Experimental Verification of On-line High Efficiency Control for a Weaving Machine

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***Abstract*-This paper demonstrates an on-line control based on the speed sensor-less vector control for a weaving machine. The system can achieve high efficiency because the exiting current can be obtained in corresponds to the load torque in realtime. The proposed on-line control is analyzed by simulation and verified experimentally. The maximum efficiency is increased by 4.4% in comparison to the the direct power grid connection.**

I. INTRODUCTION

Weaving machines are generally driven by induction motors because of the preferable low cost structure. Generally, the induction motor is connected directly to the power grid so that high speed acceleration could be achieved. However, there is a problem with the large rush current from the power grid and causing the efficiency reduced depends on load conditions. Due to the direct connection from the power grid, there is no controller involves for the system. Therefore the implementation of an inverter into this system is introduced. In addition, the motor control uses both the vector control method and the high efficiency control method to control the flux in according with the load torque [1]-[2].

However, the load of the weaving machine changes rapidly because of a cam is connecting in between the weaving machine and the induction motor. Therefore, a variable load occurs within a short cycle in according to the motor rotation frequency. Also, controlling the magnetic flux under a variable load condition will further increase the copper loss because the exciting current is changing rapidly.

In this paper, since the load of the weaving machine depends on the cyclic characteristic, high efficiency control method using average load torque is proposed [3]. The average high efficiency control method is examined and analyzed by simulation and experimentally.

However, the load characteristic of the induction motor first must be known in order to control the average flux by the average load torque. Therefore, the real load characteristic of the induction motor must be measured. Additionally, lots of adjustments are very difficult because the pattern of the load torque is difference by the kind of thread.

In this paper, two types of on-line control methods also are proposed to control the exciting current. The first one is called “continuous estimation method”, which can control the exciting current in term of on-line in addition to a variable load. The second one is called “copper loss comparison method”, which can decide the exciting current by calculating the copper loss of the motor. The effectiveness of these control methods are validated by the simulation results and the experimental results.

II. CHARACTERISTIC OF WEAVING MACHINE

A.System configuration

Fig. 1 shows the system configuration of the weaving machine, which is driven by the inverter. The induction motor and the weaving machine are connected to the pulley. So, the weaving machine becomes the conveyed power of the induction motor due to the V-belt connection. The ratio of the pulley between the induction motor and the waving machine = 81:186 in this test case. The rated speed of the induction motor is 1415 r/min, and the rated speed of the weaving machine is 653 r/min based on the pulley ratio and the rated speed of the induction motor.

The weaving machine has a speed sensor on the load side. Therefore, the speed detection includes the slip of the belt from the pulley. As a result, the control performance becomes worse because the slip of the induction motor is not adjusted properly to the slip of the belt. Overall, the efficiency of the weaving machine is further reduced.

B. Load characteristics of the weaving machine

Fig. 2 shows the load characteristic of the weaving machine. The load of the weaving machine changes rapidly because of a cam is connecting between the weaving machine and the induction motor. Therefore, a variable load occurs within a short cycle in according to the motor rotation frequency. On the other hand, the maximum load torque is 1.5 times of the rated motor torque. In addition, the recovery torque is applied to the induction motor at approximately 50% of the rated motor torque. Also, the load torque changes at around 10 Hz because of the cam moves twice each time the pulley moves once.

III. CONTROL METHOD

A. Average high efficiency control method

The high efficiency control method adjusts the magnetic flux in according to the load torque. Then the exciting current is reduced in the light load condition. As a result, the copper loss and the iron loss can be reduced in the light load region. Therefore, the exciting current is controlled in order to change the magnetic flux depends on the load torque. However, if the load torque is varied faster than the time constant of the magnetic flux in secondary side of the induction motor, then the magnetic flux changes rapidly in according to the load torque. In that case, the exciting current will increase drastically in the high efficiency control.. Due to the reason, the exciting current changes significantly because the secondary magnetic flux is changed within a fast period. As a result, the copper loss increases because of the root mean square (RMS) value of the exciting current is increased.

Nevertheless, the load of the weaving machine depends on the cyclic characteristic. If the magnetic flux is controlled at an average value, then the variable of the magnetic flux and the exciting current becomes small. As a result, the copper loss can reduce. The magnetic flux declares at the minimum loss, is given by

$$\phi = \sqrt[4]{\frac{R_1 + R_2}{R_1 + R_m}}\sqrt{TL_2} \quad \text{...(1),}$$

where, R_1 is the primary resistance, R_2 is the secondary resistance, L_m is the exciting inductance, T is the load torque and R_c is the iron resistance, L_2 is the secondary leakage inductance. Furthermore, the average torque is given from the load characteristic. Then, the exciting current is given by

$$I_{d\_\min} = \sqrt[4]{\frac{R_1 + R_2}{R_1 + R_m}}\sqrt{\frac{T}{L_m}} \quad \text{...(2).}$$

Then, the average torque T is obtained as 0.54 p.u. The exciting current can be calculated as 90% of the rated value by (2) and T=0.54pu.

B. Speed sensorless vector control method

Fig. 3 shows the speed estimation block diagram for the motor [4]-[5]. This method estimates the motor speed by the counter electromotive force. First, the flux axis angular velocity ω_1 is calculated by the counter electromotive force and the magnetic flux on the d-axis. Next, the motor speed is estimated to subtract the slip angular velocity ω_s from the flux axis angular velocity.

Fig. 4 shows the vectors on the rotating frame θ are the rotation angle of the motor control frame, where θ^* is the rotation angle of the controller frame to adjust the motor control frame equals to the controller axis, ω_1 is the angular frequency of θ^* and the primary angular frequency of the vector control method and ω_1 is the sum of the rotation angular velocity ω_r and the slip angular frequency ω_s,. e is the counter electromotive force, and ϕ_2 is the secondary magnetic flux.

The vector control method assigns the secondary magnetic flux into the d-axis, i.e. the vector control method assigns the counter electromotive force into the q-axis. When the controller frame corresponds to the motor control frame, the q-axis component of the counter electromotive force becomes zero. In other words, if the q-axis component becomes zero by controlling θ, then the controller axis is corresponded to the motor control frame. This is because the angler frequency ω_1 is obtained by the integral θ, ω_r can be estimated. However, the frame position error occurs between motor control frame (d-q) and controller frame (d'-q').

In Fig. 4, if the controller frame is faster than the motor control frame, then θ will be subtracted into e_q to compensate

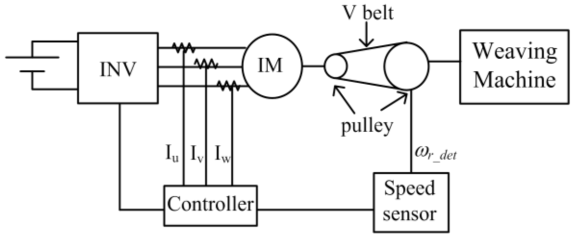

Fig. 1. System diagram of the weaving machine using the inverter.

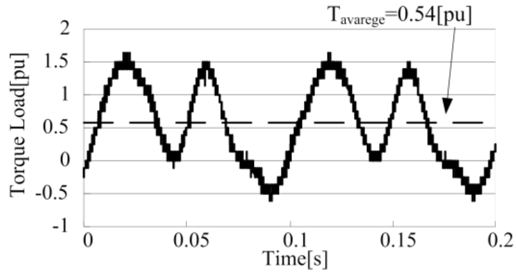

Fig. 2. Load characteristic of a weaving machine.

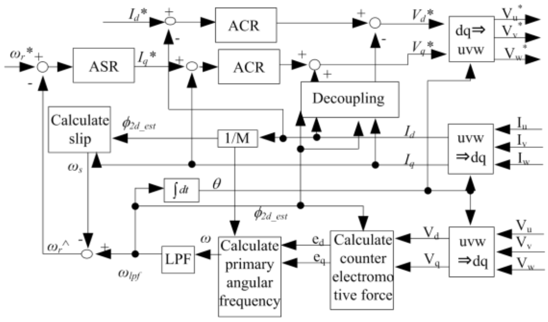

Fig. 3. Block diagram of a speed sensorless vector control.

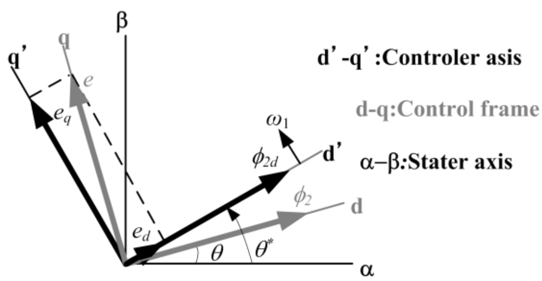

Fig. 4. Relationships among the controller frame and motor control frame in the sensorless vector control.

the frame position error. Additionally, if the controller frame is slower than the motor control frame, then θ will be added into the e_q to compensate the control frame error. The equations (3) and (4) show d-axis and-q axis components of the counter electromotive force which is observed on the control frame. In addition, the compensated value of ω_1 is shown by (5), where, K_{pem} is the compensation gain of the axis error, ϕ_{2n} is the rated secondary magnetic flux.

$$e_d = v_d - \left(R_1 + L_\sigma \frac{d}{dt}\right) i_d + \omega_1 L_\sigma i_q \quad \text{........................... (3)}$$

$$e_q = v_q - \left(R_1 + L_\sigma \frac{d}{dt} \right) i_q - \omega_1 L_\sigma i_d \text{ ....(4)}$$

$$\omega_1 = \mathrm{sgn}(e_q)\left[\frac{|e_q|}{\phi_{2d}} - K_{pem} \frac{\phi_{2d}^{*}}{\phi_{2n}} e_d \right] \text{ ....(5)}$$

C. On-line high efficiency control method

First, the load torque is estimated by the slip angular frequency of the induction motor ω_s. From that, the rated slip angular frequency ω_{sn} can be estimated by the parameter of the induction motor. Then, the estimated load torque is integrated. Then, the average load torque based on the on–line control is estimated by

$$T_{\_all} = \int_{t_1}^{t_2} \frac{\omega_s}{\omega_{sn}} dt$$

$$T_{\_average} = \frac{T_{\_all}}{(t_2 - t_1)} \text{ ....(6)}$$

where, $T_{\_all}$ is the integral value of the instantaneous value of the load torque, ω_s is the slip angular frequency of the induction motor, ω_{sn} is the rated angular frequency, and $T_{\_average}$ is the average load torque.

Fig. 5 shows the block diagram of the continuous estimation method. This method controls the exciting current in term of on-line. The variable load is estimated by the average load torque and (2) at every cycle. The average high efficiency control method calculates the exciting current based on the characteristic of the load, which is shown in Fig. 2. Therefore, if the load pattern changes or if the R1 and R2 change by the temperature of the induction motor, the error occurs on the exciting current. Thereby, the continuous estimation method controls the exciting current at every cycle of the variable load. Therefore, even if the driving condition is change every cycle, the exciting current can be controlled at the optimum value every time in according to the load torque.

Fig. 6 shows the block diagram of the copper loss comparison method. The copper loss comparison method controls the exciting current similar to the continuous estimation method in a constant time $t_{\_limit}$. From there, at the same time as calculating the exciting current, the copper loss P_{loss} is estimated by the detected motor current. In addition, the copper loss P_{loss_min} is calculated by

$$P_{loss} = (I_d^{\,2} + I_q^{\,2}) \times R_1 + I_q^{\,2} \times R_2 \text{ ....(7),}$$

where, P_{loss} is the copper loss.

Then, the exciting current where the copper loss was a minimum value in the $t_{\_limit}$ is decided. Therefore, the copper loss comparison method is different from the continuous estimation method. Additionally, the exciting current which the copper loss is minimum value can be controlled.

In order to reduce the complexity, the iron loss is neglected in this analysis because an influence of the iron loss is smaller than an influence of the copper loss.

IV. SIMULATION RESULTS

These proposed methods are verified by simulation using PSIM7.1.2 (*Power SIM Inc.*). Simulation conditions are follows, DC voltage is 560V, using the speed sensorless control method, the rated speed is 1500 r/min. Table 1 shows the motor parameters.

A. Operation waveforms

Fig. 7 shows the continuous estimation method operation. The changing of the exciting current is checked at every 10Hz.

Fig. 8 shows the operation of the copper loss comparison method. The figure shows that the minimum copper loss has found within 2.55s. At 2.55s, the optimum exciting current I_d is checked I_d=0.62pu. At that, I_d is 95% of the rerated exciting current. I_d is 90% over then the rated exciting current because the exciting current is changed not only one cycle but is approximately 20 cycles of a variable load.

B. Calculation copper loss

Fig. 9 shows the result of the copper loss based on the direct power grid connection, the average high efficiency control method, the continuous estimation method and the copper loss comparison method. The copper loss is reduced by approximately 12% comparing the direct power grid connection, to the on-line control methods. The copper loss is

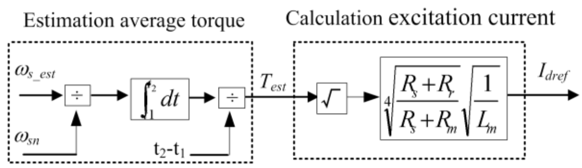

Fig. 5. Continuation method block diagram.

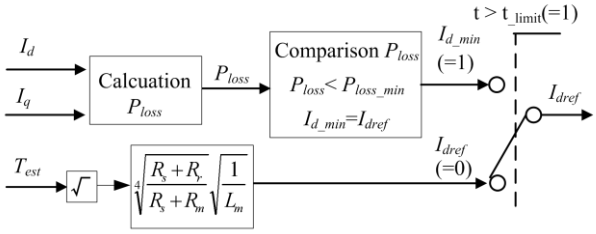

Fig. 6. Copper loss comparison method.

Table 1. Motor parameters.

Poles	4	Secondary resistance R_2	2.98Ω
Rated power	2.2kW	Primary leakage inductance L_1	6.1mH
Rated voltage	380V	Secondary leakage inductance L_2	5.4mH
Rated current	5.4A	Mutual inductance M	190mH
Rated frequency	50Hz	Excitation current I_0	3.5A
Rated speed	1500r/min	Inertia moment J_m	0.0163kgm^2
Primary resistance R_1	2.74Ω		

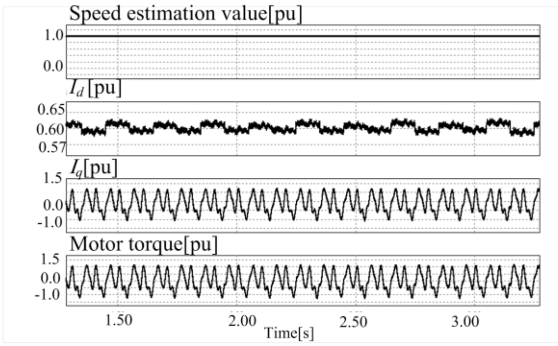

Fig. 7. Simulation results using the continuation method.

reduced based on on-line control method because the exciting current can be controlled to the optimum value at real time.

V. EXPERIMENTAL RESULTS

Effects of the proposed methods were tested by weaving machine (HANGZHOU YINCHUN MACHINE JW-832C). The experimental conditions are; DC voltage is 560V , uses the speed sensorless control method, the rated speed is 1500 r/min. The motor parameters are same as the simulation as shown in Table 1.

A. Inverter efficiency

Fig. 10 shows the inverter efficiency based on the average high efficiency control method, the continuous estimation method and the copper loss comparison method. The inverter efficiency is 96.3 % based on the continuous estimation method as shown in Fig. 10. As a result, the loss is reduced by approximately 10 % than the average high efficiency control method.

The inverter efficiency changes because the current is changed by the efficiency of the induction motor in the converter. The continuous estimation method could obtain a higher efficiency on the induction motor because the exciting current is controlled in according to the load torque.

B. Driving efficiency of the weaving machine

Fig. 11 shows the driving efficiency of the weaving machine based on the direct power grid connection, the average high efficiency control method, the continuous estimation method and the copper loss comparison method. The driving efficiency of the weaving machine was calculated by the number of weft thread for the used power. Fig. 11 shows the continuous estimation method could achieve the maximum efficiency. The driving efficiency of the weaving machine is improved by approximately 4.4 % than then the direct power grid connection. In addition, the driving efficiency of the weaving machine is approximately 0.3 % higher than the copper loss comparison method. The driving efficiency of the waving machine is given the maximum efficiency on the continuous estimation method because of the exciting current can be always controlled in according to the load torque.

VI. CONCLUSIONS

In this paper, the effectiveness of the proposed methods were validated by the simulation and the experimentally. The driving efficiency of the weaving machine was improved because the exciting current is controlled in according to the load torque.

Future work involves the high speed accelerating method and the application of the "hill climbing method" to determine the minimum loss.

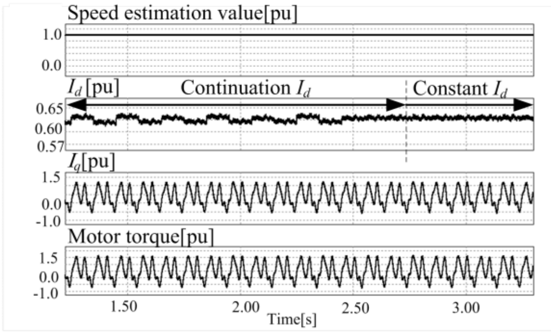

Fig. 8. Simulation results using the copper loss comparison method.

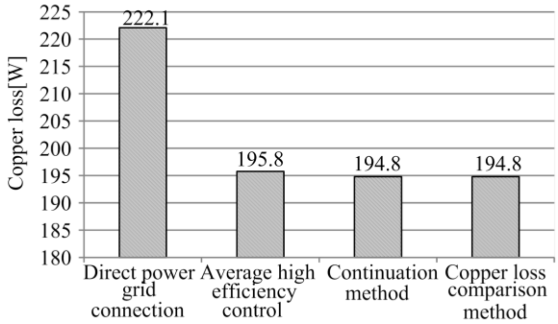

Fig. 9 Copper loss comparison based on simulation analysis.

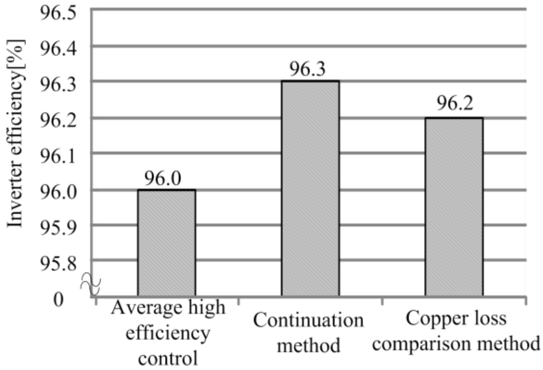

Fig. 10. Inverter efficiency.

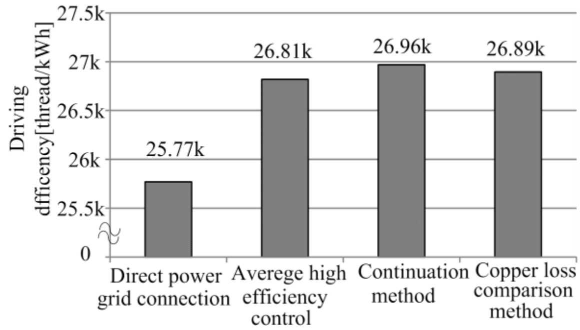

Fig. 11. Driving efficiency of weaving machine.

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