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A Brushless Three-phase Synchronous Induction Motor with Two Stators

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Abstract

In this paper, a brushless three-phase synchronous induction motor with two stators which can self-start as a wound-rotor induction motor without external secondary resistance is proposed. In the proposed motor, two excitation schemes, separately and self-ones, can be realized. In the separately excitation scheme, the proposed machine can operate as a synchronous generator-motor. The proposed machine compared with traditional brushless synchronous motor with *AC* exciter has the following advantages: the rotor structure is simple and robust, the operating reliability is high, and the high starting torque is realized.

Introduction

Brushless three-phase synchronous motor with a rotating *AC* exciter on the same shaft as the motor and the windings linked through a shaft-mounted rectifier (*Appendix I*) is widely used as medium and large capacity machines. However, this motor needs damping windings for self-starting besides the field winding in the rotor and discharge resistance with complex electronic device in order to dispose the electromagnetic force induced in the field winding at starting. Therefore, the rotor structure is very complex, and there are disadvantages especially for robust and high reliability required motor.

In order to solve this problem existing in traditional motor, authors proposed a brushless three-phase synchronous induction motor with two stators and one wound rotor[1]. The proposed motor solves the above mentioned problem due to its special two stator structure: the rotor winding operates as the secondary winding of induction motor at starting and as the field winding at synchronous operation enabled by reversing the polarity of two stator windings using change-over switch.

The proposed motor has the following characteristics:

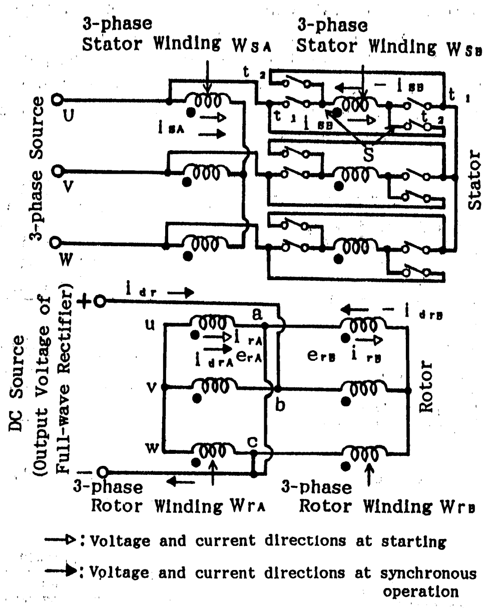
1. The motor can self-start as a wound-rotor induction motor without external secondary resistance. Therefore, damping windings and discharge resistance are not necessary, and the starting equipment is very simple and the rotor structure is robust.The motor also provides a high starting torque.
2. The generation of pulsating torque by direct current flowing in the rotor winding at starting is completely suppressed because of the two stators. This means that it is possible to start proposed machine as an induction motor under supplying direct current to the rotor windings. Therefore, it is not necessary to install the electronic device to suppress direct current like for traditional motor, which makes the operational reliability higher.
3. Two excitation schemes, self and separately-excitation ones, can be realized.

In this paper, the basic construction of the proposed motor and the principles of operation are described in detail. The experimental results at starting and pulling into synchronism are shown in order to confirm the principles of operation. Also, the experimental and the numerical results of the starting characteristics and the load ones are shown. The practical use of the proposed motor is confirmed.

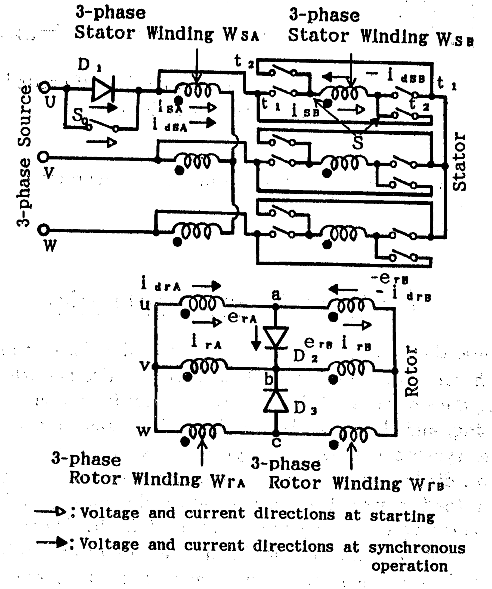
Basic Construction and Principles of Operation

Figs. 1(a) and 1(b) show the electric circuit of separately and self-excitation schemes for the proposed motor, respectively. In both excitation schemes, two three-phase rotor windings, w_{rA} and w_{rB}, are connected in series, and two three-phase stator windings, w_{sA} and w_{sB}, are connected in parallel or in series. A three-phase change-over switch S is connected to one three-phase stator winding. The methods to supply direct current to field winding are as follows: for separately-excitation method, the following two methods are considered; a method involving a rotating *AC* exciter on the same shaft as the motor and with the windings linked through a shaft-mounted rectifier just like traditional method and a method to add exciting windings to stator and rotor[2]. On the other side, the method as shown in Fig. 1(b) is proposed for self-excitation scheme; the switch S_0 and the diode D_1 are inserted in parallel with one of the three-phase stator windings, and the diodes D_2 and D_3 are connected between both three-phase rotor windings.

Next, the principles of operation for the proposed motor are explained. First, the separately-excitation method is described. In Fig. 1(a), when the contact points, t_1, of the three-phase change-over switches S are closed, the same three-phase alternating currents flow in the stator windings w_{sA} and w_{sB}, therefore i_{sA} is equal to i_{sB}. The two rotating magnetic fields, which do not interference between each other, are generated. Then, the electromotive forces, e_{rA} and e_{rB}, which have the same phase and



(*a*) Electric circuit for separately excited motor.



(*b*) Electric circuit for self-excited motor.

Fig. 1 Electric circuits for brushless three-phase synchronous induction motor with two stators.

the same magnitude, are induced in the rotor windings w_{rA} and w_{rB}, respectively. In this case, the voltage values at terminals *a*, *b*, and *c* shown in the Fig. 1(a) are the same, and the reflux phenomenon to the *DC* source does not occur.

Therefore, the alternating currents flow through w_{rA} and w_{rB}, and the motor can self-start as an induction motor. If the direct currents, i_{drA} and $-i_{drB}$, are supplied to w_{rA} and w_{rB} from the *DC* source, the torques generated by these direct currents have the opposite directions. That is, they don't influence to the starting torque. After the rotor is accelerated nearly synchronous speed, the contact points t_1 are opened, while in the same time the contact points t_2 are closed. Then, the current i_{sB} flowing through the stator winding w_{sB} reverses, and the phase difference between the magnetic fields generated by the current $-i_{sB}$ and i_{sA} becomes 180 degrees in electrical angle. As a result, the rotating direction of synchronous torques generated between the rotating magnetic field generated by i_{sA} and the direct current i_{drA} flowing through w_{rA} is the same as that generated between the rotating magnetic field generated by $-i_{sB}$ and the direct current $-i_{drB}$ flowing through w_{rB}. The motor is pulled in synchronous state.

Next, operating principles of self-excitation method are described. In Fig. 1(b), the switch S_0 and the contact point t_1 of switch *S* are closed, and the motor starts itself as an induction motor just like the separately excitation method. After the rotor is accelerated at nearly synchronous speed, the switch S_0 is opened and at the same time the contact points t_1 and t_2 are opened and closed, respectively. Then, by the action of diode D_1, the direct currents i_{dsA} and $-i_{dsB}$ flow in the *U*-phase of the stator windings w_{sA} and w_{sB}, respectively, where i_{dsA} is equal to $-i_{dsB}$. In *V* and *W*-phases, these direct currents flow simultaneously with alternating currents. The stationary and rotating magnetic fields are generated in both stators: the distributions of the magnetic fields generated by the stator windings w_{sA} and w_{sB}, respectively are out of phase to each other.

Then, by the stationary magnetic field and negative-phase-sequence components of rotating magnetic field, electromotive force is induced in w_{rA} and w_{rB}, with opposite phases ($e_{rA} = -e_{rB}$). According to the voltage differences between two terminals $a - b$ and $c - b$, the diodes D_2 and D_3 are automatically turned on. As a result, the rectified currents i_{drA} and $-i_{drB}$ flow in w_{rA} and w_rB, while i_{drA} is equal to $-i_{drB}$. The synchronous torques with the same rotating directions are generated by the positive-phase-component of the rotating magnetic fields of w_{sA} and w_{sB} and the direct current i_{drA} of w_{rA} and $-i_{drB}$ of w_{rB}. Therefore, the motor operates as a synchronous machine.

Experimental Results

In the experiment, the shafts of two wound-rotor induction motors with 4 poles and ratings 1[*kW*], 200[*V*], 60[*Hz*] are directly connected. In order to measure the currents in the rotor, the direct current source and the diodes D_2 and D_3 in Fig. 1 are connected outside the motor through the slip rings and brushes. The constants per phase of one test motor are as follows:

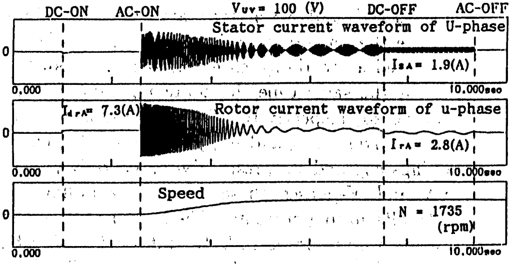
Resistance of stator winding $r_1 = 1.02[\Omega]$
Resistance of rotor winding $r_2' = 2.72[\Omega]$
Leakage reactances of stator and rotor windings $x_1 = x_2' = 1.74[\Omega]$
Exciting conductance $g_0 = 1.78 \cdot 10^{-3}[S]$
Exciting susceptance $b_0 = 29.91 \cdot 10^{-3}[S]$
Synchronous reactance (constant per three-phase) $X_s = 31.8[\Omega]$
The maximum mutual inductance between one phase of stator winding and exciting winding $M_{fa} = 15.8 \cdot 10^{-3}[H]$

The values of g_0 and b_0 are measured at half of the rated voltage and r_2' and x_2' are the values converted to the primary circuit.

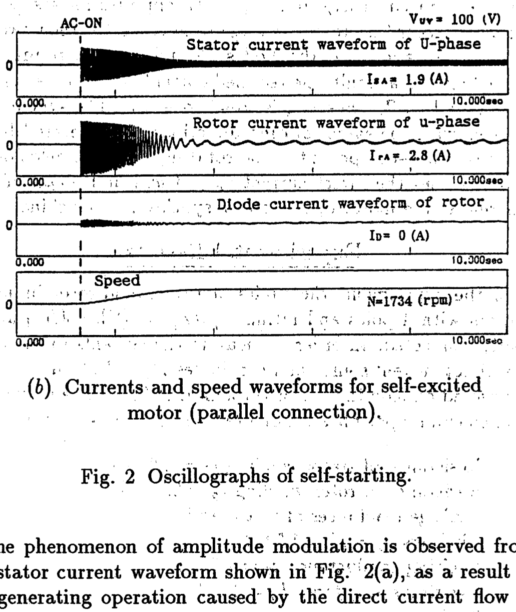
Transient Characteristics at Starting

As described in the previous section, in the brushless three-phase synchronous induction motor with two stators, the voltages at the connecting terminals *a*, *b*, and *c* are the same to each other at starting. In separately excited motor, the direct currents, i_{drA} and $-i_{drB}$, are supplied to two rotating windings at starting. The torques generated by the direct currents cancel each other because of the two stators structure. That is, the direct currents don't affect the value and the waveform of the starting torques in principle. The experimental results proved this principle.

Figs. 2(a) and 2(b) show the transient phenomena at starting for the separately and self-excited motors shown in Figs. 1(a) and 1(b), respectively, where the supply voltage to the stator is 100[V] and the direct currents supplied to two rotating windings for the separately excited motor are $I_{drA} = -I_{drB} = 7.3[A]$. From the speed waveform shown in Fig. 2(a) and the torque waveform shown in Fig. 3(a) for separately excited motor, it is obvious that the torque oscillations due to the direct current and the uneven rotation are not to be generated.



(a) Currents and speed waveforms for separately excited motor (parallel connection).



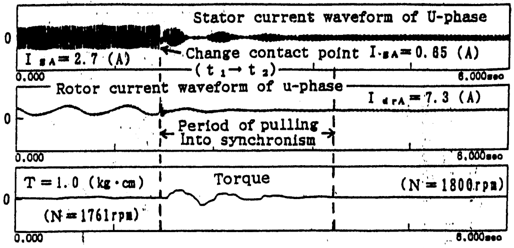
(b) Currents and speed waveforms for self-excited motor (parallel connection).

Fig. 2 Oscillographs of self-starting.

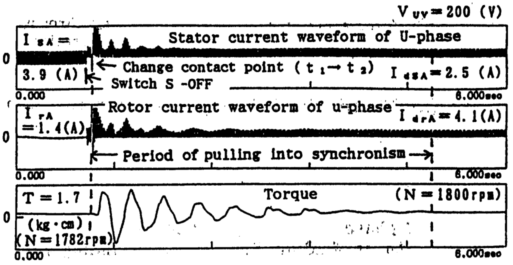
The phenomenon of amplitude modulation is observed from the stator current waveform shown in Fig. 2(a), as a result of the generating operation caused by the direct current flow in the rotor windings. In the case where two three-phase stator windings are connected in series, this phenomenon doesn't occur as shown the stator current waveform at asynchronous operation in Fig. 3(a). In self-excited motor, the diode current I_D is almost zero at steady state as shown in Fig. 2(b). This means that the voltages of two rotor three-phase windings are almost the same at the terminals a, b, and c. In the experiment however, the diode current I_D is not completely zero. The reason probably is that the connecting position of the shaft for two windings doesn't coincide with each other. The experimental results prove the principles of operation mentioned above.

Characteristics of Pulling into Synchronism

Figs. 3(a) and 3(b) show the characteristics of pulling into synchronism of separately and self-excited motors, respectively. Also, the stator current, rotor current, and torques characteristics are shown. It is obvious from Fig. 3 that the pulling into synchronism is very easy for both excitation methods. From this experimental results, the proposed motor can operate as an synchronous induction motor.



(a) Currents and torque waveforms for separately excited motor (series connection).



(b) Currents and torque waveforms for self-excited motor (parallel conection).

Fig. 3 Oscillographs of pulling into synchronism.

Starting and Load Characteristics

Here, the measured and the computed values at starting and synchronous run are shown. The characteristics are calculated using the equivalent T circuit of three-phase induction motor at starting, and the principle equations of non-salient pole three-phase synchronous motor at synchronous run. In self-excited motor, diodes are connected to the stator and rotor windings. Then, the behavior of the currents at synchronous operation are very complex and the analyses are very difficult. Therefore, the analyses of the characteristics in this case are future problems.

Fig. 4 shows the measured and the calculated values of input current and torque at starting, where the supply voltage is 100[V] because of the limits of torque meter. It is assumed that the mechanical losses are in proportion to the slip s, where the losses at synchronous operation are measured as 180[W]. Fig. 5 shows the measured and the calculated values of the input current and the output power at synchronous operation for separately excited motor. Fig. 6 shows the measured values of stator and rotor direct currents and output power at synchronous operation for self-excited motor.

The measured and the computed values in Figs. 4 and 5 coincide very well with each other. It is obvious from the direct current characteristics of stator and rotor in Fig. 6 that the proposed self-excited motor has series effect. The proposed self-excitation scheme is realized by the direct currents rectified by the stator diode D_1. Since these current are supplied from the source, it is feared that the source transformer will be magnetically saturated. Then the application of self-excitation scheme is limited for small capacity machines only.

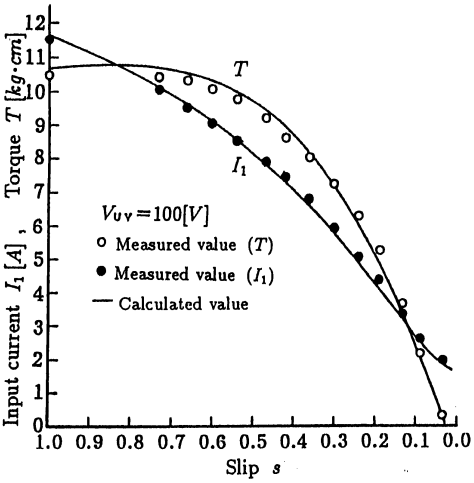


Fig. 4 Starting characteristics

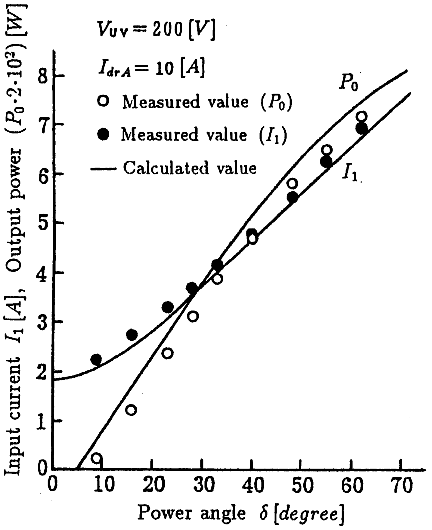


Fig. 5 Load characteristics for separately excited motor.

Conclusions

In this paper, a brushless three-phase synchronous induction motor with two stators which can self-start as a wound-rotor induction motor without external secondary resistance is proposed and its principle is described in detail. The experimental results which prove the operating principle are shown, and its practical usefulness is confirmed.

The proposed machine compared with traditional brushless synchronous motor with *AC* exciter (*Appendix I*), has the following advantages: the rotor structure is simple and robust, the operating reliability is high, and the high starting torque is realized. As the exciting scheme of proposed machines, separately and self-excitation schemes are considered. In the separately excitation scheme, the proposed machine can operate as a synchronous generator-motor. Nowadays, synchronous generators are widely used in pumping-up power station, where one rotating machine is working in both actions: as a generator and as a motor. In traditional motor operation, the synchronous motor is generally accelerated by changing frequency of inverter source and then the synchronous operation is realized by connecting to commercial frequency source. On the contrary, the proposed separately excited brushless motor can self-start as induction motor connected directly to commercial frequency source and can operate as a synchronous generator on the principle describe above. Moreover, if the proposed machine is used as the synchronous machine in pumping-up power station, there is no need of the inverter source.

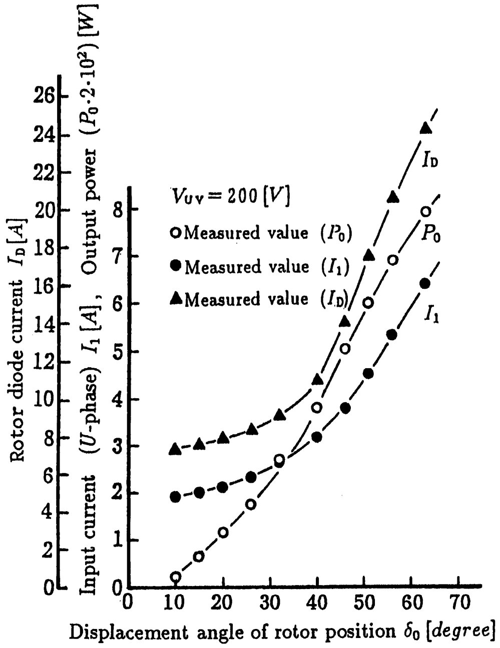


Fig. 6. Load characteristics for self-excited motor.

References

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[2] K. Inoue, H. Yamashita, E. Nakamae, T. Fujikawa, "Brushless Self-Excited Three-Phase Synchronous Generator without Exciter", Trans. of IEE of Japan, Vol. 112-D, No.6, pp. 569-578, (1992).

Appendix

The brushless three-phase synchronous machine as shown in Fig. AP-*I*, in addition to the field windings, equips damping windings for starting, discharge resistance, and other electronic devices. Therefore, the rotor structure is very complex and the reliability on operation is low.

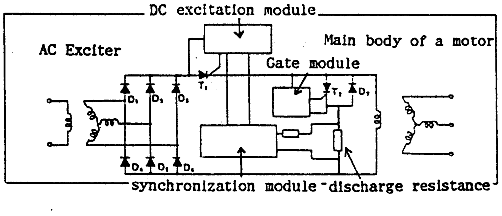

Fig. AP-*I* A brushless three-phase synchronous machine with *AC* exciter