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Automatic restarting methods of electric forklifts in the free running state

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Abstract

Generally, electric forklifts are equipped with a controller which works as an inverter that runs on battery power. The controller rotates induction motors for driving and lifting of a forklift. It also manages faults of a forklift: when a truck is under abnormal conditions, the controller is designed to stop the truck by reason of safety. Although most of the faults can be under control, the controller is also designed to cut off the power supply to induction motors under certain uncontrollable situations, such as when motors are in the free running state, since the controller cannot stop the truck electrically. Until now, operators had to press the brake pedal and steer the wheel forcedly. They could also stop the truck with more polished methods such as automatic braking system with extra sensors or special mechanical actuators attached. However, there is a way to stop the trucks without any extra devices. We propose an electrical active alternative. In this study, we will discuss an application of the restarting method of induction motors, which is used in many industries, to forklifts. This paper describes the automatic restarting methods of electric forklifts in the free running state; thereby reducing the risk of accidents.

Keywords: Automatic restart, electric forklift, induction motor, sensorless, traction control, drive

1 Introduction

Since orders of electric forklifts exceeded over 50% of all industry in 2005, electric orders have been maintained at 50~60% consistently. Furthermore, today's lift trucks offer more in the way of technology, power and performance than ever before.

The developments include everything from ergonomic improvements for operator comfort to fully automated lift trucks that operate just like an AGV(Automated Guided Vehicle). At the same time, the safety functions of lift trucks are acquired a greater importance. Particularly in relation to braking systems, many functions are developed in recent years. For examples, automatic braking system(ABS), electric brake force distribution(EBD), and adaptive cruise control(ACC) are some of the features that can be found in the brochure of any luxury cars. However, installing these features in forklifts won't be cost-effective.[5]

As mentioned at the abstract, without any extra attachment, a truck in an emergency can be stopped by the methods proposed in this paper, in detail, automatic restarting methods of vehicles in the free running state. There are two types of methods: the method with a speed sensor or without one. With a speed sensor, it can be easier to restart the vehicle. On the other hand, voltage and current information of an inverter have to be used to estimate the speed of the free running truck which has a speed sensor fault. These are based on a restarting method of an induction motor, which has been studied in the past.

1.1 Faults of an electric forklift

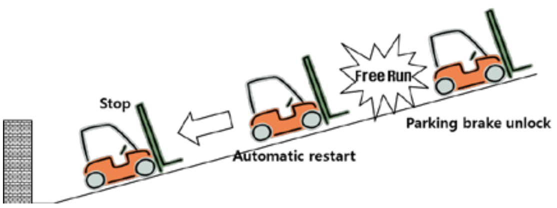
Generally, electric forklifts have two controllers, for traction and for lifting. Each controller has about 40 kinds of faults and these are assorted into two groups as table 1, representative faults are only entered in the table. Because uncontrollable faults of table 1 can cause critical problems, the controller of forklift have to cut off the power supplied to motor immediately. Of course, there are 1~2 safety sequences per each fault to prevent critical problems.

Table 1: Faults of electric forklift

Controllable	Uncontrollable
Over Temperature	Gate Driver
Analog input/output	Under/Over Voltage
Digital Input	Over Current
Parameter Setting	Current Sensor
Fingertip	Encoder Power
Communication	Contactor

It is assumed that above uncontrollable faults are occurred in the following situations.

(a) Case 1. Fault occurred on flat ground



(b) Case 2. Parking brake is unlocked on a slope

Figure 1: Emergency situations

In both cases, the collision of a truck is unavoidable if an operator doesn't put the brake.

2 Restarting methods of an induction motor

A motor speed is not zero in the free running state, so if an initial speed of restart command is 0[Hz] then the induction motor will be decelerated with a large inrush current. This can lead to over voltage or over current trips. In order to avoid these trips, the gap between motor speed and initial speed must be minimized, and knowing motor speed is very important. If a speed sensor is properly working, then restarting method becomes very simple, but if it is abnormal, an estimation algorithm of rotation speed is essential to restart the truck.

2.1 Restarting method with a sensor

A flux current can be calculated precisely with an accurate motor speed measured by sensor. So, after injecting the flux current with some slope to a target current, a torque current will be injected to control a motor speed.

$$\omega_{sl} = -\frac{R_r i_{qr}^e}{\lambda_{dr}^e} \qquad (1)$$

$$\theta_e = \int_0^t \omega_e \cdot d\tau = \int_0^t (\omega_r + \omega_{sl}) \cdot d\tau \qquad (2)$$

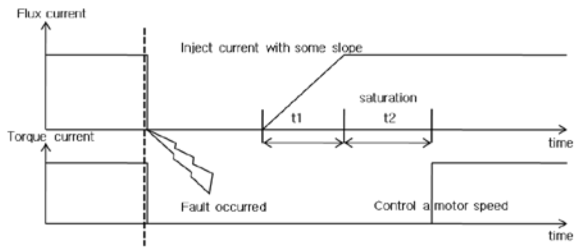


Figure 2: Injecting flux and torque currents with a measured rotor speed

In the fault situation, a q-axis current is zero, so a slip of equation (1) is zero. And a theta of equation (2) can be calculated simply with a motor speed. In addition, a saturation time, t2 of Figure 2, will make the controlling of a q-axis current more stable.

2.2 Sensorless restarting method[2][3]

Typically, there are two sensorless techniques. One is based on back-emf and the other is based on the magnetic saliency of a motor. Since the effect of the back-emf becomes noticeable as the rotor speed increases, it is proper to be at medium or high speed. So at low or zero speed, the method based on a magnetic saliency of a motor is used to estimate the rotor speed. Normally, low or zero speed means a speed under 10% of a rated speed. To utilize the magnetic saliency, a high frequency stator voltage is superimposed to the fundamental voltage component, and the rotor saliency affects the magnitude of the high frequency stator current, from which the rotor position can be identified. However, adapting this to real trucks is complicated. Of course, in many papers, relatively simple adaptive speed observers have been introduced.

The purpose of this study is to restart the induction motor and stop the truck, so if the forklift can be stopped safely, the methods based on back-emf will be used only to estimate the rotor speed, in particularly, adaptive speed observer. This method is relatively easy to implement and guaranteed a certain level of performance.

2.2.1 Adaptive Speed Observer[1][4]

The rotor flux and stator currents can be estimated using state observer equations (3), (4) which are derived from voltage equations of an induction motor. G is a gain matrix of the observer.

$$\frac{d}{dt}\hat{\mathbf{i}}_s^s = -a\hat{\mathbf{i}}_s^s + b\hat{\boldsymbol{\lambda}}_r^s - c\hat{\omega}_r \mathbf{J}\hat{\boldsymbol{\lambda}}_r^s + d\mathbf{V}_s^s + \mathbf{G}(\hat{\mathbf{i}}_s^s - \mathbf{i}_s^s) \tag{3}$$

$$\frac{d}{dt}\hat{\boldsymbol{\lambda}}_r^s = \frac{L_m}{\tau_r}\hat{\mathbf{i}}_s^s - \frac{1}{\tau_r}\hat{\boldsymbol{\lambda}}_r^s + \hat{\omega}_r \mathbf{J}\hat{\boldsymbol{\lambda}}_r^s + \mathbf{G}(\hat{\mathbf{i}}_s^s - \mathbf{i}_s^s) \tag{4}$$

Where,

$\mathbf{V}_s^s = \begin{bmatrix} V_{ds}^s & V_{qs}^s \end{bmatrix}^T$: stator voltage

$\mathbf{i}_s^s = \begin{bmatrix} i_{ds}^s & i_{qs}^s \end{bmatrix}^T$: stator current

$\boldsymbol{\lambda}_r^s = \begin{bmatrix} \lambda_{dr}^s & \lambda_{qr}^s \end{bmatrix}^T$:estimated rotor flux

$\hat{\omega}_r$: estimated rotor angular frequency

$$\tau_r = \frac{L_r}{Rr}, \quad a = \frac{R_s + R_r(\frac{L_m}{L_r})^2}{\sigma L_s},$$

$$b = \frac{R_r(\frac{L_m}{L_r^2})}{\sigma L_s}, \; c = \frac{L_m}{\sigma L_s L_r}, \; d = \frac{1}{\sigma L_s},$$

$$\sigma = L_s - \frac{L_m^2}{L_s L_r}, \; \mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

$$G = \begin{bmatrix} g_1 & g_2 & g_3 & g_4 \\ -g_2 & g_1 & -g_4 & g_3 \end{bmatrix}$$

And the rotating speed is obtained by adaptation using equation (5). Where, k is a positive constant.

$$\frac{d\hat{\omega}_r}{dt} = \frac{k}{c}\left[(i_{ds}^s - \hat{i}_{ds}^s)\hat{\lambda}_{qr}^s - (i_{qs}^s - \hat{i}_{qs}^s)\hat{\lambda}_{dr}^s\right] \tag{5}$$

In order to obtain motor speed, a PI control is used. G, a gain matrix of the observer, is set that a pole of the whole system including the observer can be proportional to a pole of an induction motor. In this case, the whole system works stably because an induction motor is stable by itself.

Figure 3 is a block diagram for sensorless control.

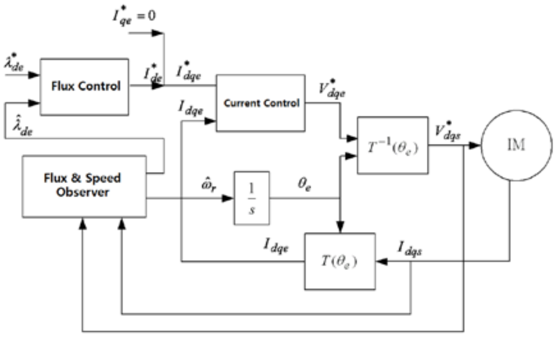


Figure 3: Block diagram for estimation of the motor speed

In case of using such as above sensorless control technique with an adaptive speed observer, the practical control characteristics can be obtained at the 1~2% of a rated speed. To get a better performance, an exact terminal voltage of an induction motor is essential.

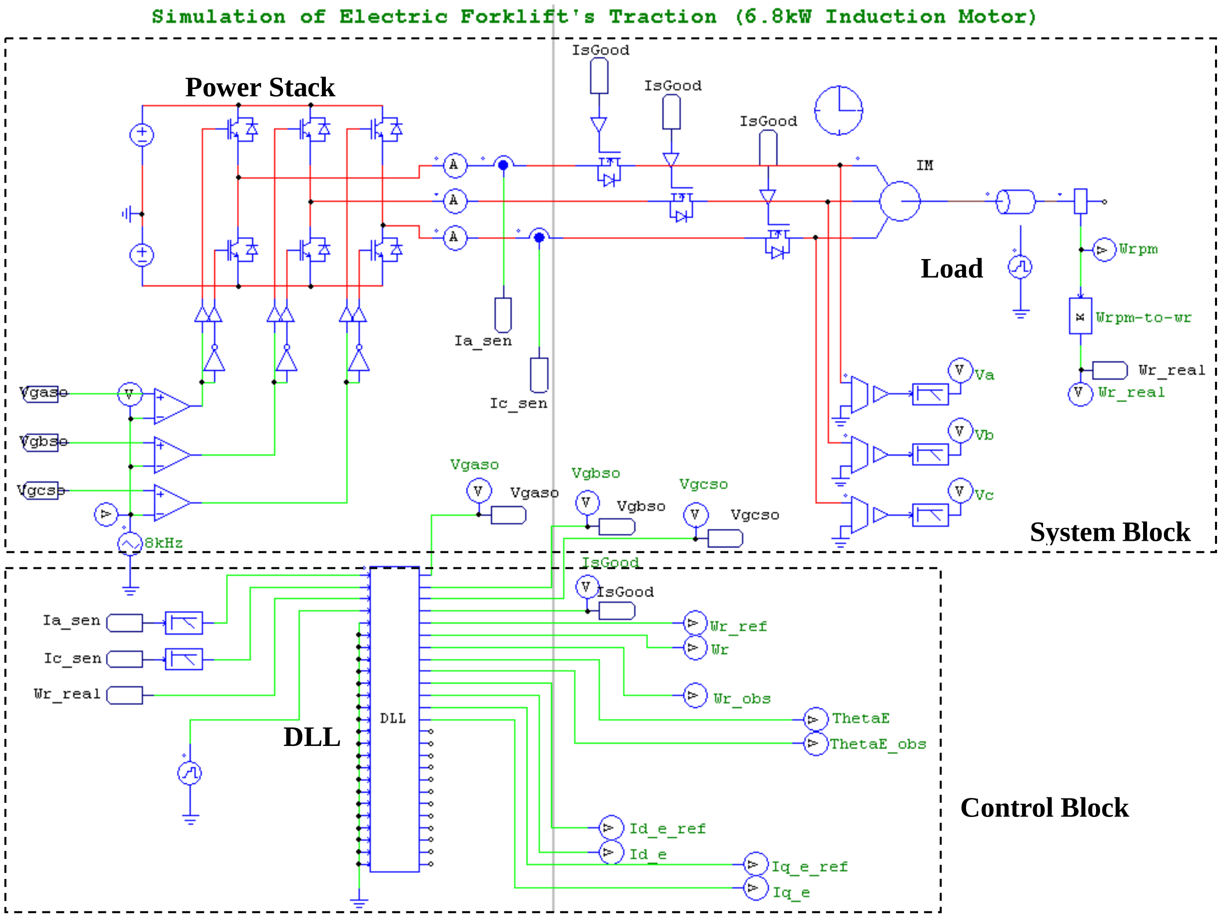


Figure 4: Block diagram for simulation

3 Simulation results

Proposed restarting methods of forklift are verified by computer simulation. Figure 4 shows a block diagram for simulation and the parameters of the simulation system is shown in the table 2.

Table 2: Parameters of Simulation

Motor	6.8kW-30V-134A
Inertia, J	0.4kg.m^2
Switching Frequency	8kHz
Speed Controller	1msec period
Current Controller	125us period
Torque for traction	6Nm

A system block of figure 4 represents a forklift system and a DLL(Dynamic Link Library) block represents a controller.

Assumptions for this simulation are as follows:

- The switching time of IGBT is zero.
- Motor parameters for control are equal to the real.

The DLL file is built with real codes of a real controller except gains of a speed control. Gains of a speed control are modified for matching a response of simulation with a real forklift.

3.1 Restarting method with a sensor

Gate signals for driving are cut off as soon as critical fault is occurred. After 100msec, a d-axis current is injected with a proper slope. After a d-axis current is arrived at a rated d-axis current, a time for saturation is needed. It is dependent on gains of a current control. A d-axis current is injected with reference to a motor speed, so a q-axis current can be injected with the smallest strain. A reference speed follows a real speed at the moment of injecting a d-axis current. The result of simulation is figure 5 and 6.

Figure 5 is for speeds and figure 6 is for dq-axis currents. Dash line is for reference and solid line is for real value.

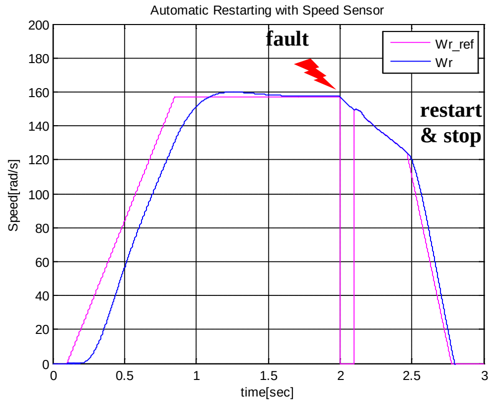


Figure 5: Simulated speeds with a speed sensor

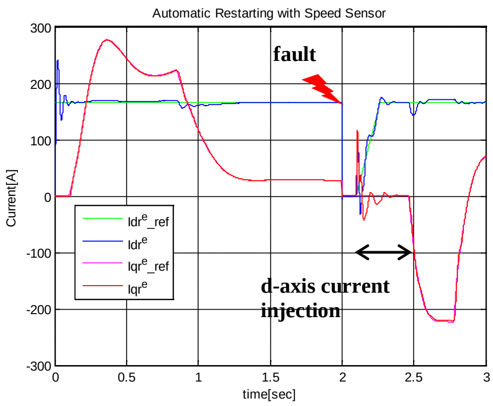


Figure 6: Simulated dq-axis currents with a speed sensor

A variation of dq-axis currents at the starting point after a fault is not appeared at experimental results. The reason of variation is supposed that gains of a current control are not proper at the simulation.

3.2 Sensorless restarting method

When certain encoder power circuit faults occur, a motor speed has to be estimated to restart. Figure 7, 8 and 9 are the results of sensorless restarting method.

An estimated speed is well tracing a real speed before the fault. But the observer can't estimate a speed very well during the d-axis injecting. So, more time was given to saturate until the error between two speeds is smaller.

One more problem remains: the error around low speed is still large. To solve this matter, as mentioned before, a high frequency stator voltage has to be injected. The speed is about 20 rad/s, it can be converted to the real speed of truck, roughly, 4rpm. This problem was not appeared in an experimental test.

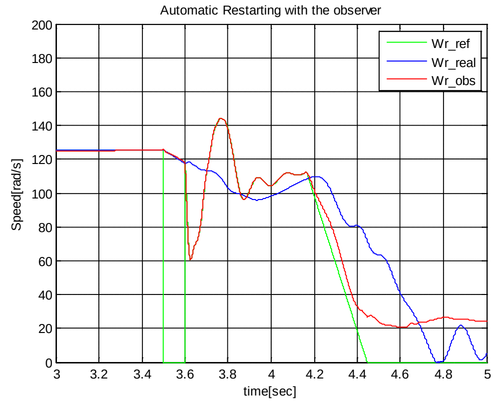


Figure 7: Simulated speeds with an adaptive observer

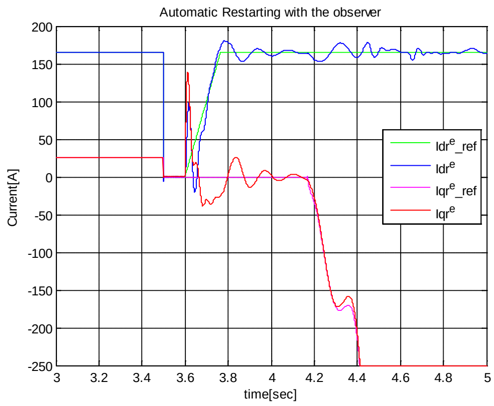


Figure 8: Simulated dq-axis currents with an adaptive observer

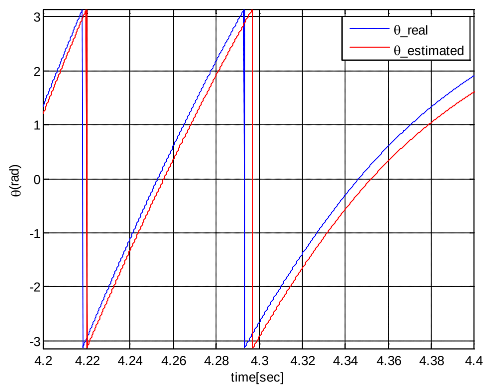


Figure 9: Simulated thetas in transient state with an adaptive observer

A q-axis current is limited to a max current in figure 8. The reason is that a responsibility for estimating is not good at transient state. It has to be tuned at experimental test.

4 Experimental results

Proposed methods are verified one more time by an experiment in a lab. Figure 10 shows a test set of a battery, a controller, and a motor. The experimental results of the restarting method with speed sensor are shown in figure 11 and 12. And those with an adaptive speed observer are shown in figure 13 and 14.

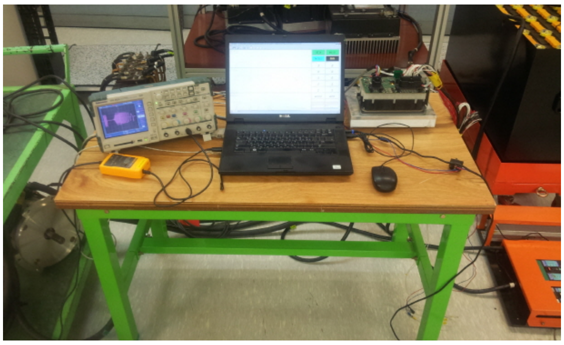


Figure 10: Experimental test set

Figure 11and 13 are screenshots of a monitoring tool which is created by our lab. This monitoring tool uses a serial communication, and the sampling time is 100msec. This monitoring tool is used since an estimated speed and dq-axis currents can't be measured.

Figure 11 shows speeds and dq-axis currents of a restarting method with a speed sensor. Figure 12 shows a phase current of a motor.

The results of this experiment are better than those of a simulation. The reason is supposed that the gains of a controller are optimized than those of the simulation.

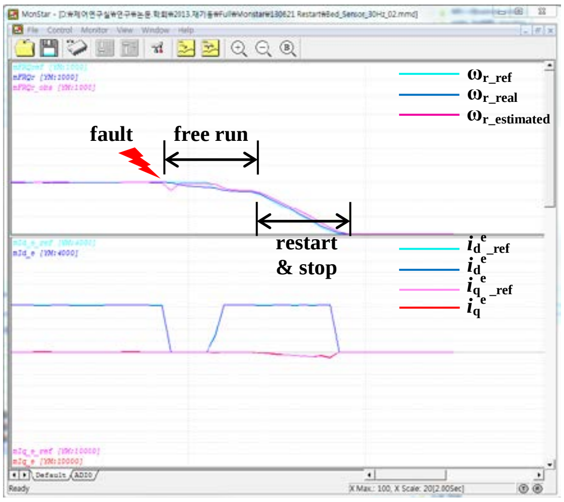


Figure 11: Speeds and dq-axis currents of a restarting method with a speed sensor

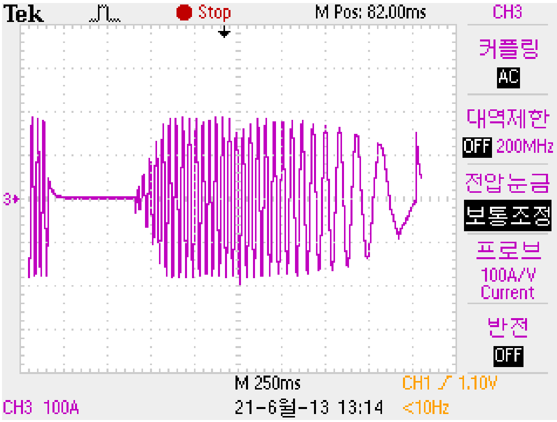


Figure 12: Phase current of a motor

Figure 13 and 14 are the results of a restarting method with an adaptive speed observer.

These results are also better than those of the simulation.

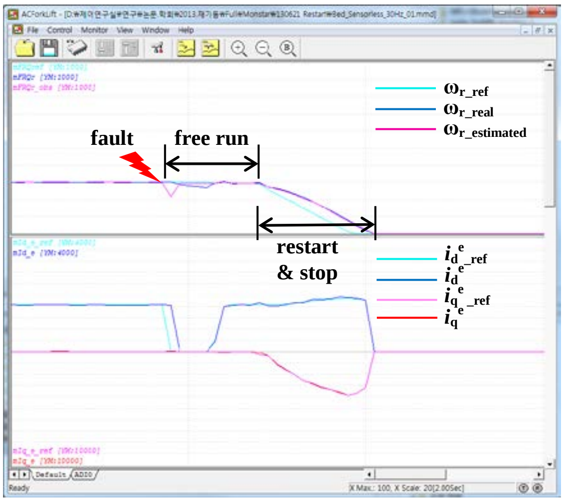


Figure13: Speeds and dq-axis currents of a restarting method with an adaptive observer

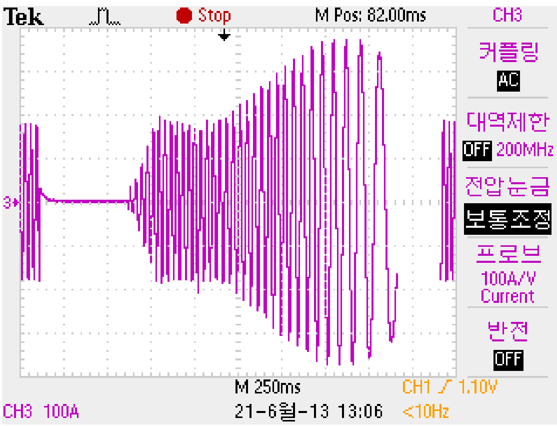


Figure14: Phase current of a motor

5 Electric forklift test

Figure 15 is a forklift which is owned by our lab for research. Specifications of this truck are shown in the table 3.

Figure 15: Electric forklift for test

Table3: Specifications of the forklift

Model	30BR-9 Proto
Type	Reach
Rated Load	3.0 ton
Traction Motor	6.8kW
Battery	48V – 365AH
Weight	3202kg
Max Speed	11km/h

This truck is a prototype for our research. To verify the proposed methods, the truck is equipped with a laptop and a scope as shown in figure 16.

Figure16: One-column figure

Figure 17 and 18 are the results of proposed restarting methods of electric forklifts.

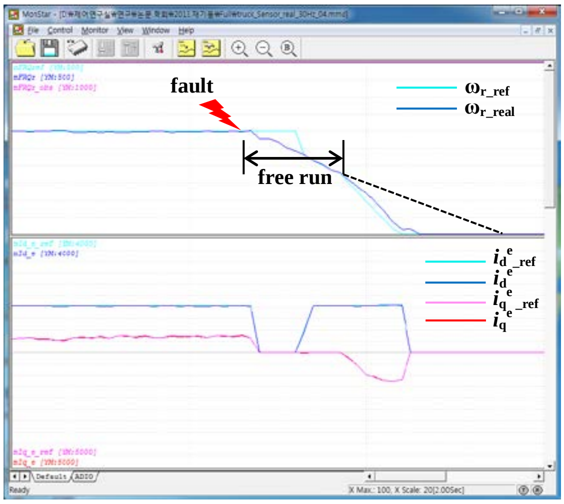


Figure 17: Speeds and dq-axis currents of a restarting method with a speed sensor in the forklift.

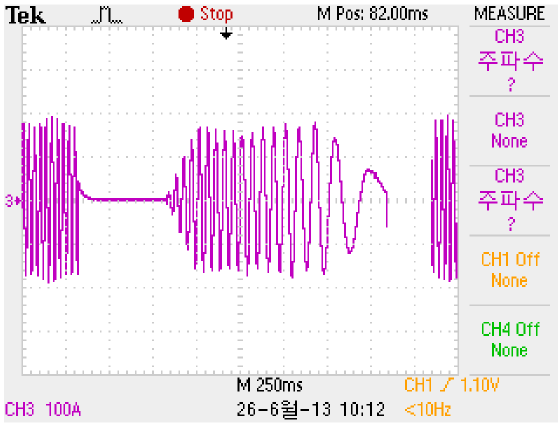


Figure 18: Phase current of a restarting method with a speed sensor in the forklift.

Of the two proposed methods, the restarting method is verified by the forklift truck test as shown figure 17 and 18. The test is performed under a loose condition, at a low speed and on a flat ground. Thus, tests under a severe condition, at a high speed or on a slope, need to be formed. However, safety equipment should be attached to the forklift during the tests. Also, the sensorless restarting method did not yield the expected results in the forklift truck test. The forklift truck did stop, but the margin of error in speed estimation was relatively high which resulted in inefficient control. The inertia in the forklift test is higher than the one in the experimental test done at our lab. In addition, a few assumptions which were made to estimate a motor speed are not proper. These two appear to have caused problems in our tests. Studies on the restarting method of an induction motor need to be reviewed more and applied in the forklift truck tests in the future.

6 Conclusions

This paper presents automatic restarting methods of an electric forklift using an induction motor. It is focused on an application of the existing studies to a forklift. A restarting method with motor speed is relatively simple and the experimental results are almost equal to the simulation. Another restarting method with an adaptive speed observer is also verified during the experimental test and the truck test. Although the speed is limited to the truck test, in the future, more various tests will be performed and verified. Proposed automatic restarting methods will be adopted for a mass production after formal verification tests and durability tests.

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