Li Pengcheng, Liu Chengxi. Characteristic analysis and mitigation strategy for SSCI in series-compensated DFIG-based wind farm controlled by a virtual synchronous generator. *ISA transactions*. 2024;150:92-106. <https://doi.org/10.1016/j.isatra.2024.05.021>.
24. Xiaoshan Gao, Chunming Yuan, Guilin Zhang. Ritt-Wu's characteristic set method for ordinary difference polynomial systems with arbitrary ordering. *Acta Mathematica Scientia*. 2009;29(4):1063-1080. [https://doi.org/10.1016/S0252-9602\(09\)60086-2](https://doi.org/10.1016/S0252-9602(09)60086-2).
25. Chertovskikh R., Pogodaev N., Staritsyn M., Aguiar A.P. Optimal control of diffusion processes: infinite-order variational analysis and numerical solution. *IEEE Control Systems Letters*. 2024;8(1):1469-1474. <https://doi.org/10.48550/arXiv.2403.01945>.

INFORMATION ABOUT THE AUTHORS

Jianhua Chen,

Postgraduate,
School of Electrical Engineering and Automation,
Harbin Institute of Technology,
92 Xidazhi St., Harbin 150001, China
chenjianhua@stu.hit.edu.cn

Liguo Wang,

Professor,
School of Electrical Engineering and Automation,
Harbin Institute of Technology,
92 Xidazhi St., Harbin 150001, China
✉ wlg2001@hit.edu.cn

Alena Dreglea,

Cand. Sci. (Phys-Math.), Associate Professor,
Senior Researcher of the Research Department,
Irkutsk National Research Technical University,
83 Lermontov St., Irkutsk 664074, Russia
adreglea@istu.edu
<https://orcid.org/0000-0002-5032-0665>

Elena Chistyakova,

Cand. Sci. (Phys-Math.), Associate Professor,
Senior Researcher of the Research Department,
Irkutsk National Research Technical University,
83 Lermontov St., Irkutsk 664074, Russia;
Research Fellow,
Matrosov Institute for System Dynamics
and Control Theory of Siberian Branch of
Russian Academy of Sciences,
134 Lermontov St., Irkutsk 664033, Russia
chistyak@istu.edu

Chunlai Yu,

Dr. Sci. (Eng.),
Associate Professor,
School of Marine Engineering,
Dalian Maritime University,
1 Linghai Road, Dalian 116026, China
hepri_yu@163.com

ИНФОРМАЦИЯ ОБ АВТОРАХ

Цзяньхуа Чэнь,

аспирант,
факультет электротехники и автоматизации,
Харбинский технологический институт,
150001, г. Харбин, ул. Сидачжи, 92, Китай
chenjianhua@stu.hit.edu.cn

Лиго Ван,

профессор,
факультет электротехники и автоматизации,
Харбинский технологический институт,
150001, г. Харбин, ул. Сидачжи, 92, Китай
✉ wlg2001@hit.edu.cn

Алена Дрегля,

к.ф.-м.н., доцент,
старший научный сотрудник,
научно-исследовательский отдел,
Иркутский национальный исследовательский
технический университет,
664074, г. Иркутск, ул. Лермонтова, 83, Россия
adreglea@istu.edu
<https://orcid.org/0000-0002-5032-0665>

Елена Чистякова,

к.ф.-м.н., доцент,
старший научный сотрудник,
научно-исследовательский отдел,
Иркутский национальный исследовательский
технический университет,
664074, г. Иркутск, ул. Лермонтова, 83, Россия;
старший научный сотрудник,
Институт динамики систем и теории управления
им. В.Ф. Матросова СО РАН,
664033, Иркутск, ул. Лермонтова, 134, Россия
chistyak@istu.edu

Чуньлай Юй,

д.т.н.,
доцент,
Школа морской инженерии,
Даляньский морской университет,
116026, г. Далянь, ул. Линхай, 1, Китай
hepri_yu@163.com

Authors' contribution

The authors contributed equally to this article.

Conflict of interests

The authors declare no conflict of interests.

The final manuscript has been read and approved by all the co-authors.

Information about the article

The article was submitted 01.10.2024; approved after reviewing 31.10.2024; accepted for publication 25.11.2024.

Заявленный вклад авторов

Все авторы сделали эквивалентный вклад в подготовку публикации.

Конфликт интересов

Авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Информация о статье

Статья поступила в редакцию 01.10.2024 г.; одобрена после рецензирования 31.10.2024 г.; принята к публикации 25.11.2024 г.