A Simplified State Switching Control Strategy for Survivable Variable-Speed Induction Generators

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***Abstract*-Induction machines are one of the most widely used electric machines in wind power applications. However, the control of an induction generator is complicated if advanced control strategy is employed in order to maximize the performance. Also, the complexity of advanced control strategies and their high demand on hardware and sensors can lower the overall reliability of the generator system and potentially result in system malfunction, leading to unscheduled maintenance and power yield reduction. In this paper, an effective, yet simple and low-cost state switching control technique is proposed and implemented as a backup control strategy in case of control or sensor failure. This state switching control system is only allowed to operate at two different duty cycles of PWM which produces phase voltages with different magnitudes. At the same time, the frequency of the phase voltages is derived from the reference speed. By switching between these two states, precise speed regulation can be achieved. Owing to its simplicity, the control strategy can be implemented on a low cost FPGA or embedded into existing controllers for use as a backup strategy. In addition since it does not require the use of current sensors, it is very suitable for survivable operation. Simulation and experimental results are included to validate our claims.**

Keywords: Induction Generator (IG), State Switching Control, Pulse Width Modulation (PWM)

I. INTRODUCTION

Due to robustness, simple construction and low cost, induction machines (IM) have been prime candidates for a variety of generator applications. With increasing popularity of wind energy in recent years [1], [2], induction generators (IG) have become one of the most common generators used in wind turbines. Squirrel cage induction machines are often utilized for low power-level wind turbines. For medium and high power-level wind applications, wound rotor induction machines (or Double Fed Induction Machine) are often employed. In addition to wind generators, induction machines have also been a popular choice in hydropower and hybrid electric and electric vehicle applications.

In order to obtain the maximum power output from the induction generator, many sophisticated control methods have been proposed to control it in variable-speed operation mode. Among these methods, Vector Control and Direct Torque Control (DTC control) are the most widespread control strategies. Vector control [3]-[5] has gained popularity over the last three decades due to its high efficiency and superior transient performance. It is also one of the most efficient and promising control strategies for induction machine. However, the implementation of vector control is complicated and expensive. It not only requires fast processing devices to meet its large computational requirements and perform accurate identification of machine parameters, but also needs multiple sensors to provide necessary feedback information including phase currents and rotor position. DTC control [6], [7] is simpler than vector control due to the absence of PI controller, coordinate transformations and current regulators. However, similar drawbacks also exist in hardware requirement and implementation. Failure of current sensor or even the drift of system parameters may result in system malfunction. Therefore, while vector control and DTC control are efficient control strategies, they are not usually most reliable. The complex control strategy and the requirement of additional devices reduce reliability of the system and increase its cost. This makes it necessary to implement a simple, cost-effective and reliable control strategy as a backup control strategy to make the system fault tolerant.

In recent years, digital control has been proposed in literature [8]-[11]. This control method is extremely simple and effective for many applications, such as BLDC control and DC-DC converter control. In this method, two different states (state “High” and state “Low”) are predefined, these states can be voltage, current and PWM duty cycle. Then, state is switched between these two values by comparing the actual output value with the reference. This allows the machine to be treated as a digital system and the system output can be well regulated. Therefore, there is no need for major computation controllers or even PI controllers. Reduction of feedback sensors also improves reliability of this method.

In this paper, an effective, yet simple and low-cost State Switching Control technique is proposed and implemented for a three phase induction generator system. This control method is based on the principle of digital control specifically designed for an induction machine. By applying state switching control, two specific PWM duty cycles are applied to the converter and produce excitation phase voltages with different magnitudes. Speed regulation is achieved by switching between these two different PWM duty cycles with the frequency of the excitation phase voltage directly derived 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

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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.

II. Fundamentals Of Induction Generator

In order to operate the induction machine in generating mode, reactive power is needed for the excitation of its magnetic field. There are two excitation methods which are often used to initially start the induction generator, self-excitation and source excitation. Self excitation [12] is often utilized by standalone induction generators with their output connected with capacitors in parallel. Due to the residual magnetism on the rotor, the rotation of the rotor gradually builds up a terminal voltage on the stator winding. However, in this method, the output voltage and frequency is a complex function of several parameters, which makes it challenging to be controlled if the shaft speed changes. Source excitation method is often used when induction generator is connected to the grid or other power sources. In this case, magnetizing current is drawn from the source and therefore the phase voltage and frequency can be controlled.

For a three phase induction machine, the most frequently used active converter topology for source excited induction generator is illustrated in Fig.1. This converter includes six switches (MOSFETs or IGBTs) and six anti-parallel diodes. By applying specific switching signals to these switches, the magnitude and the frequency of the phase voltage can be fully controlled.

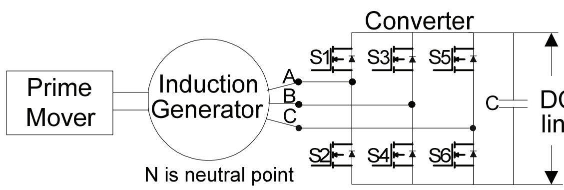

Fig.1. Active converter for source excited induction generator

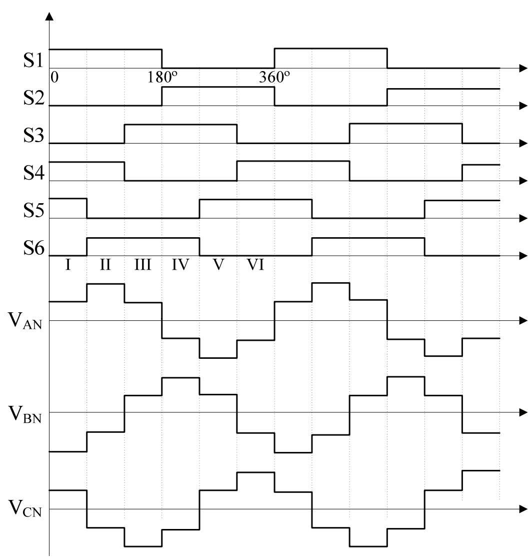

Fig.2. Six-Step waveform

Six-step method [13] is one of the simplest methods to excite the induction generator. Gate signals for the converter are shown in Fig.2. In every electrical cycle, a switch is turned on for 180 electrical degrees and only three switches are turned on for every 60 electrical degrees. For a wye-connected three phase induction machine, three six-stepped and quasi-sine phase voltages can be formed in the stator winding as illustrated in Fig.2. Therefore, by applying these gate signals to the converter with proper frequency, the induction generator can be controlled.

III. Proposed State Switching Control Method For Induction Generator

A. Principle of State Switching Control of Induction Generator

It is well known that by applying phase voltages with proper magnitude and frequency to the stator windings, an IM can be operated in motoring mode when its shaft speed is lower than synchronous speed. Under this condition, if a negative torque from the prime mover is applied to the shaft of the induction machine, the shaft speed increases to super-synchronous speed, which enables the induction machine to work as a generator. Therefore, if the torque of the prime mover is constant, speed regulation of the induction generator mainly involves two parameters--the magnitude and the 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.

If the frequency of the phase voltage is defined, the synchronous speed is set according to equation (1). By changing the frequency of the phase voltage, the synchronous speed can be changed. At the same time, the variation of synchronous speed causes a change of the shaft speed since shaft speed is a slightly higher than the synchronous speed at steady-state in generating mode. Therefore, the shaft speed can be determined mainly by the frequency of the phase voltage. Additionally, if the reference speed of the shaft is defined, frequency of phase voltages that should be applied to the induction generator can be calculated using equations (1) and (2).

The magnitude of applied phase voltage is a factor which can also affect the shaft speed of IM in generating mode. This relationship is shown in Fig.3. If magnitude of the applied phase voltages is increased (V1>V2), electromagnetic torque of the IG (opposing the prime mover torque) increases as well. As a result, shaft speed decreases slightly ($\omega 1<\omega 2$), but the synchronous speed remains the same.

Based on the above analysis as well as the six-step method, a state switching control technique can be designed and expressed in Fig.4. According to the reference speed (ω_{ref}), the applied phase voltage frequency can be calculated using equation (1) and (2) with a constant slip (5% in our case). By applying this frequency to the induction machine, the shaft speed will settle down to a value 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). This allows the actual speed (ω_{act}) of the IG to be precisely regulated.

The magnitude of applied phase voltages can be changed by PWM-integrated six-step excitation method. As shown in Fig. 5, compared to traditional six-step method which is shown in Fig.2, switches are given PWM signals instead of turning them "ON" all the time for 60 electrical degrees. Therefore, by changing the duty cycle of the PWMs, the magnitude of the phase voltages can be changed. As a result, the operating principle of state switching control of an IG is shown in Fig. 6.

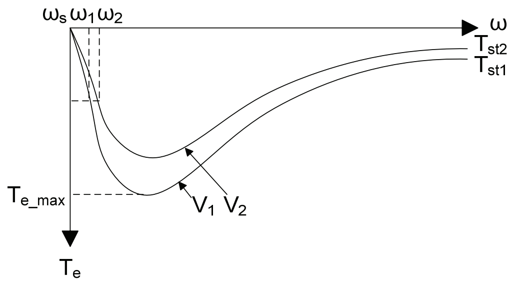

Fig.3 Speed torque characteristics of IG at different voltage level

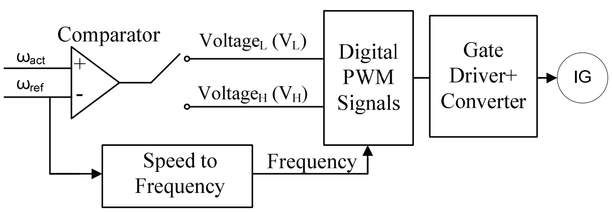

Fig.4 Principle of state switching control of induction generator

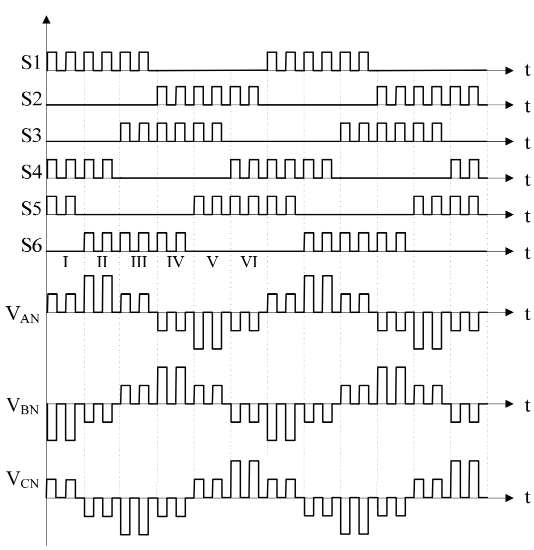

Fig.5 PWM-integrated six-step waveform

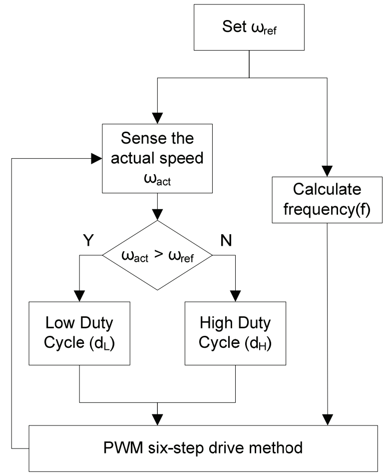

Fig.6 Principle of state switching control of induction generator

B. Controller Design of State Switching Control of IG

From the generator torque equation, we have

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

Where T_e 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

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

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

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

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

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

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

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

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

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

Meanwhile, the frequency of the applied voltage can be calculated using equation (10) which is derived from equation (1) and (2). A constant slip of 5% is considered in all simulations and experiments.

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

IV. SIMULATION RESULTS

In order to verify the feasibility of the proposed state switching control of induction generator, the control strategy was implemented in Matlab/Simulink. The block diagram of the proposed state switching control of induction generator in simulation is shown in Fig.7, in which a 60Hz, 4 pole induction machine is used with the rated speed is 1725rpm. Two PWM duty cycles are defined at 30% and 90%.

Simulation results are shown in figures 8 to 10. Fig.8 shows the speed response of the IG controlled by the proposed state switching technique. It can be observed that transients quickly settle down and the reference speed is precisely tracked. Fig.9 shows the steady-state speed error between reference speed, actual speed and the corresponding duty cycle adjustment. Fig.10 shows the DC-link current flowing into the power source. The average DC-link current is positive, which indicates that the induction machine is working in generating mode and supplying power to the source.

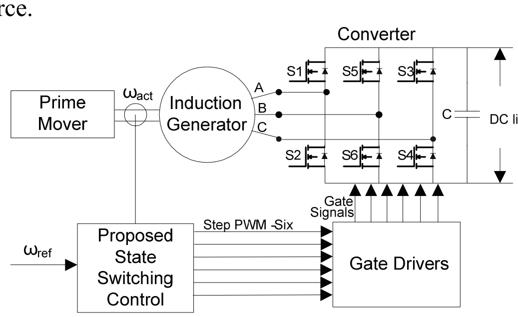

Fig.7 Block diagram of the proposed state switching control of IG

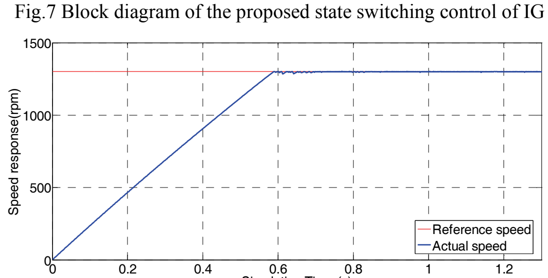

Fig.8 Speed response of the state switching control of induction generator

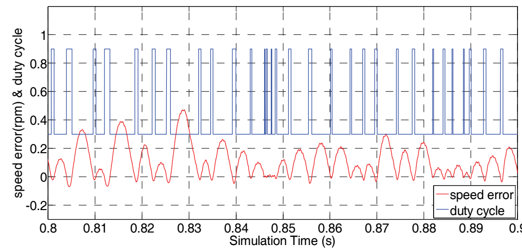

Fig.9 Steady state error and change of duty cycle

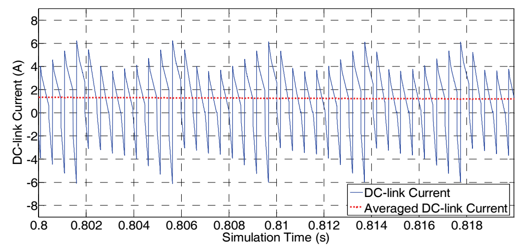

Fig.10 DC-link current flowing into the source

V. EXPERIMENTAL VERIFICATION

In order to verify the effectiveness of the proposed state switching control method for induction generator, an experimental setup has been developed as shown in Fig.11. It includes a 3.9kW DC power source connected to a 2.2kW induction machine, a 3kW permanent magnet DC programmable dynamometer used as a prime mover, a TMS320F2812 based DSP controller, three phase converter and gate drivers, speed sensor, and a dump resistor. Specifications regarding the induction machine and the PM DC machine are listed in Table I.

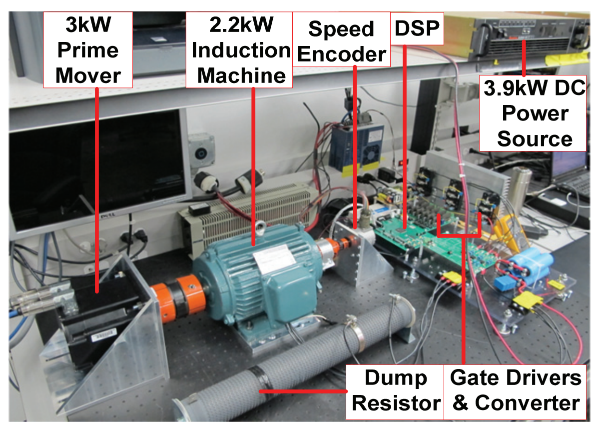

Fig.11 Hardware setup for experimental verification of proposed state switching control strategy of an Induction Generator

TABLE I
PROPERTY OF THE INDUCTION GENERATOR 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

Figures 12 to 20 show experimental results obtained from the setup under different operating conditions. Fig.12 shows the speed response of the induction generator when reference speed is set to 1025rpm and the torque of prime mover is 1Nm. Since the prime mover is turned on before starting the induction generator, initial speed at startup increases to 1500rpm. Once the induction generator is started and state switching control is applied, speed quickly settles down to the reference speed with a steady state error lower than 7%. Fig.13 shows the generated DC link voltage and DC link current flowing into the dump resistor and the change of duty cycle between D_H and D_L. It is clear that the average DC link current is positive which confirms the operation of the IM in generating mode. Fig.14 shows the steady state phase current as well as the change of duty cycle. It can be observed that the phase current has significant harmonics which is the main trade-off in the implementation of this control technique.

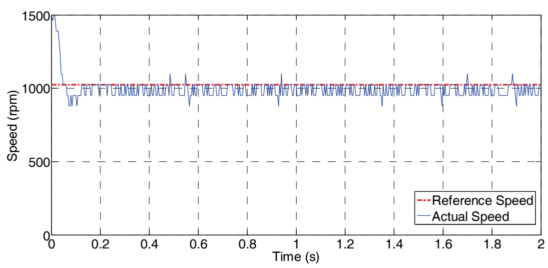

Fig.12 Speed response when reference speed is 1025 rpm

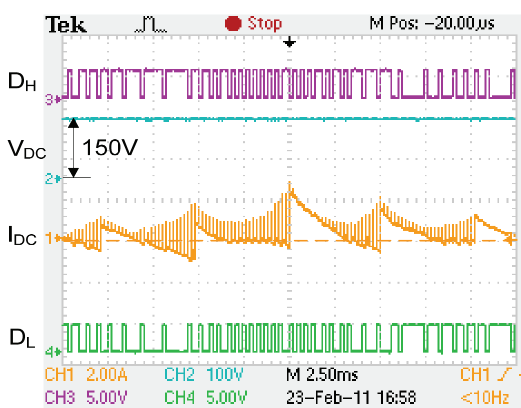

Fig.13 DC link voltage, current and change of duty cycle

Figures 15 to 17 show results when the reference speed is 586rpm and the prime mover torque is 1Nm. Fig.15 shows the speed response of the induction generator. The initial speed is 1150rpm before exciting the induction generator. After the induction generator is excited, shaft speed quickly goes down and tracks the reference speed. Fig.16 shows the DC link voltage and DC link current flowing into the dump resistor and the change of duty cycle. Fig.17 shows the steady state phase current and the change of duty cycle. From these figures, it can be noticed that the proposed state switching control method also has a good speed tracking performance at relatively low speeds.

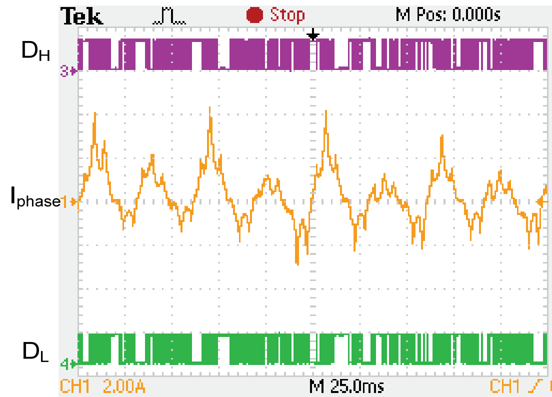

Fig.14 Phase current and change of duty cycle

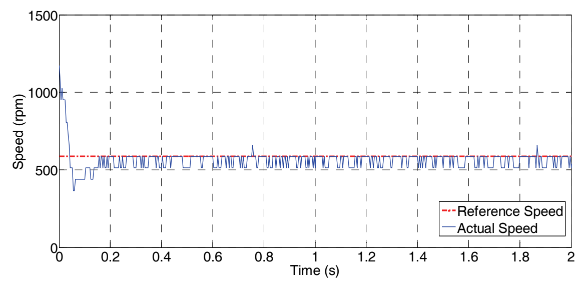

Fig.15 Speed response when reference speed is 586rpm

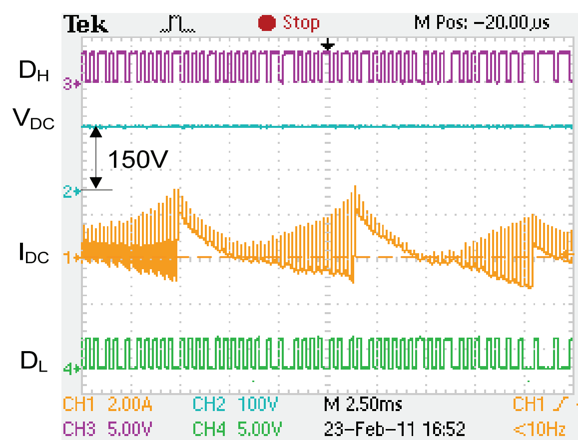

Fig.16 DC link voltage, current and change of duty cycle

The generated DC link voltage and current for a step change in torque from 1Nm to 2Nm from the prime mover are shown in Fig.19. It is clear that when the prime mover torque becomes larger, more power is generated and transmitted to the dump resistor. In addition, a step change of reference speed is also applied to the machine. Fig.20 shows the speed response of the induction generator when reference speed changes from 1025rpm to 586rpm. The actual speed again can track the reference speed precisely.

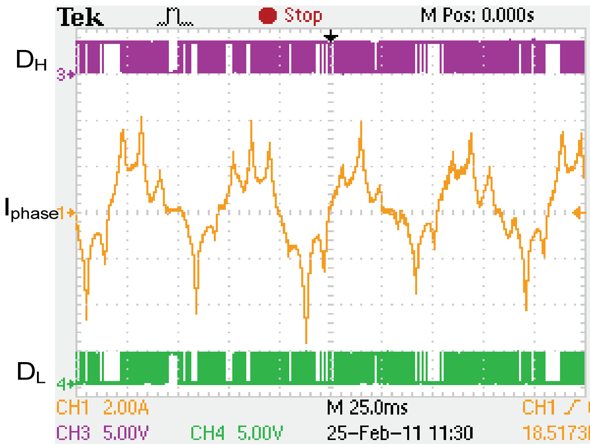

Fig.17 Phase current and change of duty cycle

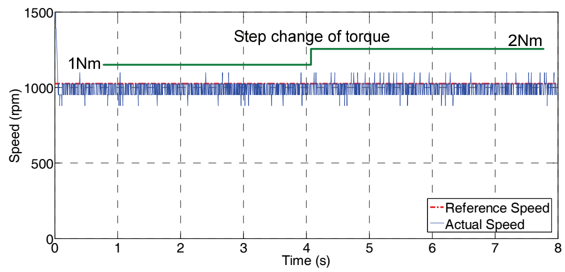

Fig.18 Speed response under step change of prime mover torque

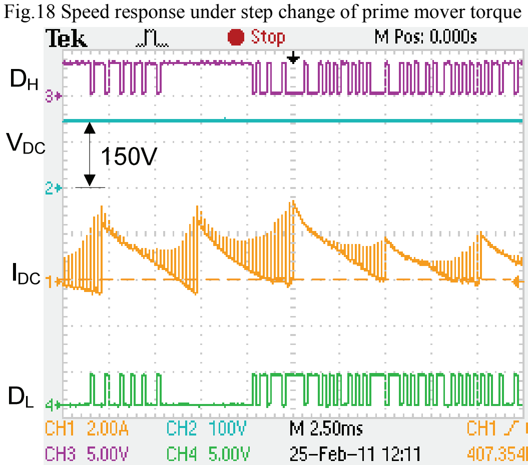

Fig.19 DC link voltage, current and change of duty cycle at 2Nm

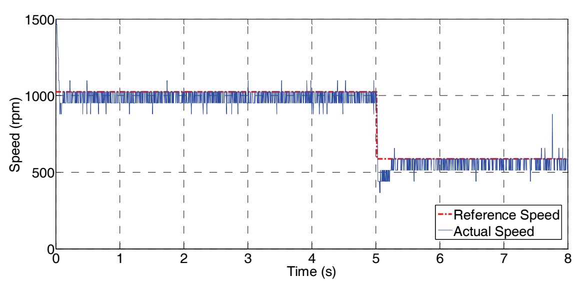

Fig.20 Speed response under step change of reference speed

From the results obtained, it can be seen that the speed ripple was found in an acceptable range under different conditions. This shows the effectiveness of the control scheme.

VI. Conclusion

This paper presents a simple, low-cost and effective state switching control technique for the speed regulation of the induction generator. Owing to its simplicity, this method can significantly enhance the reliability of the drive system with highly acceptable speed tracking performance. It does not need any current sensors and requires very little computational capacity. This enables implementation of the control strategy on a low-cost FPGA. Therefore, this technique can be used as a backup control strategy for induction generators in the event of failure of sensors used in or advanced control methods. Challenges of this control method are the distortion of phase currents and the torque ripple. But as a backup control strategy, this method is very effective and shows acceptable performance. Simulation and experiment results verify the feasibility of the proposed approach.

Acknowledgement

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