Wind farm aggregation method based on motion equation concept: a case study

Zhichao Cui, Xiaoming Yuan, Meiqing Zhang

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, People’s Republic of China
E-mail: cuizhichao@hust.edu.cn

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Abstract: With large number of wind farms integrating into grid, the dynamic behaviour of power system has been impacted significantly. To study the impacts of wind farm on power system, the dynamic modelling of wind farm is important. Compared with modelling all the wind turbines of wind farm in detail, aggregating the wind farm to reduce the complexity of model is a better choice. Several studies have put forward some aggregation methods, such as single-machine representation and multi-machine representation. However, applicability of these methods is limited and they cannot aggregate different types of wind turbines. This study proposes a wind farm aggregation method based on motion equation concept. By defining bus voltage as internal voltage of the aggregation model, the relationship between internal voltage and unbalanced power of wind farm is established. An aggregated model of wind farm in DC-link voltage control timescale is built and time-domain simulation results are presented to verify the feasibility of this model. The aggregation method can aggregate wind turbines regardless of their types and working status. In addition, this aggregation method can be applied to modelling other systems in other timescales based on motion equation concept.

Nomenclature

| Symbol     | Description                                      |
|------------|--------------------------------------------------|
| $P_{av}, P$| active power input and output of VSC             |
| $Q$        | reactive power output of VSC                    |
| $E, \theta$| VSC internal voltage magnitude and phase        |
| $U, \theta$| terminal voltage magnitude and phase            |
| $U', \theta'$| infinite-bus voltage magnitude and phase        |
| $\sigma_p, \theta_p$| angular frequency and output angle of PLL    |
| $U_{dc}, \theta_{dc}$| DC-link voltage                              |
| $C$        | DC-link capacitance                             |
| $X_{fi}, C_{fi}, X_{gi}$| filter reactance, capacitance and transmission line reactance |
| $k_{p1}, k_{i1}$| proportional–integral (PI) control parameters of DC-link voltage control |
| $k_{p2}, k_{i2}$| PI control parameters of terminal voltage control |
| $k_{p3, k3}$| PI control parameters of current control        |
| $U_{dc,ref}$| reference value of DC-link voltage and terminal |
| $U_{ref}$  | voltage                                         |
| $i_{dc,ref}, i_{ref}$| reference value of current in dq reference frame |

Superscript

- $p$ in PLL synchronised reference frame

Subscripts

- $d, q$ $dq$-axis components in PLL synchronised reference frame
- $abc$ in three-phase stationary reference frame

1 Introduction

Wind energy is being put into wide use in modern power systems in recent years. As a result, the dynamic behaviour of power system has been impacted significantly. For example, the integration of wind farm has caused subsynchronous oscillation in the grid of Xinjiang Province [1], which brought great damage to power system. In order to investigate the influence of wind farms on the power system stability, an applicable method for the dynamic modelling of wind farm is in great need.

Generally, a wind farm contains hundreds of wind turbines. Hence, it will result in high computational complexity to model all the wind turbines of a wind farm in detail. Therefore, aggregating the wind farm including hundreds of wind turbines to study the influence of wind farm’s whole behaviour on power system can be a preferable method. In general, the current commonly used aggregation methods can mainly be divided into two kinds: single-machine representation and multi-machine representation. On the one hand, the single-machine representation refers to using a wind turbine model to represent the whole wind farm, which has been used in [2–4]. The authors in [2, 3] divide the aggregation of wind farm into two parts: a frequency-dependent network equivalent model that represents the frequency response of the passive components and a dynamic low-frequency equivalent model that represents the aggregated dynamic model of the wind turbines, their local controls and the WPP supervisory control. These two parts are combined to represent the wind farm. However, this aggregation method covers up lots of information inside wind farm, making it impossible to study the inner dynamics of wind farm, such as dynamic interaction among wind turbines which may lead to equipment failure or instability of internal and external systems. On the other hand, many studies use multi-machine representation. The authors in [5–8] apply the coherency method to the aggregation of wind farm, and they choose one or more variables as the index to characterise the working status of the wind turbine. According to the similarity of these variables, the turbines which have similar working status are aggregated as a wind turbine. However, all the methods mentioned above cannot aggregate different types of wind turbines, and they have to be aggregated separately. In general, there is no unified method to describe the dynamic characteristics of devices, making wind farm aggregation
become a difficult project. Therefore, it is significant to find a generalised means to describe the characteristics of different devices.

In this paper, a wind farm model aggregation method based on motion equation concept is proposed. The modelling of power electronic device based on motion equation concept has been presented and obtained good applications in [9–11]. This modelling method uses physical concepts to summarise the details of devices, and different devices can be modelled in the form of motion equations, which is convenient for system analysis. Based on motion equation concept, this paper develops the model of wind turbine, and further establishes the relationship between internal voltage and unbalanced power of wind farm by defining the bus voltage as the internal voltage of the aggregation model. The proposed method can provide the basis for the study of the influences of wind farm’s inner dynamics and can be conveniently applied to modelling other systems in all timescales based on motion equation concept. The rest parts of this paper are organised as follows. In Section 2, introduction of motion equation concept and how to describe the characteristics of device are given. Section 3 proposes the wind farm model aggregation method based on motion equation concept. In Section 4, an aggregation model of wind farm in DC-link voltage control (DVC) timescale is built and time-domain simulation is conducted to verify the feasibility of this model. Section 5 discusses the extension of the method and future work. Section 6 draws the conclusion.

2 Introduction of motion equation of type-4 wind turbine in DVC timescale

This section introduces the concept of motion equation and takes the type-4 wind turbine’s phase motion equation in DVC timescale as an example to illustrate the advantage of applying the motion equation concept to the aggregation of wind farms.

2.1 Concept of motion equation

The motion equation describing the vibration of single-degree-of-freedom systems can be expressed as follows:

\[ m\ddot{u} + c\dot{u} + ku = f \]  

(1)

where \( m \) is mass, \( c \) is damping coefficient and \( k \) is stiffness coefficient. \( \ddot{u} \) is acceleration, \( \dot{u} \) is velocity and \( u \) is displacement of mass, and \( f \) stands for external force. The motion equation concept has been used to describe the dynamic characteristics of wind turbine’s internal voltage can also be described based on motion equation concept. The authors in [9–12] have applied motion equation concept to modelling of wind turbine in different timescales and got good applications.

2.2 Phase motion equation of wind turbine in DVC timescale

Fig. 1 shows the control system of grid side converter of type-4 wind turbine. The active power control is realised by the DVC and \( \delta \)-axis current control. DVC is designed to keep the DC-link voltage constant. The reactive power control is realised by terminal voltage control and \( \gamma \)-axis current control. Terminal voltage control is used to keep the terminal voltage stable. The PLL is used to detect the phase of terminal voltage fast and accurately. The output of PLL is a synchronisation signal which is used to realise the transformations between \( dq \) and \( abc \) frames. \( E \) is the internal voltage of the wind turbine which is produced by pulse-width modulation.

The internal voltage can reflect the external characteristics of the device seen from grid. For a wind turbine connecting to the grid, the grid-side converter output voltage can be defined as its internal voltage. The DVC timescale involves DVC, terminal voltage control and PLL. To simplify the model of wind turbine’s internal voltage in DVC timescale, several assumptions are made: (i) As the electromechanical timescale is much longer than DVC timescale, the dynamics of controllers in rotor side converter can be ignored. Therefore, it is reasonable to see the wind turbine as a VSC and assume that \( P_m \) is constant. (ii) As the AC current control timescale is much shorter than DVC timescale, the dynamics of current controller can also be ignored so that current is assumed to instantaneously track the reference values. (iii) The dynamics of filter inductor currents and losses of resistances are ignored. Under these assumptions, the small-signal model of type-4 wind turbine in DVC timescale is deduced as follows.

Linearising the DVC, terminal voltage control and PLL, (2)–(4) can be obtained, and \( U_{dc0} \) is the initial value of DC-link voltage in steady state

\[ \Delta e_p = \frac{1}{sU_{dc0}} \left( k_{q1} + k_{01} \right) \left( \Delta P_m - \Delta P \right) \]  

(2)

\[ \Delta e_q = \frac{1}{sU_{dc0}} \left( k_{r2} + \frac{k_{f2}}{s} \right) \left( \Delta u_t - \Delta u_t^* \right) \]  

(3)

\[ \Delta \theta_p = \frac{1}{sU_{dc0}} \left( k_{q1} + \frac{k_{01}}{s} \right) \left( \Delta \theta_t - \Delta \theta_t^* \right) \]  

(4)

The internal voltage vector \( E \) can be expressed by

\[ E = jX_I \dot{I} + U_t \]  

(5)

where \( I \) is current vector and \( U_t \) is terminal voltage vector. Decomposing internal voltage into \( dq \) components and linearising them around operating points, (6) and (7) can be obtained

\[ \Delta \theta = \frac{\cos \theta_0}{E_0} \left( X_t \Delta \theta'_p + U_{dc0} \Delta \theta'_q \right) + \frac{\sin \theta_0}{E_0} \left( X_t \Delta \theta'_q - U_{dc0} \Delta \theta'_p \right) \]  

(6)

\[ \Delta E = \cos \theta_0 \left( -X_t \Delta \theta'_p + \Delta U_t \right) + \sin \theta_0 \left( X_t \Delta \theta'_q + U_{dc0} \Delta \theta'_q \right) \]  

(7)

where \( \theta_0 \) is the angle between \( E \) and \( U_t \) in steady state and \( U_{dc0} \) is initial value of terminal voltage. In order to describe the wind turbine’s self-characteristics based on motion equation concept, the terminal voltage’s variations should be replaced equivalently by active and reactive power in wind turbine. The active and reactive power generated by wind turbine can be expressed as

\[ P = E U_t \sin(\theta - \theta_0) / X_t \]  

(8)

\[ Q = E^2 / X_t - E U_t \cos(\theta - \theta_0) / X_t \]  

(9)

Linearising (8) and (9) around operating points, the magnitude and phase of terminal voltage can be expressed as follows. \( E_0 \) is the
initial value of internal voltage

\[ \Delta \theta_i = \Delta \theta + \frac{2 \sin \theta_0}{U_{i0}} E \Delta E - \frac{X_i \cos \theta_0}{U_{i0}} \Delta P - \frac{X_i \sin \theta_0}{U_{i0}} \Delta Q \]  
(10)

\[ \Delta U_i = \left( 2 \cos \theta_0 - \frac{U_{i0}}{E_0} \right) \Delta E + \frac{X_i \sin \theta_0}{E_0} \Delta P - \frac{X_i \cos \theta_0}{E_0} \Delta Q \]  
(11)

As \( P_{in} \) is assumed to be constant in DVC timescale, there is

\[ \Delta P_{in} = 0 \Rightarrow \Delta P = -(\Delta P_{in} - \Delta P) \]  
(12)

Neglecting the effects of voltage amplitude and reactive power’s dynamics, (6) and (10) can be simplified as

\[ \Delta \theta^k = \frac{\cos \theta_0}{E_0} (X_i \Delta \theta^P + U_{i0} \Delta \theta^Q) \]  
(13)

\[ \Delta \theta_i = \Delta \theta - \frac{X_i \cos \theta_0}{E_0} \Delta P \]  
(14)

Combining (13) and (14), following equations can be obtained:

\[ \Delta \theta^k = \frac{X_i \cos \theta_0}{E_0 - U_{i0} \cos \theta_0} \Delta \theta^P - \frac{X_i \cos \theta_0}{U_{i0} (E_0 - U_{i0} \cos \theta_0)} \Delta P \]  
(15)

\[ \Delta \theta^P = \frac{X_i \cos \theta_0}{E_0 - U_{i0} \cos \theta_0} \Delta \theta^P - \frac{X_i \cos^2 \theta_0}{E_0 (E_0 - U_{i0} \cos \theta_0)} \Delta P \]  
(16)

Based on the above derivation, the model can be expressed by Fig. 2, where \( k = E_0 - U_{i0} \cos \theta_0 \) and

\[ G_i(s) = \frac{X_i \cos \theta_0}{U_{i0} k} + \frac{X_i \cos \theta_0}{k} \left( \frac{1}{C U_{i0} s} \right) \left( k_{p1} + \frac{k_{i1}}{s} \right) \]  
(17)

As it can be seen, the dynamics of phase is determined by the unbalanced power on DC-link capacitor. By dividing the phase dynamics into synchronising and damping powers components, Fig. 2 can be transformed into Fig. 3

\[ M_{VSC}(s) = C U_{i0} G_M(s) \]  
(18)

\[ G_M(s) = \frac{1}{\left( K_1 s^2 + K_2 + K_3 / s^2 \right)} \]  
(19)

\[ D_{VSC}(s) = M_{VSC}(s) \cdot \left( K_4 + K_5 / s^2 \right) \]  
(20)

The \( M_{VSC}(s) \) and \( D_{VSC}(s) \) represent the equivalent inertia and damping coefficient of the VSC, respectively, and they are determined by the operating points and parameters of VSC. The explanation of transfer function relationship between equivalent inertia \( M_{\text{eq}}(s) \) of VSC phase motion and physical mass \( C \) has been given in [9]. Just as the phase motion of synchronous generator’s internal voltage is driven by unbalanced torque on the rotor, the phase motion of VSC’s internal voltage is driven by unbalanced active power \( P_{dc} \) on DC capacitance, which can be seen from Fig. 3. This relationship between the unbalanced active power on DC capacitance and internal voltage’s phase determines the dynamic characteristic of VSC’s internal voltage in DVC timescale.

It can be seen from above that the phase motion equation provides clear mechanism understanding about how the power electronic devices work, and makes internal voltage a common quantity to represent the external characteristics of devices. Other types of wind turbines such as DFIGs can also be modelled as motion equation which has been proved feasible in [10–12]. Therefore, this model method is very suitable for the aggregation of models.

3 Wind farm aggregation method based on motion equation concept

3.1 Definition of aggregation model’s internal voltage

The internal voltage actually is the bridge between the devices and the network. On the one hand, the variation of internal voltage will affect the power exchanged between devices and grid via the network. On the other hand, the exchanged power will also affect the variation of the internal voltage via the device. The relationship between the variation of internal voltage and variation of exchanged power reflects the dynamic characteristics of devices.

In order to study the impact of whole behaviours of wind farm on the external systems, the wind farm can be seen as a black box and there should be a quantity to represent its external characteristics. If the wind farm is considered as a device, the bus voltage is a quantity which can be seen from grid. As a result, the bus voltage can be defined as the internal voltage of the wind farm. In this way, by establishing the relationship between the dynamics of bus voltage and the dynamics of power delivered from wind farm to grid, the dynamic characteristics of wind farm can be obtained.

3.2 Aggregation steps of wind farm

Fig. 4 shows the structure of a simple wind farm which consists of two wind turbines. \( E_1, \theta_1 \) and \( E_2, \theta_2 \), respectively, represent the amplitude and phase of two wind turbines’ internal voltage, \( E' \) and \( \theta' \) represent the amplitude and phase of bus voltage. \( P_1, Q_1 \) and \( P_2, Q_2 \) represent the power at wind turbines, \( P'_1, Q'_1 \) and \( P'_2, Q'_2 \) represent the power at bus, and \( P_{dc}, Q_{dc} \) represent the power delivered from wind farm to grid. \( X_1 \) is line reactance. As is discussed above, the bus voltage is defined as the internal voltage of the
aggregation model. The form of the aggregation model of wind farm can be expressed as in Fig. 5. The relationships between \( \theta' \), \( E' \) and \( P_g, Q_g \) can reflect the external characteristics of wind farm.

The aggregation steps can be summarised as follows.

1. Establish the relationship between \( E_1 \) and \( P_1, Q_1 \) based on motion equation concept.
2. Establish the relationship between \( E' \) and \( P_1', Q_1' \).
3. Follow the same steps above to establish the relationship between \( E' \) and \( P_2', Q_2' \).
4. Define \( E' \) as the internal voltage and establish the relationship between \( E' \) and \( P_g, Q_g \).

4 Aggregation of wind farm in DVC timescale

4.1 Aggregation model of wind farm in DVC timescale

The aggregation of wind farm consisting of two wind turbines which is shown in Fig. 4 is used to verify the applicability of the method. As the dynamics of inductor currents and losses of resistances are ignored, \( P_1 = P_1' \) and \( P_{in} = P_{in}' \) are reasonable. The power at internal voltage \( E_1 \) can be expressed by

\[
P_1 = \frac{E_1 E'}{X_L + X_f} \sin(\theta_1 - \theta')
\]

(21)

Linearise (21), the following equations can be obtained:

\[
\Delta P_1 = \frac{E_1 E'}{X_L + X_f} \sin(\theta_{10} + \frac{E_1 \Delta E'}{X_L + X_f} \sin \theta_{10} + \frac{E_1 \Delta E'}{X_L + X_f} \cos \theta_{10}(\Delta \theta_1 - \Delta \theta')
\]

(22)

where \( \theta_{10} \) is the angle between \( E_1 \) and \( E' \) in steady state. Neglecting the effects of amplitude of voltage, (22) can be simplified as

\[
\Delta P_1 = \frac{E_1 E'}{X_L + X_f} \cos \theta_{10}(\Delta \theta_1 - \Delta \theta')
\]

(23)

The phase motion equation of wind turbine’s internal voltage in DVC timescale can be expressed as follows:

\[
(\Delta P_{in} - \Delta P_1) \frac{1}{sM_1(s)} \left( D_1(s) + \frac{1}{s} \right) = \Delta \theta_1
\]

(24)

where \( M_1(s) \) and \( D_1(s) \) represent the equivalent inertia and damping coefficient of first wind turbine, and \( M_1(s) = M_{in}(s), D_1(s) = D_{in}(s) \).

Combining (23) and (24), the relationship between \( \theta' \) and \( P_1' \) can be expressed as

\[
(\Delta P_{in} - \Delta P_1) \left[ \frac{1}{sM_1(s)} \left( D_1(s) + \frac{1}{s} \right) + \frac{X_L + X_f}{E_1 E'_0 \cos \theta_{10}} \right] = \Delta \theta'
\]

(25)

Arranging (25), we can get (26)

\[
\left( \Delta P_{in} - \Delta P_1 \right) \frac{1}{sM_1(s)} \left( D_1(s) + \frac{1}{s} \right) = \Delta \theta'
\]

(26)

\[
D_1(s) = D_1(s) + \frac{s(X_L + X_f)M_1}{E_1 E'_0 \cos \theta_{10}}
\]

(27)

The relationship between \( \theta' \) and \( P_1' \) can be deduced in the same way, and the relationship between bus voltage and power delivered from wind farm can be obtained by the following derivation:

\[
\Delta P_{in} - \Delta P_1 = \Delta \theta' \frac{s^2 M_1(s)}{sD_1(s) + 1}
\]

\[
\Delta P_{in} - \Delta P_2 = \Delta \theta' \frac{s^2 M_2(s)}{sD_2(s) + 1}
\]

(28)

\[
\Delta P_{in} - \Delta P_1 - \Delta P_2 = \Delta \theta' \left( \frac{s^2 M_1(s)}{sD_1(s) + 1} + \frac{s^2 M_2(s)}{sD_2(s) + 1} \right)
\]

The \( M_2(s) \) and \( D_2(s) \) are the equivalent inertia and damping coefficient of second wind turbine. The relationship between phase of bus voltage and active power delivered from wind farm can be expressed in

\[
\left( \Delta P_{in} - \Delta P_1 - \Delta P_2 \right) \left( \frac{sD_1 D_2 + D_1 + D_2}{s(D_2 M_1 + D_1 M_2) + M_1 + M_2} \right) = \Delta \theta'
\]

(29)

As it can be seen from (29), the dynamics of the bus voltage’s phase is driven by the unbalanced power exchanged between wind farm and external system. The characteristics of it are determined by the operating points, the control parameters of two wind turbines in DVC timescale and line inductances. However, the equivalent inertia of the aggregation model is not just \( M_1 + M_2 \), the equivalent damping coefficient is not just \( D_1 + D_2 \) either, which may involve the interactions between two devices. As for how to describe the interaction, it will be involved in the future work.

4.2 Verification of the aggregation model

The proposed aggregation model is verified by comparing with the detailed model in MATLAB/Simulink. The parameters of this simple system are given in the Appendix. When a small disturbance happens (the phase of \( U_g \) decreases 5°) at 5.0 s, the responses of internal voltage’s phase and active power delivered from wind farm to grid are compared between aggregation model and detailed model in Fig. 6. It can be seen that the responses of the aggregation model are consistent with the responses of detailed model. Therefore, the aggregation method is feasible for the dynamic modelling of wind farm in DVC timescale.

5 Discussion

In this section, how the method can be used for complicated wind farm modelling and the shortcoming of this method are discussed. Furthermore, how the proposed aggregation model can be used to the analysis of system stability and how to further simplify the aggregation model are discussed.

5.1 Extension of proposed aggregation method

Fig. 7 shows a wind farm which consists of two arrays of wind turbines. To build an aggregation model of this wind farm, the method...
between wind farm and external system. This work will be advanced in the future.

The model proposed in this paper does not consider the effect of voltage amplitude and reactive power, which will be improved in the future. The simplification of the aggregation model also is an important part of the future work. As the amount of wind turbines increasing and the topology of wind farm becoming complicated, the calculation of the aggregation model will be difficult. In this way, the regularity which lies in the difference between the characteristics of single device and the characteristics of multiple devices is essential to be found out. The simplification also involves the physical description of the aggregation model, which is a great challenge in the future.

6 Conclusion

In this paper, the aggregation method based on motion equation concept is proposed. First, the wind turbine is modelled based on motion equation concept. Then, by defining the bus voltage as the internal voltage of the aggregation model, the relationship between internal voltage and the total unbalanced power at bus is established. In order to verify the effectiveness of this method, the aggregation model of wind farm of two wind turbines in DVC timescale is obtained using the proposed method and the simulation comparison is conducted. The time-domain simulation results indicate that the aggregation method is feasible. The method can aggregate wind turbines regardless of their types and working status and can also be extended to model other system in other timescale. In addition, how the method can be applied in complex wind farm is presented, and the application of the aggregation model and how to simplify the model are discussed.

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9 Appendix

The expressions of $K_1$–$K_5$ are given as follows:

$$K_1 = \frac{C U_{dc0} X_f \cos^2 \theta_0}{E_0 (E_0 - U_{in} \cos \theta_0)}$$

$$K_2 = \frac{X_f \cos \theta_0 k_p1 k_i4}{E_0 - U_{in} \cos \theta_0} + \frac{X_f \cos \theta_0 k_i1}{U_{in} (E_0 - U_{in} \cos \theta_0)}$$

$$K_3 = \frac{X_f \cos \theta_0 k_i2 k_i4}{E_0 - U_{in} \cos \theta_0}$$

$$K_4 = \frac{X_f \cos \theta_0 k_i1}{C U_{dc0} (E_0 - U_{in} \cos \theta_0)} + \frac{X_f \cos \theta_0 k_i2}{U_{in} (E_0 - U_{in} \cos \theta_0)}$$

$$K_5 = \frac{X_f \cos \theta_0 (k_p4 k_i4 + k_p4 k_i1)}{C U_{dc0} (E_0 - U_{in} \cos \theta_0)}$$

The parameters of studied wind farm are given in Table 1.

### Table 1 Parameters of studied wind farm

| Parameter          | Value     |
|--------------------|-----------|
| $S_{base}$         | 2.1 MW    |
| $U_{base}$         | 690 V     |
| $U_{base}$         | 2$\pi f_{base}$ |
| $f_{base}$         | 50 Hz     |
| $U_{dcbase}$       | 1100 V    |
| $U_{dc}$           | 1 p.u.    |
| $C$                | 0.047 F   |
| $X_f$              | 0.2 p.u.  |
| $X_L$              | 0.2 p.u.  |
| $U_{t*}$           | 1 p.u.    |
| $U_{g}$            | 1 p.u.    |
| $X_g$              | 0.9 p.u.  |
| $k_p1$             | 1.25 p.u. |
| $k_i1$             | 3.125 p.u.|
| $k_p2$             | 1.5 p.u.  |
| $k_i2$             | 10 p.u.   |
| $k_p3$             | 4 p.u.    |
| $k_i3$             | 200 p.u.  |
| $k_p4$             | 40 p.u.   |
| $k_i4$             | 1400 p.u. |

$U_{base}$ is phase-to-phase RMS value. The second wind turbine’s parameters are the same as first wind turbine except that the DVC parameters are $k_p = 3.75$, $k_i = 87.5$, $P_{in1} = 0.35$ p.u. $P_{in2} = 0.3$ p.u.