Research on Stator Winding Open Circuit Faults of Permanent Magnet Wind Turbine

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***Abstract*--In view of the appearance of parallel stator winding open circuit fault in large capacity permanent magnet wind turbines, the negative sequent current is caused in stator windings, which may endanger the stability of the wind turbine. With the 2-D transient electromagnetic field, the negative sequence current with the rated condition and fault condition is calculated. Further more, the change rule of the negative sequence current with degree and position is studied, which provides a theoretical basis for fault diagnosis of stator windings of permanent magnet wind turbines.**

***Index Terms*-- Permanent Magnet Wind Generator, Stator Winding Open Circuit Fault, Negative Sequence Current, Temperature Field.**

I. INTRODUCTION

Wind power is one of the most important renewable energy development projects that attracts close attention to all over the world this year. Wind turbines are the core components that convert wind energy into electrical energy. The same as other rotating machines, stator winding will be affected by high temperature, mechanical force and electromagnetic force in the course of its operation, which may cause the stator winding open circuit faults[1-2].

At present, from the domestic and foreign literature, the research on stator winding faults of permanent magnet motor mainly focus on short-circuit of stator winding and ground fault [8-15], while the analysis of the stator winding branch open circuit fault is relatively few. Therefore, in this paper, take a 1.5MW, 32 pole, 4 parallel branch of the permanent magnet wind turbine as an example, and calculate the stator current of the permanent magnet wind generator after the parallel stator winding open circuit faults, and then study the influence of the degree, position and wind speed on the stator negative sequence current that can provide some meaningful conclusions for the fault diagnosis of the permanent magnet wind turbine.

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II. PERMANENT MAGNET WIND TURBINE MODEL

The two-dimensional electromagnetic field calculation model of permanent magnet wind turbine is shown in figure1. Basic parameters of permanent magnet synchronous wind generator are presented in Table I.

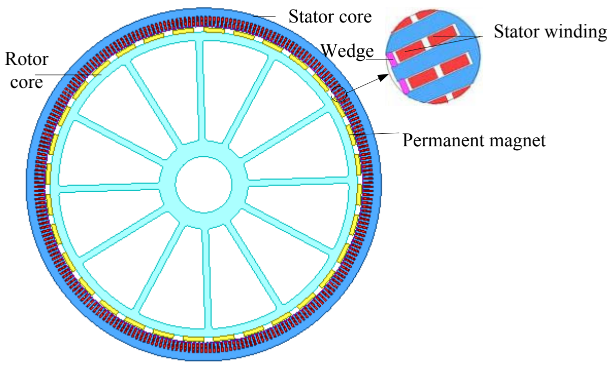

Figure. 1. Calculation model of wind turbine

TABLE I
BASIC PARAMETERS OF PERMANENT MAGNET WIND TURBINE

PARAMETERS	Value
Rated Capacity/kW	1500
Rated voltage/V	690
Rated rotate speed/ $r \cdot \min^{-1}$	150
Stator external diameter/mm	2200
Permanent magnet thickness/mm	26
Number of poles/slots	32/252
Stator core length/mm	620
Stator inner diameter /mm	1970

III. FAULT MODEL OF WIND TURBINE

In order to study the influence of the degree and position of stator windings on the stator negative sequence current, seven kinds of fault types of wind turbine are established, such as phase A and phase B, as shown in Table II. And Finite element simulation of the external circuit diagram of Faulty type I is shown in Figure 2 [17].

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TABLE II
PARALLER STATOR WINDING OPEN CIRCUIT FAULT TYPES

Fault type	Stator winding of phase A				Stator winding of phase B			
	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
I	×	√	√	√	√	√	√	√
II	×	×	√	√	√	√	√	√
III	×	√	×	√	√	√	√	√
IV	×	√	√	√	×	√	√	√
V	×	√	√	√	√	×	√	√
VI	×	×	×	√	√	√	√	√
VII	×	×	×	×	√	√	√	√

Note: × for the fault branch; √ for the normal branch.

In table II, Fault I, fault II and fault VI are regarded as in-phase faults of stator winding branches in different degrees; Fault II and fault III are regarded as in-phase fault of stator winding branches of adjacent branch and un-adjacent branch; Fault IV and fault V are regarded as faults of stator winding open circuit of different phase of adjacent branch and non-adjacent branch; fault VII is considered as stator winding single-phase open circuit fault.

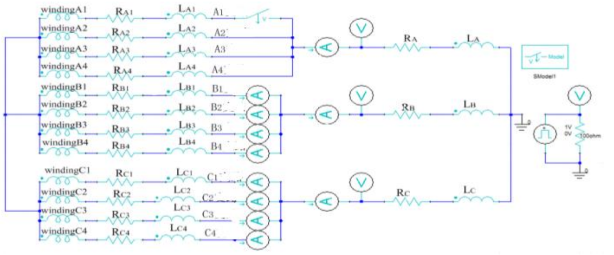


Figure. 2. Finite element simulation of the external circuit diagram of Faulty type I

IV. CALCULATION AND ANALYSIS OF NEGATIVE SEQUENCE CURRENT

The method of symmetrical component is used to calculate the negative sequence component of the open branch fault of stator winding. Positive sequence component, negative sequence component and zero sequence component, and the transformation relation between three asymmetrical phasor and three-phase symmetrical phasor is given as follow:

$$\begin{bmatrix} \dot{I}_{a(+)} \\ \dot{I}_{a(-)} \\ \dot{I}_{a(0)} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} \quad (1)$$

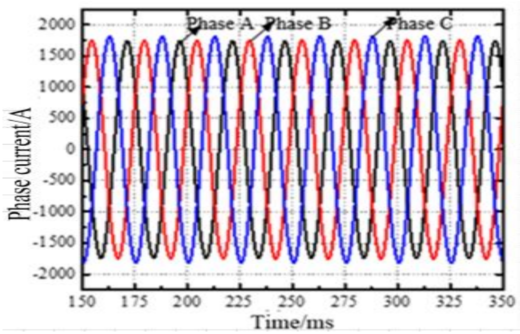
Formula $a = e^{j120^\circ}$, the negative sequence component of the fundamental component is considered only in this paper. The positive sequence, negative sequence and zero sequence are expressed by subscript "+", "-", "0" respectively. The corresponding three phases are represented by subscript a, b, and c respectively.

A. The influence of the degree of disconnection of stator winding parallel branch on negative sequence current

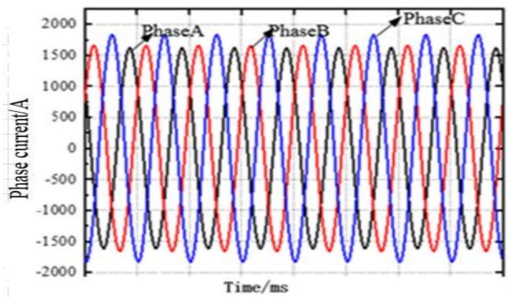
In order to study the influence of the degree of disconnection of stator winding parallel branch on negative sequence current, by changing the number of open circuit branches of the paralleled stator winding to simulate and defines the break coefficient "β" to measure the degree of opening of the stator winding branch circuit and its expression can be $\beta = \frac{N_1}{N} \times 100\%\ (0 \le \beta \le 1)$.

Where: "N" means the total number of parallel stator windings; "N_1" means the number of broken circuit branches for phase stator winding.

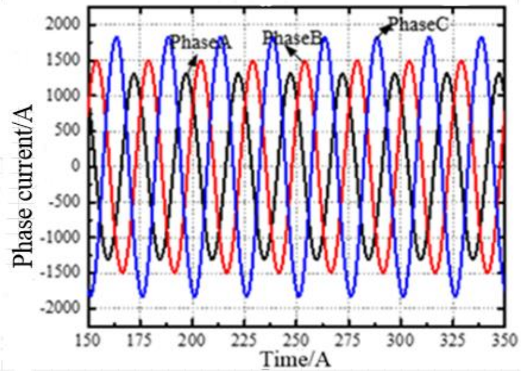
The generator is calculated and analyzed under the condition that the permanent magnet wind-driven generator with rated load operation at rated wind speed. The waveform and phase angle of the three-phase current of the stator winding are shown in Figure 3 and table 3, respectively, when the stator winding has different degrees of branch welding faults (faults I, faults II and fault VI).



(a) Faulty type I



(b) Faulty type II



(c) Faulty type VI

From Figure 3 (a), (b) and (c), it can be seen that the three-phase current of the stator winding is no longer symmetrical after the stator winding branch of the permanent magnet wind-driven generator has been opened and welded. With the increase of the breaking factor, the asymmetry of the three-phase current is increasing. With the increase, the current in the fault phase is decreasing, and the current is minimum compared with other two phase non fault phase.

Table III
PHASE ANGLE DIFFERENCE OF THREE-PHAS CURRENT OF STAOR WINDING UNDER NORMAL AND DIFERENCT FAULTY STATES

Phase	*Phase angle difference/ (°)*			
	Normal	*faults I*	*faults II*	*fault VI*
β	*0*	1/4	2/4	3/4
Phase AB	*121°*	*118°*	*112.3°*	*100.8°*
Phase AC	*121°*	*121°*	*121°*	*121°*
Phase BC	*118°*	*121°*	*126.7°*	*138.2°*

At the same time, from table III it can be found that the symmetry of the three-phase current phase difference was also damaged, the phase angle of non-fault phase deviate in 120 degrees, and with the increase of , the angle of non-fault phase difference deviation from the 120 degree increased significantly. The cause of this phenomenon can be explained by the three-phase current vector triangle. Figure 4 shows the three-phase current vector triangle.

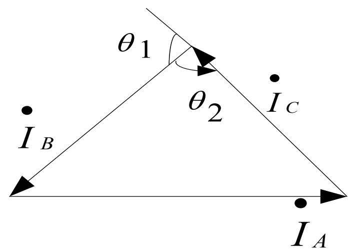


Fig. 4. Three-phase current vector diagram

As shown in Figure 4, the angle between the non-fault phase B and C is $\theta_1 = 180^\circ - \theta_2$, and it also can be seen:

$$\theta_2 = \arccos\frac{I_C^2 + I_B^2 - I_A^2}{2I_C I_B} \quad (3)$$

Because the speed of A phase current reduced more than B phase, and the changes of C phase current can be neglected, the value of θ_2 in the non-fault phase angle decreases, it also means the phase difference of non-fault phase increase , but the phase difference of other two phase depend on the specific circumstances.

On this basis, by using formula 1, the negative sequence current and positive sequence current of stator current under different degrees of branching of stator winding under open welding are calculated, as shown in table 4.

TABLE IV
NEGATIVE SEQUENCE CURRENT IN RATED UNDER DIFFERENT FAULT CONDITIONS

Operating status	I_2(A)	I_1(A)	I_1/I_N (%)	I_1/I_2 (%)
Normal	1272	0	0	0
Fault I	1242.4	29.4	2.3	2.37
Fault II	1191.7	96.5	7.5	8.10
Fault VI	1072	196.7	15.4	18.35

Table 4 shows: It only has the positive sequence in the stator current with normal three-phase generator rated symmetrical load running, but when the generator stator winding branch circuit fault, stator current will appear negative sequence current which has positive correlation with the degree of stator winding branch open welding. But the positive sequence current is opposite. With the increase of breaker coefficient ,the percentage of the negative sequence current of the circuit increases gradually.

B. The influence of the opening position of the stator winding branch on the negative sequence current

In order to study the influence of the opening position of the stator winding branch on the negative sequence current, with the permanent magnet wind turbine rated at 12m/s and stator winding has the same circuit branch number, calculate the negative sequence current of the stator winding fault II- fault V four fault , the calculation results are shown in figure 5.

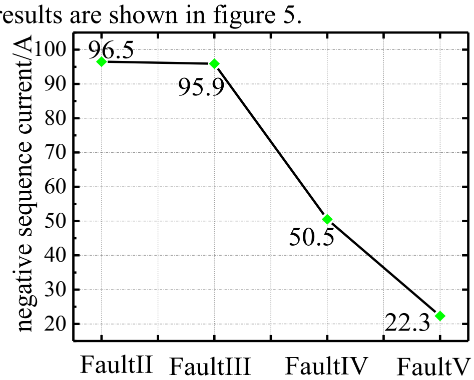


Fig. 5. Relation between negative sequence current and stator winding branch opening position

Figure 5 shows that the permanent magnet synchronous generator with multiple parallel branch, when the number of branches of the stator winding circuit belongs to the same phase, when the stator current in negative sequence current is largest, but negative sequence current by the space position influence the opening branch is very small which can be neglected; but when the number of branches of the stator winding circuit belong to different phase, the negative sequence current of adjacent branch circuit fault is bigger than the negative sequence current of non-adjacent branch circuit fault.

C. *Influence of wind speed on negative sequence current*

Due to the frequent variation of wind speed of wind turbine generator, the three-phase current of the generator will change when the wind speed is different, or it may change the negative sequence current, thus this paper studies the relationship between negative sequence current and wind speed of the stator winding of the permanent magnet wind-driven generator, the generator in wind v=8m/s, 10m/s, v=12m/s rated wind speed occurs in stator winding fault I fault, II fault and VI are calculated, the negative sequence current as shown in Figure 6.

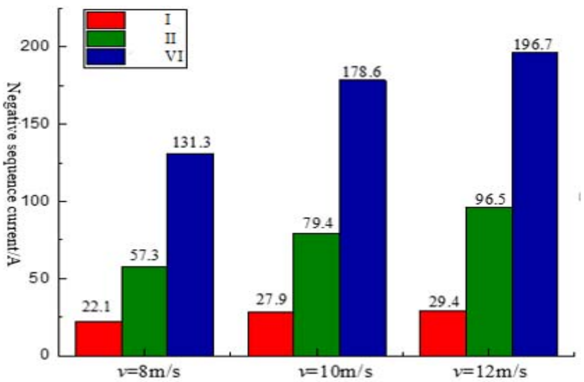


Fig. 6. Relationship between negative sequence current and breaking branch number at different wind speeds

As can be seen from Fig. 6, when the permanent magnetic wind generator operates in the fault I state, the wind speed has less influence on the negative sequence current, especially when the wind speed approaches the rated wind speed, and the negative sequence current hardly changes, that is mainly because the permanent magnet wind generator with multi parallel branches occurs single branch circuit fault of stator windings, stator three-phase current unbalance degree is small, but the negative sequence current is directly affected by the stator three-phase unbalanced current effect, the smaller the imbalance, the smaller the value of the negative sequence current.

V. CONCLUSION

1) For the permanent magnet wind generator with multiple parallel branches, the negative sequence current in stator current is positively related to the severity of the opening when the stator winding branch circuit fault occurs; but with the increase of the stator winding circuit number, phase angle of non-fault phase difference deviation from the 120 degree increased significantly;

2) when the number of branches of the stator winding circuit belongs to the same phase, when the stator current in negative sequence current is largest, but negative sequence current by the space position influence the opening branch is very small which can be neglected;

3) the wind speed has a certain influence on the negative sequence current, but it is less than the influence of the stator winding open circuit severity on the negative sequence current.

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