Concept and Implementation of a Simplified Speed Control Strategy for Survivable Induction Motor Drives

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***Abstract*-Induction machine is one of the most widely used machines in residential and industrial applications. Traditional drive methods for induction machines such as vector control usually require complex control routines, fast processing unit and multiple system status feedbacks. The complexity of these methods greatly reduces the reliability of the system since the failure of the sensor or even the drift of system parameters could potentially result in system malfunction. This creates the need for a simple, cost-effective and reliable control strategy as a backup to continue operation of the system in case of failure of current and voltage feedback sensors. In this paper, an effective, yet simple and low-cost state switching control technique is proposed and implemented for a three phase squirrel cage induction machine system. This state switching control operates at two specific duty cycles of PWM which produces phase voltages with different magnitudes across the phase windings. At the same time, the frequency of phase voltages is derived from the reference speed. By switching between these two states, precise speed regulation can be achieved. This new control method makes the controller extremely simple in design and implementation for induction machine. Simulation and experimental results are included in this paper to validate our claims.**

Keywords: Induction Machines (IM), State Switching Control, Survivable Drive, Pulse Width Modulation (PWM)

I. INTRODUCTION

Induction machines (IM) have been widely used in a variety of industrial and residential applications. This is primary due to their compactness, reliability, and low costs. In order to control induction machine properly and efficiently, different kinds of control strategies emerged in the past. Among these control strategies, most commonly used control strategies are constant V/f control and vector control.

Constant V/f control [1], [2] is popular for induction machine mainly because of its simplicity. In general purpose applications, most constant V/f controls are open-looped and control the voltage and frequency proportionally. By applying a specific phase voltage and frequency to induction machine, it can settle down at a desired speed. However, the speed control of conventional constant V/f controls lacks accuracy due to the existence of the rotor slip. When load increases or frequency decreases, rotor slip increases. This results in the increase of error between reference speed and actual speed. In order to deal with these problems, stator voltage boost [3]-[5] and slip compensation methods [4], [5] are often used. However, these methods increase the complexity of the system and require additional voltage or current sensors.

Vector control strategy [6]-[8] has gained popularity over the last three decades due to its high efficiency and better transient performance. This method controls the flux and torque of induction machine separately and hence enables an easy and effective control as for DC-machines. Vector control turns out to be the most efficient and promising control strategy for induction machine. However, the practical implementation of vector control is complicated and expensive. Fast processing devices, such as DSP and even computer, are often required to perform complex calculations including Clark, Park transformation and Rotor Flux Estimation with the knowledge of induction machine parameters. In addition, at least two current sensors and one position sensor is necessary to meet the minimum feedback requirements of vector control. As a result, the failure of the sensor or even the drift of system parameters could potentially result in system malfunction.

The possibility of system failure when advanced control methods are utilized creates the need for a simple, cost-effective and reliable control strategy as a backup control strategy to continue operate the system in case of failure of current and voltage feedback sensors. One of the techniques that have shown promising performance in recent years is “Digital Control” [9]-[12]. This control method has been shown to be simple and effective for several applications, such as BLDC & SRM control and DC-DC converter control. This technique requires no additional hardware and is not computationally intensive, which also makes it ideal for FPGA implementation. Therefore, use of such a control technique as a backup control strategy to continue operate the induction generator when fault happens, system would become much more reliable and fault tolerant.

This paper presents the concept and implementation of state switching control technique for induction machine based on the principle of digital control but specifically designed for induction machine. Specific gate signals for inverter are derived from six-step drive method [1] by integrating PWM signals to conventional gate signals of six-step drive. This enables the change of phase voltage magnitude by manipulating the duty cycle of PWM signal. Meanwhile, frequency of phase voltage is directly calculated from reference speed. As a result, by applying state switching control, the induction generator system is only allowed to operate at two different duty cycles of PWMs which are given to the inverter and produce phase voltages with different

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magnitudes. Speed regulation is achieved by switching between these two different PWM duty cycles with the frequency of the phase voltage directly obtained from the given reference speed. Therefore, this controller is extremely simple in implementation and only speed sensor is required for speed regulation. This enhances reliability of the control technique and reduces complexity in hardware implementation. While phase current distortion is a challenge due to the lack of current observation, the overall performance of this method is highly acceptable and thus can be used as a backup control strategy. Simulation and experiment results presented in this paper prove the effectiveness of the proposed approach.

II. SIX-STEP DRIVE METHOD FOR INDUCTION MACHINE

For a three phase induction machine, the most frequently used driver topology is the three phase inverter which can be illustrated in Fig.1. This inverter includes six switches (MOSFETs or IGBTs) and six freewheeling diodes. By applying specific signals to these switches, induction machine can be operated properly.

Six-step drive method [1] is one of the simplest methods to drive the induction machine. Gate signals from the inverter are shown in Fig.2. In every electrical circle, each switch is turned on for 180 electrical degrees. The switching status of the upper and lower switches of each phase is always complementary in order to avoid short circuit. At the same time, for different phases, switching statuses are 120 electrical degrees phase shifted from each other. In other words, only three switches are turned on for every 60 electrical degrees. Two in high side and one in low side, or one in high side and two in low side. Therefore, for a wye-connected three phase induction machine, three six-stepped and quasi-sine phase voltages can be formed in the stator winding of the induction machine. These phase voltages are illustrated in Fig.2.

The implementation of the six-step drive method is also very simple. The electrical cycle is first divided into six equivalent regions with 60 degrees each. Each region corresponds to a specific combination of switching status. These combinations can be described in Table I. Finally, by generating these gate signals and applying them to the inverter with proper frequency, the induction machine can be operated.

III. PROPOSED STATE SWITCHING CONTROL METHOD FOR INDUCTION MACHINE

A. *Principle of State Switching Control of Induction Machine*

Speed control of induction machine involves two parameters--the magnitude and frequency of the applied voltage across the phase winding. The frequency of the applied phase voltage mainly determines the shaft speed of the induction machine. This relationship can be explained in the following equations.

$$\omega_s = \frac{2\pi f_s}{P} \tag{1}$$

$$\omega_r = \omega_s(1-s) \tag{2}$$

where ω_s is the synchronous speed of the induction machine in rad/s, f_s is the frequency of the applied phase voltage in Hz, P is the number of pole pairs, ω_r is the speed of the shaft in rad/s and s is the slip rate.

By changing the frequency of the phase voltage, synchronous speed can be changed. At the same time, the variation of the synchronous speed results in the change of the shaft speed since shaft speed is very close to the synchronous speed at steady-state. Therefore, the shaft speed can be determined mainly by the frequency of the phase voltage. On the other hand, if the reference speed of the shaft is defined, frequency of the applied phase voltage can also be determined using equation (1) and (2).

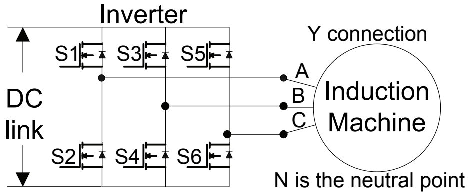

Fig.1. Inverter for induction machine

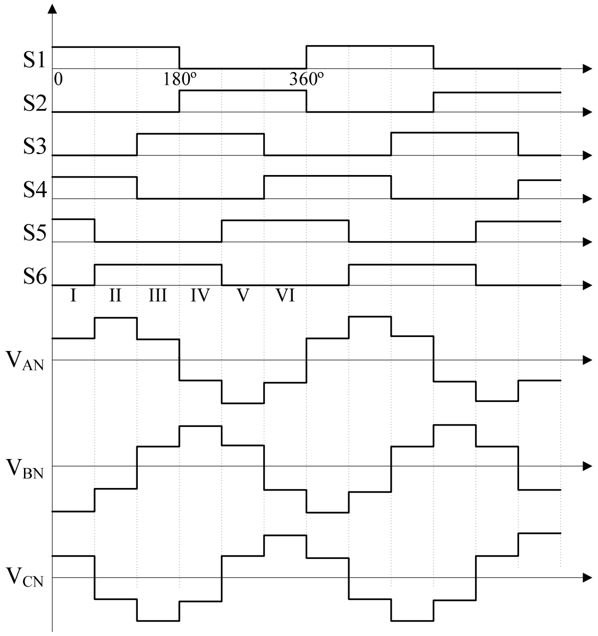

Fig.2. Six-Step waveform

TABLE I

SWITCHING STATUS FOR DIFFERENT REGIONS OF SIX-STEP DRIVE METHOD

Region No.	Switch Status					
	S1	S2	S3	S4	S5	S6
I	ON	OFF	OFF	ON	ON	OFF
II	ON	OFF	OFF	ON	OFF	ON
III	ON	OFF	ON	OFF	OFF	ON
IV	OFF	ON	ON	OFF	OFF	ON
V	OFF	ON	ON	OFF	ON	OFF
VI	OFF	ON	OFF	ON	ON	OFF

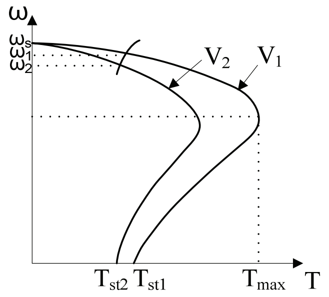

Fig.3 Speed torque characteristics at different voltage level

The magnitude of applied phase voltage is also a factor which could affect the shaft speed. This relationship is shown in Fig.3 [13]. If the magnitude of the applied phase voltages is increased (V1>V2), the torque performance of the induction machine will be changed, as a result, the shaft speed will increase slightly (ω1>ω2), but the synchronous speed will be the same.

Based on the above analysis as well as the six-step drive method, a state switching control technique can be designed and expressed in Fig.4. Based on the reference speed (ω_{ref}), the applied phase frequency can be defined using equation (1) and (2) if slip is approximated to be constant (5% in this case). By applying this frequency to the induction machine with proper magnitude of the phase voltage, shaft speed can be obtained, which is close to the reference. Then, by comparing the actual speed to the reference speed, the magnitude of the phase voltage can be switched between high voltage level (V_H) and low voltage level (V_L). As a result, the actual speed (ω_{act}) of the induction machine can be regulated accurately. In other words, the definition of the synchronous frequency achieves the coarse tuning of the shaft speed while the switching between two PWM duty cycles accomplishes the fine tuning of the shaft speed.

The change of the magnitude of the applied phase voltage is done by a new drive method—PWM six-step drive method. As shown in Fig.5 and Table II, compared to traditional six-step drive method which is shown in Fig.2, switches are given PWM gate signals instead of turning them "ON" all the time for 60 electrical degrees. As a result, in Fig.5, the phase voltages are also PWM shaped if the load is resistive. Therefore, by changing the duty cycle of the PWM, the magnitude of the phase voltage of the induction machine can be changed.

Therefore, the principle of the state switching control of induction machine can be shown in Fig.6 and concluded as follow:

1. The reference speed determines the frequency of the applied phase voltage. In our case, it determines the frequency of the six-step waveform.
2. The duty cycle (d_L or d_H) of the PWM is determined by comparing the actual speed (ω_{act}) with the reference speed (ω_{ref}). The frequency of the PWM is set to 5 kHz in our case.

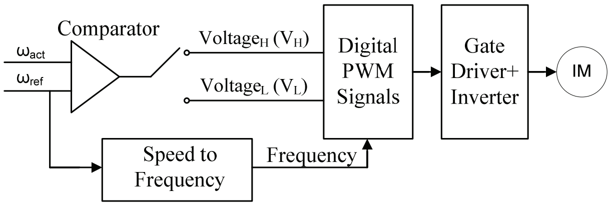

Fig.4 Principle of state switching control of induction machine

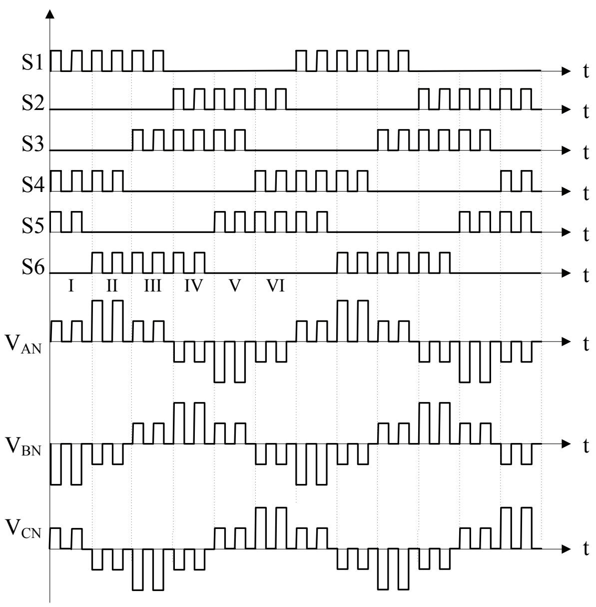

Fig.5 PWM six-step waveform

TABLE II

SWITCHING STATUS OF PWM SIX-STEP DRIVE METHOD

Region No.	Switch Status					
	S1	S2	S3	S4	S5	S6
I	PWM	OFF	OFF	PWM	PWM	OFF
II	PWM	OFF	OFF	PWM	OFF	PWM
III	PWM	OFF	PWM	OFF	OFF	PWM
IV	OFF	PWM	PWM	OFF	OFF	PWM
V	OFF	PWM	PWM	OFF	PWM	OFF
VI	OFF	PWM	OFF	PWM	PWM	OFF

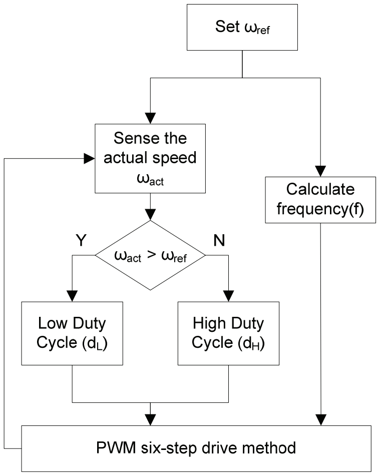

Fig.6 Principle of state switching control of induction machine

B. *Controller Design of State Switching Control of Induction Machine*

From the torque equation, we have

$$T_e = J\frac{d\omega_m}{dt} + b\omega_m + T_L \tag{3}$$

Where *Te* is the generated electromagnetic torque, ω_m is the rotor speed in rad/s, *J* is the rotor moment of inertia, *b* is the viscous friction constant and T_L is the load torque.

The rotor induced torque [14] of the induction machine is

$$T_e = \frac{3V_s^2 R_2 / s}{\omega_s\left[\left(R_1 + R_2 / s\right)^2 + \left(X_1 + X_2\right)^2\right]} \tag{4}$$

Where V_s is the magnitude of the applied phase voltage, ω_s is the synchronous speed of the induction machine in rad/s, *s* is the slip, R_1 and X_1 refers to the stator impedance, R_2 and X_2 refers to the rotor impedance.

Substituting (4) into (3), we get

$$\frac{3V_s^2 R_2 / s}{\omega_s\left[\left(R_1 + R_2 / s\right)^2 + \left(X_1 + X_2\right)^2\right]} = J\frac{d\omega_m}{dt} + b\omega_m + T_L \tag{5}$$

At steady state, the shaft speed ω_s and the slip s is constant. Meanwhile, stator and rotor impedances are also constant. As a result, equation (5) can be simplified as

$$kV_s^2 = b\omega_{mss} + T_L \tag{6}$$

Where ω_{mss} is the rotor steady state speed and $k = \frac{3R_2 / s}{\omega_s\left[\left(R_1 + R_2 / s\right)^2 + \left(X_1 + X_2\right)^2\right]}$.

Therefore, the relationship between voltage magnitude and rotor speed can be obtained as

$$V_s = \sqrt{\frac{b\omega_{mss} + T_L}{k}} \tag{7}$$

In six step method, the magnitude of the applied phase voltage V_s is 2/3 of the DC link voltage V_{DC}. If the duty cycle of the PWM is *d*, we get

$$\frac{2}{3}dV_{DC} = \sqrt{\frac{b\omega_{mss} + T_L}{k}} \tag{8}$$

Therefore, the relationship between the duty cycle and the rotor speed of the induction machine can be expressed as

$$d = \frac{3\sqrt{\frac{b\omega_{mss} + T_L}{k}}}{2V_{DC}} \tag{9}$$

Meanwhile, the frequency of the applied voltage can be calculated using equation (10) which is derived from equation (1) and (2). Slip is considered as a constant which equals to 5% in our simulation and experiment.

$$f = \frac{\omega_{ref} P}{2\pi(1-s)} \tag{10}$$

IV. SIMULATION RESULTS

In order to verify the feasibility of the proposed state switching control of induction machine, simulation is implemented in Matlab/Simulink. The block diagram of the proposed state switching control of induction machine in simulation is shown in Fig.7, in which a 60Hz, 4 pole induction machine is used with a rated speed of 1725rpm.

Fig.8 shows the speed response of the proposed digitally controlled induction machine. Although the actual speed has a little oscillation during starting period, it quickly settles down and precisely tracks the reference speed.

Fig.9 and Fig.10 are simulation results in steady-state. Fig.9 shows the steady-state speed of the induction machine. The speed error between reference speed and actual speed is very small due to high sampling rate of actual speed. Fig.10 shows the change of duty cycle during steady-state.

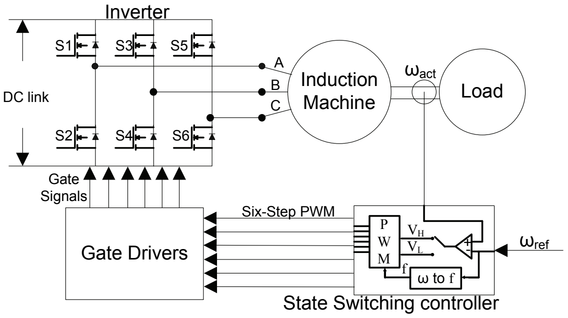

Fig.7 Block diagram of the state switching control of Induction Machine

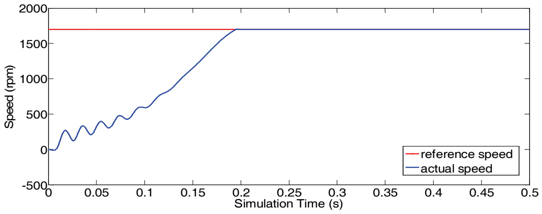

Fig.8 Speed response of the state switching control of induction machine

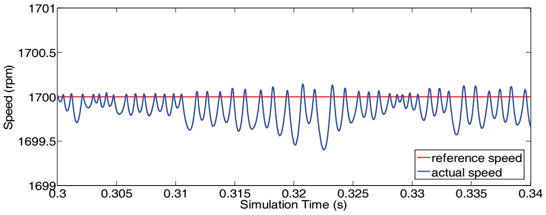

Fig.9 Speed response in steady-state

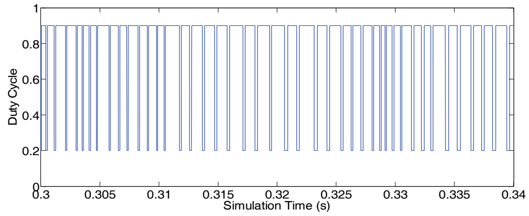

Fig.10 Change of duty cycle in steady-state

V. EXPERIMENTAL VERIFICATION

In order to verify the effectiveness of the proposed state switching control method for induction machine as well as its simulation results, an experimental setup has been developed which is shown in Fig.11. It includes a 3.9kW DC power supply, a TMS320F2812 based DSP controller, three phase inverter and gate drivers, a 2.2kW induction machine and a 3kW PM DC Load. Specifications regarding the induction machine and the PM DC load are listed in Table III.

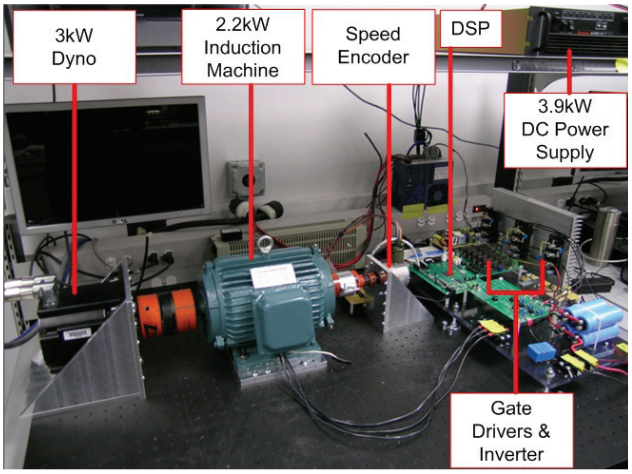

Fig.11 Hardware setup for experimental verification of proposed state switching control strategy of an Induction Machine

TABLE III
PARAMETERS OF THE INDUCTION MACHINE AND PM DC LOAD

	Induction Machine	PM Dyno
Rated Power	2.2kW	3 kW
Rated RPM	1420	6000
Rated Volts	380/Y Conn.	640DC
Rated Current	5A/phase	12.4A/phase
No. of poles	4	N/A
No. of phases	3	3

Fig.12 to Fig.19 show experimental results obtained from the setup under different operating conditions. Fig.12 shows the speed response of the induction machine when reference speed is 1025rpm and load torque is 1Nm. It can be seen that the actual speed of the induction machine quickly settles down to the reference and tracks it precisely without any overshoots, which shows fast dynamic response of this control method. Fig.13 shows the phase current profile and the change of PWM duty cycle between D_H and D_L. The phase current is distorted with harmonics which is the main trade-off in the implementation of this control technique.

Similarly, Fig.14 and Fig.15 show results when reference speed is 366rpm and load is 1Nm. From these figures, it can be noticed that the proposed state switching control method also has a wide range of speed regulation capability.

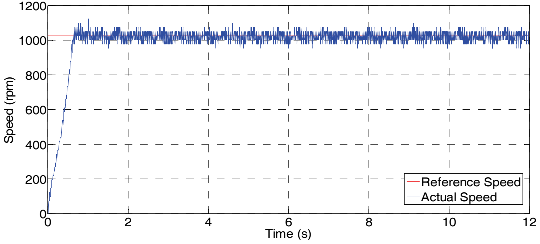

Fig.12 Speed response when reference speed is 1025rpm and load torque is 1Nm

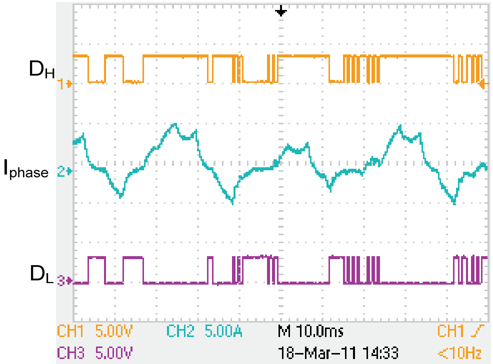

Fig.13 Phase current and change of PWM duty cycle when reference speed is 1025rpm

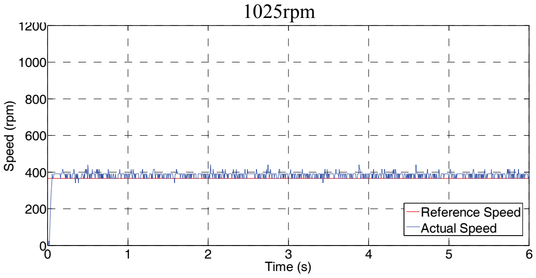

Fig.14 Speed response when reference speed is 366rpm and load torque is 1Nm

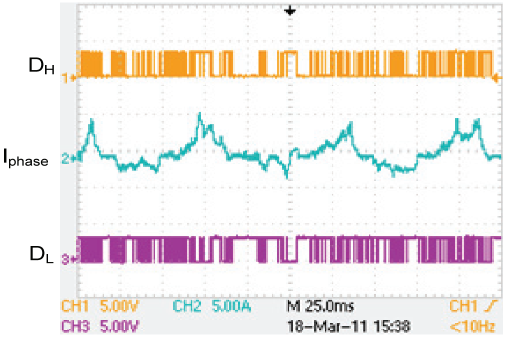

Fig.15 Phase current and change of PWM duty cycle when reference speed is 366rpm

In order to test the performance of the control strategy for sensitivity to change in operating conditions, a step change in load torque and reference speed was applied to the machine. Fig.16 shows the speed response of the induction machine when load torque was changed from 0.5Nm to 1.5Nm. Fig.17 and Fig.18 shows the phase current, change of PWM duty cycle before and after torque change respectively. Fig.19 shows the speed response of the induction machine when reference speed was changed from 1025rpm to 366rpm (load torque is 1Nm). System can responds to any change in speed command within an acceptable time period.

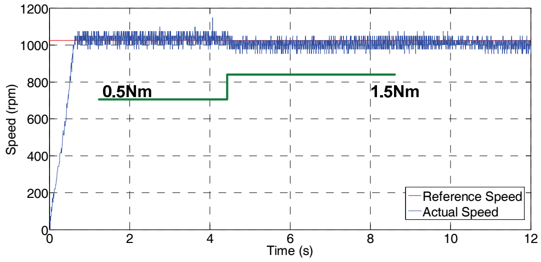

Fig. 16 Speed response when reference speed is 1025rpm and load torque changes from 0.5Nm to 1.5Nm

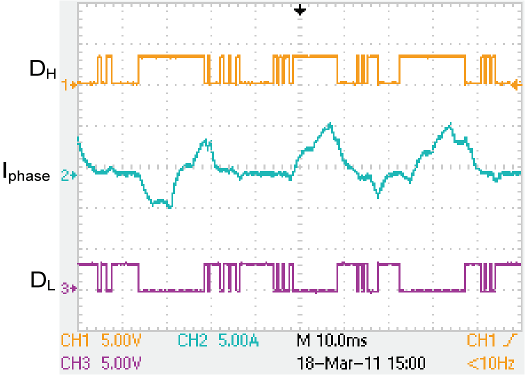

Fig. 17 Phase current and change of PWM duty cycle when load torque is 0.5Nm

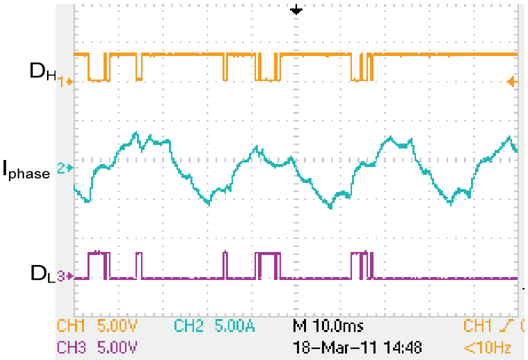

Fig.18 Phase current and change of PWM duty cycle when load torque is 1.5Nm

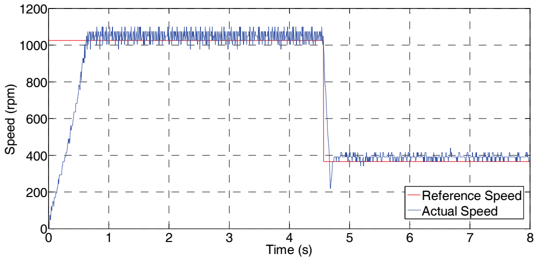

Fig.19 Speed response when reference speed changes from 1025rpm to 366rpm

VI. CONCLUSIONS

This paper presents a simple, low-cost and effective state switching control technique which has wide speed regulation capability and can be used as backup control strategy in the event of sensor failure. This method is based on PWM six-step drive method, in which two different PWM duty cycles are predefined. At the same time, the frequency of the phase voltage is directly derived from the reference speed. By switching between two PWM duty cycles, the shaft speed of the induction machine can be accurately regulated. Owing to its simplicity, this strategy can be implemented on device with low computational capability and therefore requires no additional hardware. In addition, only speed feedback is necessary for this method, which significantly enhances the reliability of the system with highly acceptable performance. Simulation and experiment results presented in this paper demonstrate feasibility of the proposed approach.

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