Fast Starting Method using both Inverter and Delta-Star Starter for Weaving Machine Drive Systems

Masakazu Kato, Koji Orikawa, and Jun-ichi Itoh
Department of Electrical Engineering
Nagaoka University of Technology
Niigata, Japan
katom@stn.nagaokaut.ac.jp

Noboru Saitoh
Department of Engineering
HOKUETSU DENKEN Co.,Ltd
Niigata, Japan
noboru-saitoh@post.hdnet.co.jp

***Abstract*— This paper proposes a fast accelerating method for the weaving machine drive system, which an open winding of the induction motor is used and connected in series to an inverter and a switching unit. Generally, the star(Y)-delta(Δ) switching method is used in the start-up mode in order to suppress the rush current in general applications. However, in weaving machine, the rush current is required in the start-up mode in order to increase starting torque. If the starting torque is not enough to the induction motor, deficiencies of fabric cloth which is called "start-up marks" will happen[1]. We proposes the Δ-Y switching method that achieve high rush current in order to increase starting torque for weaving machine drive system. From the experimental results, the start-up time of the proposed system is kept to the same as the direct power grid connection. In addition, rush current of the proposed system is decreased to 37.7% comparing to the direct power grid connection.**

I. Introduction

Weaving machines are generally driven by induction motors because of a preferable low cost structure. Generally the induction motor is connected directly to the power grid, and then an inverter is applied in order to improve the driving efficiency of the weaving machine [2]. However, the driven of inverter results that the start-up time of weaving machine becomes slower because the rush current in the start-up can be suppressed by the inverter. The quality of the fabric cloth which is produced by the weaving machine decreases due to the slow start-up time. In order to increase a starting torque of the motor, the inverter needs to output larger voltage to the motor.

One simple way to increase the output voltage of the inverter is the use of a boost converter into the weaving machine drive system [3]. However, the large voltage is only required for the starting period of the motor. Taking account of the conduction loss from the boost converter, the overall efficiency of power conversion becomes worse.

This paper proposes a fast accelerating method for the weaving machine drive system by connecting the inverter and a switching unit to an open winding induction motor. Δ-connection is used to increase the voltage of the primary wiring of the motor at the start-up of the weaving machine. When the speed of the weaving machine reaches the desired value (rated speed), the motor wiring is switched to Y -connection. As a result, the proposed method can achieve a fast accelerating time equivalent to that is achieved from the direct power grid connection.

II. Characteristics of the 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. Thus, the weaving machine becomes the conveyed power of the induction motor due to the V-belt connection. Fig. 2 shows the external appearance of the weaving machine (JW-832C). The

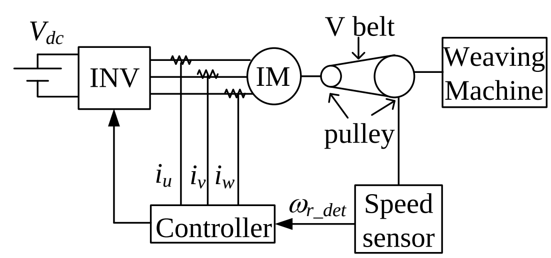


Fig. 1 System configuration of the weaving machine, which is driven by an inverter.

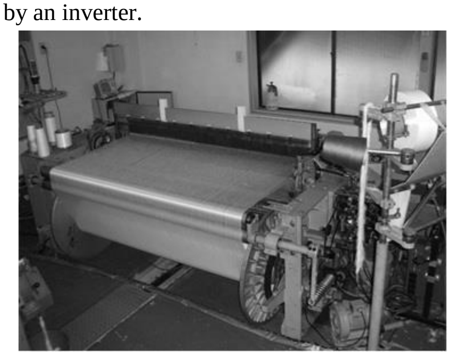


Fig. 2 The weaving machine (JW-832C).

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. 3 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 of loads occurs in 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 the cam moves twice each time the pulley moves once.

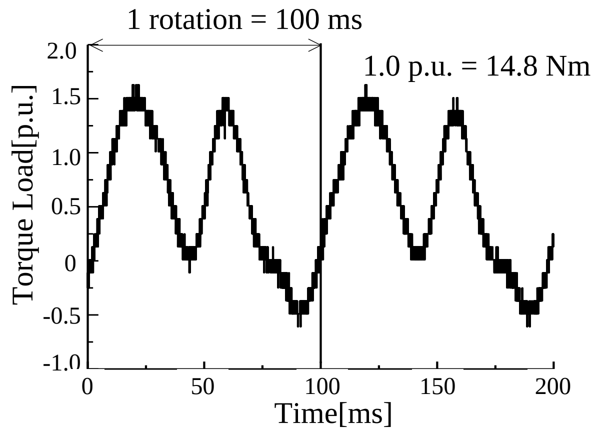


Fig. 3 Load characteristic of a weaving machine. A variable of loads occurs in a short cycle in according to the motor rotation frequency.

III. Introduction of Two Switching Method for Weaving Machine

Fig. 4 shows a general switching method which is called Y - Δ switching method using a switching unit. Induction motors are generally started by a switching unit. The switching unit is a magnetic contactors switch unit. MC_Y is the switch unit for Y-connection, and MC_Δ is the switch unit for Δ-connection. The Y-connection is used in the start-up mode in order to suppress the rush current into the induction motor in general application which is a large capacity.

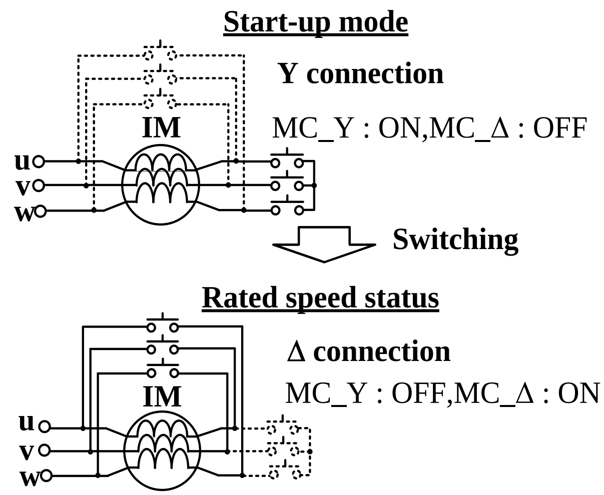


Fig. 4 A general switching method that is called Y - Δ switching method.

Table 1 shows the difference between Y-Δ switching method and Δ-Y switching method. Generally, Y-connection is used in the start-up mode in order to suppress the rush

Table 1. Comparison of Y–Δ switching method with Δ-Y switching method: V_{n_Δ}, I_{n_Δ} and T_{n_Δ} are rated voltage, rated current and rated torque at steady operation of Y-Δ switching method, respectively, V_{n_Y}, I_{n_Y} and T_{n_Y} are rated voltage, rated current and rated torque at steady operation of Δ-Y switching method, respectively

	Change of wiring connection	**Voltage of primary wiring in start-up mode**	**Rush current**	**Starting torque**	**Application**	**Purpose of using this method**
Y-Δ switching method (General method)	Change from Y to Δ	$\frac{V_{n\_\Delta}}{\sqrt{3}}$	$\frac{I_{n\_\Delta}}{3}$	$\frac{T_{n\_\Delta}}{3}$	Large capacity induction motors	Suppression of the rush current in order to prevent burnout of the induction motor.
Δ-Y switching method (Using this paper)	Change from Δ to Y	$\sqrt{3}\ V_{n\_Y}$	$3I_{n\_Y}$	$3T_{n\_Y}$	Weaving machines	Increase of the rush current and starting torque in order to prevent any deficiencies due to lower acceleration of start up mode. (Note that, there is little possibility of burnout of the induction motor in start up mode of weaving machine. Because the time of current flowing is shorter than another applications due to the start-up time is several one hundred millisecond.)

current. However, for weaving machines, the Δ-connection is used to increase starting torque. During the Δ-connection, the voltage which is applied to the primary wiring of the motor is the square root of three times the voltage that can be achieved from Y-connection. The applied voltage is three times as large as the Y-connection torque according to (1). That is, the starting torque of the Δ-connection is equivalent to the three times that can be achieved from the Y-connection. As a result, the Δ-connection enables fast accelerating of the motor.

IV. Fast Accelerating Method of the Weaving Machine by Using Δ-Y Switching Method

The relationship between the motor torque T and the motor input voltage V1 is indicated in (1).

$$T = \frac{3\omega_1 L_m{}^2 (R_2 / s) V_1{}^2}{\left\{\frac{R_1 R_2}{s} - \omega_1{}^2 \left(L_1 L_2 - M^2\right)\right\}^2 + \left(\frac{\omega_1 L_1 R_2}{s} + \omega_1 L_2 R_1\right)^2} \quad (1)$$

where, ω_1 is the angular velocity of the motor primary side [rad/s], R_1 is the primary resistance [Ω], R_2 is the secondary resistance [Ω], L_1 is primary inductance [H], L_2 is secondary inductance [H], M is mutual inductance [H], and s is the slip. According to (1), the motor torque is increased with the increment of the voltage to the motor.

Fig 5 shows the circuit structure with an inverter and a boost converter. One simple way to increase the output voltage is the use of a boost converter into the weaving machine drive system The boost converter is connected at the DC bus in order to increase the inverter output voltage. The operation of the boost converter can be classified into two mode; in mode I, the DC bus voltage is boosted-up so that the inverter can deliver high output voltage during the accelerating time. In mode II, the output voltage of the boost converter is regulated to the same level of the DC bus voltage since the high voltage is not required in steady state operation. However, in either of the operation modes, the power loss is increased because the switching devices in boost converter generate conduction loss.

Fig. 6 shows the proposed configuration of the weaving machine drive system. The inverter and the switching unit (which is a magnetic contactors switch unit, MC_Δ is the switch unit for Δ-connection, and MC_Y is the switch unit for Y-connection) are connected in series to the open winding induction motor. In order to achieve fast acceleration, the primary side wiring of the motor is first connected as a Δ-connection, MC_Δ is turned ON, and MC_Y is turned OFF. After the motor reaches the rated speed, the primary side wiring of the motor is then converted to the Y-connection, MC_Δ is turned OFF, and MC_Y is turned ON. Note that the Y-connection is used in the start-up mode in general in order to suppress the rush current in general application. However for weaving machine, the Δ-connection is used to increase starting torque. During the Δ-connection, the voltage which is applied to the primary wiring of the motor is one over the square root of three of the voltage that can be achieved from Y-connection, that is three times as large as the Y-connection torque according to (1). That is, the starting torque of the Δ-connection is equivalent to the three that can be achieved from the Y-connection. As a result, the Δ-connection enables fast accelerating, furthermore, since the switching unit are two magnetic contactors (MC), no additional losses during the steady state operation.

V. High Efficiency Control and Restart Method for Induction Motor

A. *High efficiency control*

Fig. 7 shows the T-Itype equivalent circuit of the induction motor. The high efficiency control method adjusts the exciting current in according to the load torque. Once the

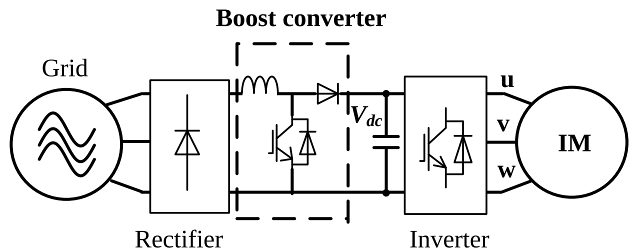
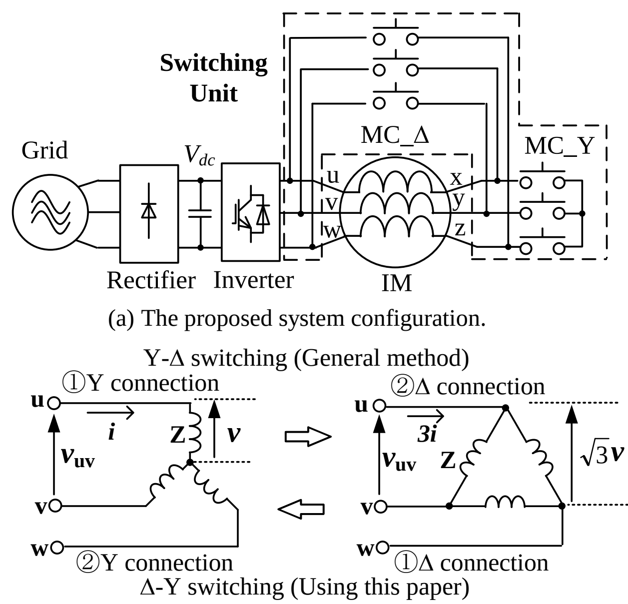


Fig. 5. Circuit structure with an inverter and a boost converter.



(a) The proposed system configuration.

(b) The switching method of proposed system.

Fig. 6. The proposed system configuration. The primary side wiring of the motor is first connected as a Δ-connection.

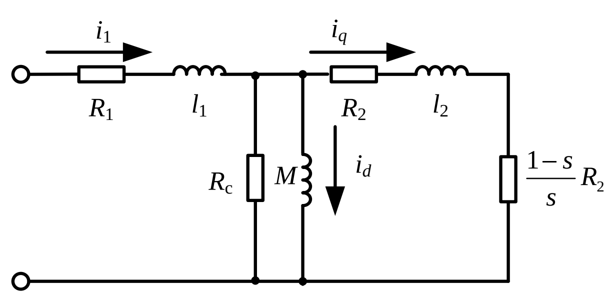


Fig.7 . T-type steady state equivalent circuit.

exciting current is controlled and decreased, the copper loss can be decreased at the same time. Then, the copper loss P_{loss} of Fig. 6 is given by

$$P_{Loss} = 3\left\{ (R_1 + R_2) i_q^{\ 2} + \left(R_1 + \frac{\omega_1^{\ 2} M^2}{R_c} \right) i_d^{\ 2} \right\} \quad (2)$$

Then, the torque current i_q is given by (3)

$$i_q = \frac{T}{\phi_{2d}} = \frac{T}{M i_d} \quad (3).$$

The copper loss P_{loss} is substituted the equation (3). In addition, the exciting current i_{d} is differentiated. Then, the condition which achieves that the differential value of i_d is zero is calculated. Therefore, the $i_{\mathrm{d\_min}}$ at the minimum copper loss is given by

$$R_m = \frac{\omega_1^{\ 2} M^2}{R_c} \quad (4)$$

$$\frac{dP_{loss}}{di_d} = -6(R_1 + R_2)\left(\frac{T}{M}\right)^2 \frac{1}{i_d^{\ 3}} + 6(R_1 + R_2) i_d = 0 \quad (5)$$

$$i_{d\_\min} = \sqrt[4]{\frac{R_1 + R_2}{R_1 + R_m}} \sqrt{\frac{T}{M}} \quad (6)$$

The exciting current at the minimum copper loss changes in according to the load torque shown by (3). Therefore, the high efficiency control method controls the exciting current according to the load torque. As a result, the copper loss and the iron loss are decreased. In this paper, the iron loss is not considered for simplicity.

B. Speed sensor-less control

Fig. 8 shows the block diagram of a speed sensor-less vector control. Weaving machines have a speed sensor on the load side. Therefore, the speed detection includes the slip of the V-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. In order to eliminate the effect of the slip, the system is controlled by speed-senseless vector control [4] [5] [6].

Fig. 9 shows the definition of the control frames. θ is the rotation angle of the motor control frame, 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 ωr and the slip angular frequency ω_s, and 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 the motor control frame (d-q) and the controller frame (d'-q').

In Fig. 8, if the phase of the controller frame is lead compared with the motor control frame, then θ will be subtracted into e_q to compensate the frame position error. Additionally, if the phase of the motor control frame is lead compared with the controller frame, then θ will be added into the e_q to compensate the control frame error. The equations (7) and (8) show the 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 (9), where, K_{pem} is the compensation gain of the axis error, ϕ_{2n} is the rated secondary magnetic flux.

$$e_d = v_d - \left(R_1 + L_\sigma \frac{d}{dt} \right) i_d + \omega_1 L_\sigma i_q \quad (7)$$

$$e_q = v_q - \left(R_1 + L_\sigma \frac{d}{dt} \right) i_q - \omega_1 L_\sigma i_d \quad (8)$$

$$\omega_1 = \mathrm{sgn}(e_q) \left[\frac{|e_q|}{\phi_{2d}} - K_{pem} \frac{\phi_{2d}^{\ *}}{\phi_{2n}} e_d \right] \quad (9)$$

C. Restart Method for Induction Motor

When the motor wirings is switching from Δ-connection to Y-connection, the system requires a dead time period. During the dead time period, both MCs are turned off. Therefore, the primary current of the motor becomes zero in the dead time period. Since the primary current is zero, it is necessary to restart the weaving machine from the free-run state. In the speed-senseless control, there is a possibility that the rush current is generated in the motor which will damage the motor [7] [8]. The q-axis current controller is preferable with high

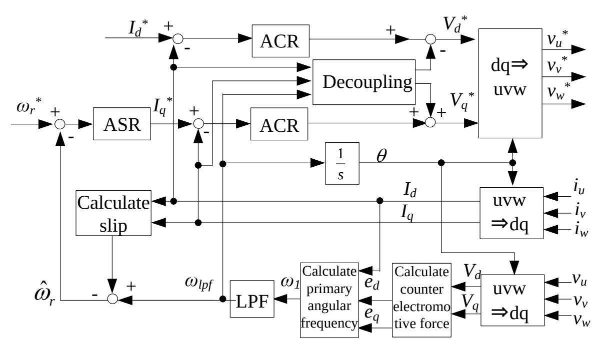


Fig. 8. Block diagram of a speed sensor-less vector control.

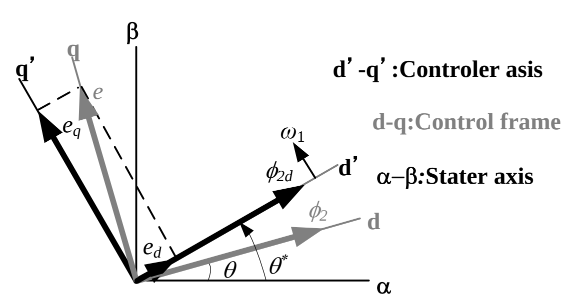


Fig. 9. Relationships among the controller frame and motor control frame in the sensor-less vector control.

gain to reduce the rush current.

VI. THERMAL ANALYSIS

Table 2 shows the induction motor parameters. Fig. 10 shows a simulation result of primary current of a motor. In the proposed method, inrush current is generated in the motor in order to achieve first starting. The inrush is required while start-up period of the weaving machine. The cost of the inverter is increased due to the rush current.

Fig. 11 shows the rise of junction temperature ΔT_j. The analysis conditions are; the DC link voltage in the inverter is 560 V, and primary current of the motor shown in Fig. 10. It is noted that the case temperature is 80 degrees. The results show that higher rate current of IGBT module provides smaller ΔT_j. ΔT_j of IGBT is 28.4 degrees and ΔT_j of FWD is 5.7 degrees when the rate current of IGBT module is one – half of maximum of inrush current. If the rush current is twice as large as the rate current of a IGBT module, the junction temperature is less than a storage temperature of a IGBT module. Therefore, the propose method has no problem of cost up.

VII. EXPERIMENTAL VERIFICATIONS

The experimental conditions are; the DC link voltage in the inverter is 560 V, and the rated speed of the induction motor is 1415 r/min. The experimental vilifications were implemented on the weaving machine JW-832C shown in Fig. 2.

Fig. 12 shows the acceleration characteristics of the weaving machine, which is obtained from the following controls, (i) the direct power grid with Y-connection(Y starting), (ii) the direct power grid connection with a Δ-Y switching unit (Δ-Y starting), (iii) the inverter with the vector control method, (iv) the inverter with the direct torque control (DTC) method [9], (v) the inverter with the Δ-Y swathing unit (Proposed method) and (vi) the proposed method with sensor-less vector control. The results show that the start- up time of Δ-Y starting is approximately 80 ms. On the other hand, the start- up time of the vector control and DTC is approximately 125 ms, respectively. The results clearly demonstrated that the proposed method can achieve the accelerating time similar to that of the direct power grid connection (Δ-Y starting).

Fig. 13 shows the relationship between maximum rush current and start-up time based on three different conditions which is the direct power grid connection, inverter operation only and inverter with the MC switching unit. The maximum rush current is reduced to 42.0% comparing to the direct power grid connection to the inverter. However, the start-up time is also increased to 56.3%. In contrast, the maximum rush current is reduced to 37.7% comparing the direct power grid connection to the inverter with switching unit. Meanwhile the start-up time can maintain equivalent to the direct power grid connection.

Fig. 14 shows the maximum variation of the q-axis current waveforms when the start-up sequence of the weaving machine is repeated by10 times. The primary side wiring of the motor changes from Δ-connection to Y-connection between 300 ms and 320 ms. From the result, the differential value of the q-axis current for the vector control with speed sensor is approximately within 1.0 p.u.. On the other hand, in the sensor-less vector control, the differential value of the q-axis current is within 1.6 p.u.. The fluctuation of the q-axis current is also equivalent to the torque fluctuation. As a result, it is seen that there is a possibility that the thread will be cut by a large torque fluctuation. However, based on the

Table.2 Induction motor parameters.

Parameter	Value
Poles	4
Rated power	2.2 kW
Rated voltage	380 V
Rated current	5.4 A
Rated frequency	50 Hz
Rated speed	1500 r/min
Primary resistance R_1	2.74 Ω
Secondary resistance R_2	2.98 Ω
Primary leakage inductance l_1	6.1 mH
Secondary leakage inductance l_2	5.4 mH
Mutual inductance M	190 mH
Excitation current I_0	3.5 A
Inertia moment J_m	0.0163 kgm^2
Rated acceleration time	173 ms

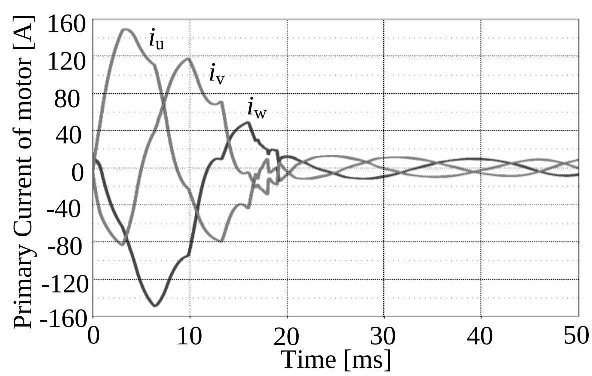


Fig. 10. Simulation result of primary current of a motor

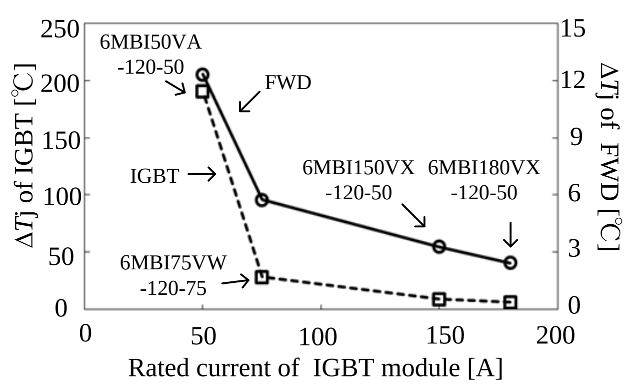


Fig. 11. Rise of junction temperature. ΔT_j of IGBT is 28.4 degrees and ΔT_j of FWD is 5.7 degrees when the rate current of IGBT module is one – half of maximum of inrush current.

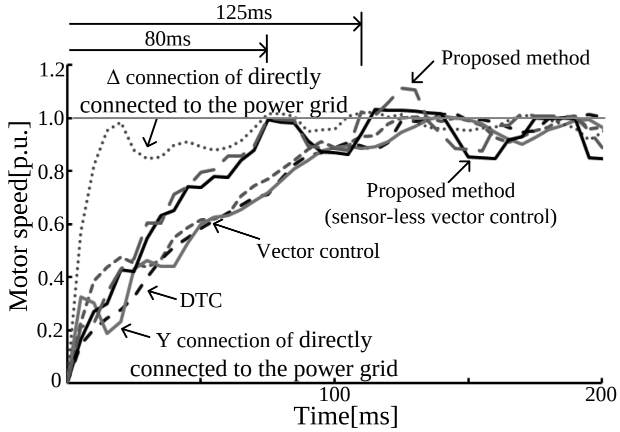


Fig. 12. Relationship between maximum inrush current and start-up time for each control. The Propose method can achieve the accelerating time similar to that of the direct power grid connection (Δ-Y starting).

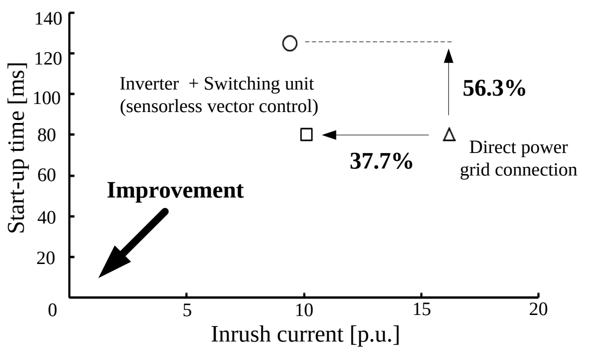


Fig. 13. Relationship between maximum rush current and start-up time for each control. The maximum rush current is reduced by 37.7%.

differential value in the q-axis current for the sensor-less vector control which is approximately 30% at the time of start-up, it can be concluded that the weaving machine is unlikely to stop.

Fig. 15 shows the driving efficiency of the weaving machine based on the direct power grid connection, the vector control with speed sensor of weaving machine, and the speed-sensor-less control. The driving efficiency of the weaving machine was calculated by the number of weft thread for the used power. The driving efficiency of the vector control with the speed sensor is the same as that of the direct power grid connection. On the other hand, the driving efficiency of the speed sensor less control is improved by approximately 3.6% more than that of the direct power grid connection.

VIII. CONCLUSION

In this paper, the effectiveness of the proposed methods was validated experimentally. The start-up time of the proposed system is the same as the direct power grid connection. In addition, the rush current of the proposed system is decreased to 37.7% comparing to that of the direct power grid connection. If the rush current is twice as large as the rate current of a IGBT module, the junction temperature is less than a storage temperature of a IGBT module. The driving efficiency of speed-sensor-less control is improved by approximately 3.6% more than that of the direct power grid connection.

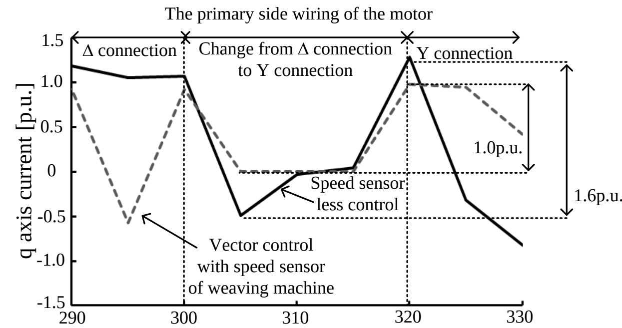


Fig. 14 The maximum variation of the q-axis current waveforms when the start-up sequence of the weaving machine is repeated by10 times.

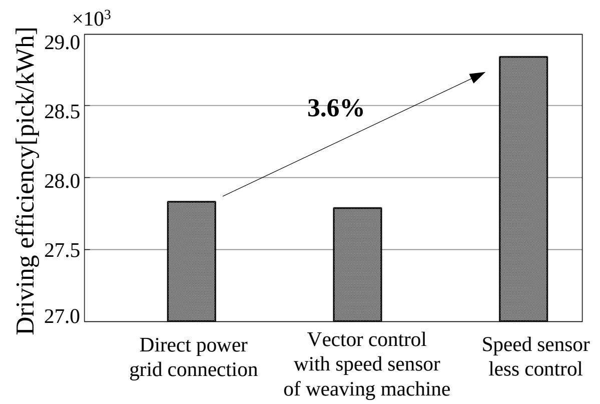


Fig. 15. The driving efficiency of the weaving machine based on the direct power grid connection, the vector control and the speed-sensor-less control.

REFERENCES

[1] Qihong Zhou, Yongyi He, Ronglian Chen, Jinbao He, Minglun Fang: "Electronic Let-off and Electronic Take up System Based on Servocontrol", Intelligent Control and Automation, 8545-8549 (2006)

[2] R. Tateno, J. Itoh, N. Saitoh: "Experimental Verification of On-line High Efficiency Control for a Weaving Machine", IEEE 9th PEDS, No. 345 (2011)

[3] H. Matumoto: ‘’Charge Strategy in Boost Motor Driver With EDLCs”, IEE Transactions, Vol. 25, No. 9,pp.2276-2286(2010)

[4] G.Yang, T.Chin: “Adaptive Speed Identification Scheme Motor Drive”, in Conf. Conf. Rec. 1991 IEEE IAS Ann. Mtg., pp404-408

[5] T.Ohtani, N.Takada, and K.Tanaka, “Vector control of induction motor without shaft encoder”, in Conf. Conf. Rec. 1989 IEEE IAS Ann. Mtg., pp500-507

[6] H.Tajima,Y.Matsumoto,H,Umida : ” Speed Sensorless Vector Control Method for an Industrial Drive System” Trans.IEEJ,Vol.116-D,No.11. (1996)

[7] J. Itoh, H. Tajima, S. Ishii, and H.Umida:”Restart Method for Induction Motor Drive System without Speed Sensor”, IEEJ Transactions, Vol. 119, No. 2,pp.211-216(1999)

[8] Se-Jong Jenong, Young-Min Park, and Gi-Jun Han: ”An Estimation metod of Rotation Speed for Minimizing Speed Variation on Restarting of Induction Mortor”, Power Electronics and ECCE Asia,697-704, (2011)

[9] I.Takahashi, and T.Noguchi, ”A New Quick-Response and High-Efficiency ControlStrategy of an Induction Motor,” IEEE Trans.on Ind. App., 22, 5, 820-827 (1986).