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# A high performance svm-dtc scheme for induction machine as integrated starter generator in hybrid electric vehicles

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**Abstract**

The control of induction machine as integrated starter generator forms an interesting academic and practical solution for future 42V PowerNet in hybrid electric vehicles. In this paper, an alternative control method is proposed for induction machine, which enjoys the advantages of stator vector control and direct torque control and avoids some implementation difficulties of either of the two control methods. To obtain a fixed switching frequency and low torque ripple, the proportional–integral controllers and space vector modulation technique are used. Furthermore, by controlling the machine's torque, the required DC-bus voltage can be regulated within the 42V PowerNet specifications.

*Keywords:* Induction machine ; direct torque and flux control ; vector control ; integrated starter generator (ISG) ; space vector modulation (SVPWM) ; 42V PowerNet

## 1. Introduction

In recent years, integrated starter generator (ISG) has attracted significant research interest in order to provide greater electrical generation capability and to improve the fuel economy and emissions of modern hybrid electric vehicles. This innovated machine has been proposed as solution to implement the new PowerNet architecture in vehicles, an increase of the electrical bus voltage from 14V to 42V [1-3], to cope with the increasing electric power demand. The ISG system combines both starter and generator functions in a single electric machine, instead of having two separate machines, as is the case in conventional vehicles [4]. In this context, the machine selection and design are being investigated intensively to meet the challenges of the 42V PowerNet [5-7]. The machine designed for an ISG should be capable of providing a high starting torque to crank the engine in short starting time. After the engine is started above the idle speed, the ISG machine operates in generation state to supply a constant voltage for charging the battery of automobile.

Also, the machine controller is one of the most important aspects of any vehicular drive system including the ISG. Therefore, rotor field oriented control (RFOC) of AC machines appears to have drawn much interest, and it was natural to extend to the ISG application [8-13]. However, RFOC has several disadvantages such as high computational requirement, high parameter dependence and speed signal for the coordinate transformation. Also, the direct torque control (DTC) technique has gained wide acceptance in motor drive [14,15], and has been considered for the ISG application [16]. Although the DTC is a simple control scheme with low computational requirement and has merits like inherent sensorless operation and reduced parameter sensitivity, it has some drawbacks such as operation with variable switching frequency and large torque ripple, due to the hysteresis control and the switching table method [17,18]. To overcome these problems, the variable switching frequency problem and the torque ripple can be addressed by Proportional-Integral (PI) controllers plus space vector modulation (SVM) [19-23]. Those reported works was extended to an ISG system [24,25]. However, the calculation of the voltage command vector requires the derivative of the stator flux vector, which is kept moving and can be a potential source of errors.

This paper presents an alternative scheme for torque and stator flux control of an induction machine for ISG application. The proposed scheme investigates the basic DTC idea, which considers the torque of induction machine proportional with the slip frequency if the amplitude of stator flux vector is kept constant. For that, stator vector control (SVC) is used to avoid the requirement of the derivative of stator flux vector and to develop the relationships between the controlled variables and the machine torque. Hence, with the combined SVC and DTC methods, the torque and stator flux vector can be regulated with PI controllers, and the required voltage vector can be applied to the induction machine by the space vector modulation (SVM). The estimation of the torque and stator flux is based on voltage mode estimator with minimized sensors numbers. In fact, speed sensor is eliminated and only DC-bus voltage sensor and two AC current sensors are needed. As the torque of induction machine is controlled, the DC-bus voltage can be regulated to meet the specification of the 42V hybrid electric vehicle.

This paper is organised as follows: the proposed torque and stator flux control principle is detailed and developed in Section 2. The ISG based induction machine control is described in Section 3. The effectiveness of the approach is examined in Section 4 using computer simulation experiments. Finally, the conclusion is drawn in Section 5.

## 2. The proposed direct torque and flux control

The dynamic model of the induction machine can be represented in the (d,q) frame as:

$$\begin{aligned} v_{ds} &= R_s i_{ds} + \frac{d\Phi_{ds}}{dt} - \omega_s \Phi_{qs} \\ v_{qs} &= R_s i_{qs} + \frac{d\Phi_{qs}}{dt} + \omega_s \Phi_{ds} \end{aligned} \quad (1)$$

$$\begin{aligned} 0 &= R_r i_{dr} + \frac{d\Phi_{dr}}{dt} - \omega_{sl} \Phi_{qr} \\ 0 &= R_r i_{qr} + \frac{d\Phi_{qr}}{dt} + \omega_{sl} \Phi_{dr} \end{aligned} \quad (2)$$

$$\begin{aligned} \Phi_{ds} &= L_s i_{ds} + L_{sr} i_{dr} \\ \Phi_{qs} &= L_s i_{qs} + L_{sr} i_{qr} \end{aligned} \quad (3)$$

$$\begin{aligned} \Phi_{dr} &= L_r i_{dr} + L_{sr} i_{ds} \\ \Phi_{qr} &= L_r i_{qr} + L_{sr} i_{qs} \end{aligned} \quad (4)$$

$$T_{em} = p\left(\Phi_{ds} i_{qs} - \Phi_{qs} i_{ds}\right) \quad (5)$$

In which the known entities are: the stator currents ($i_{ds}$,$i_{qs}$) and the input voltages ($v_{ds}$,$v_{qs}$). The unknown, who need to be estimated, are: the stator fluxes ($\Phi_{ds}$,$\Phi_{qs}$) and the rotor fluxes ($\Phi_{dr}$,$\Phi_{qr}$), the electromagnetic torque $T_{em}$ and the slip angular speed $\omega_{sl} = \omega_s - \omega_m$, in which $\omega_s$ and $\omega_m$ are the synchronous and rotor angular speed respectively. ($i_{dr}$,$i_{qr}$) are the rotor currents. $R_s$, $R_r$ are the stator and rotor resistances, $L_s$, $L_r$ are the stator and rotor inductances, $L_{sr}$ is the mutual inductance, and $p$ is the number of pole pairs.

### *2.1. Stator flux control*

The stator field-orientation method is based on the alignment of stator flux vector with $d$-axis and setting the stator flux to be constant equal to its rated value, which means:

$$\Phi_{ds} = \Phi_s ; \Phi_{qs} = 0 \quad (6)$$

Then, (1) and (5) can be simplified to:

$$\begin{aligned} v_{ds} &= R_s i_{ds} + \frac{d\Phi_s}{dt} \\ v_{qs} &= R_s i_{qs} + \omega_s \Phi_s \end{aligned} \quad (7)$$

$$T_{em} = p\Phi_s i_{qs} \quad (8)$$

Next, the rotor currents and rotor fluxes can be expressed as:

$$\begin{aligned} i_{dr} &= \frac{1}{L_{sr}}\left(\Phi_s - L_s i_{ds}\right) \\ i_{qr} &= -\frac{L_s}{L_{sr}} i_{qs} \end{aligned} \quad (9)$$

$$\begin{aligned} \Phi_{dr} &= \frac{L_r}{L_{sr}}\left(\Phi_s - \sigma L_s i_{ds}\right) \\ \Phi_{qr} &= -\frac{\sigma L_r L_s}{L_{sr}} i_{qs} \end{aligned} \quad (10)$$

Therefore, by substituting (9) and (10) in (2) and considering the Laplace operator (s = d/dt), (11) can be obtained:

$$\begin{aligned} \Phi_s(s) &= \left(\left(1+\sigma T_r s\right) I_{ds} + \sigma T_r I_{qs} \omega_{sl}\right) \frac{L_s}{1+T_r s} \\ I_{qs}(s) &= \left(\frac{1}{L_s}\Phi_s - \sigma I_{ds}\right) \frac{T_r \omega_{sl}}{1+\sigma T_r s} \end{aligned} \quad (11)$$

Thus, the stator voltages become:

$$\begin{aligned} V_{ds}(s) &= \frac{1+\left(T_r+T_s\right)s+\sigma T_r T_s s^2}{T_s\left(1+\sigma T_r s\right)} \Phi_s - \frac{\sigma R_s T_r}{1+\sigma T_r s} I_{qs} \omega_{sl} \\ V_{qs}(s) &= R_s I_{qs} + \omega_s \Phi_s \approx \omega_s \Phi_s \end{aligned} \quad (12)$$

in which $T_s = L_s / R_s$ and $T_r = L_r / R_r$ are the stator and rotor time constants, and $\sigma = 1 - L_{sr}^2 / \left(L_s L_r\right)$ is the total leakage constant.

From (12), it can be seen that the stator flux can be regulated by the *d*–component of stator voltage. Fig. 1 shows the relationship between $\Phi_s$ and $V_{ds}$; a second-order equivalent system with a disturbance $E_d$.

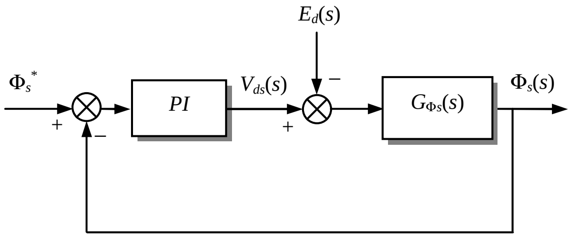


Fig. 1. Closed-loop control of stator flux.

where:

$$G_{\Phi s}(s)=\frac{T_s(1+\sigma T_r s)}{1+(T_r+T_s)s+\sigma T_r T_s s^2}$$
$$E_d(s)=-\frac{\sigma R_s T_r}{1+\sigma T_r s} I_{qs}\omega_{sl} \quad (13)$$

*2.2. Electromagnetic torque control*

From (11), the *q*-component of stator current can be expressed as:

$$I_{qs}(s)=\frac{T_r(1-\sigma)}{L_s}\frac{\Phi_s\omega_{sl}}{(1+\sigma T_r s)^2+(\sigma T_r\omega_{sl}(s))^2} \quad (14)$$

Hence, the expression (8), giving the electromagnetic torque, becomes:

$$T_{em}(s)=p\frac{T_r(1-\sigma)}{L_s}\frac{\Phi_s^2\omega_{sl}}{(1+\sigma T_r s)^2+(\sigma T_r\omega_{sl})^2} \quad (15)$$

From the basic DTC principle, if the amplitude of stator flux vector is kept constant and equal to its reference value $\Phi_s^*$, the torque of induction machine is proportional with the slip angular speed. Therefore, with the small values of the slip angular speed and $\sigma T_r << 1$, (15) can be simplified to:

$$T_{em}(s)=p\frac{T_r(1-\sigma)\Phi_s^{*2}}{L_s}\left(\frac{\omega_s-\omega_m}{1+2\sigma T_r s}\right) \quad (16)$$

Thus, the electromagnetic torque can be regulated by controlling the rotating speed of the stator flux vector. Fig. 2 shows the relationship between the machine torque $T_{em}$ and stator pulsation $\omega_s$; a first-order equivalent system with a disturbance $\omega_m$ (mechanical pulsation).

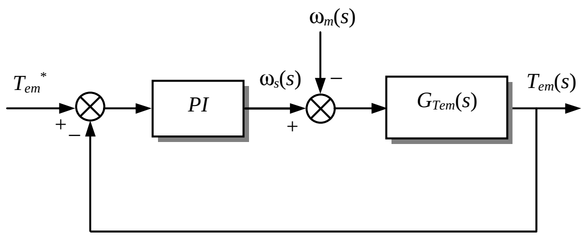


Fig. 2. Closed-loop control of electromagnetic torque.

where:

$$G_{Tem}(s)=p\frac{T_r(1-\sigma)}{L_s}\frac{\Phi_s^{*2}}{1+2\sigma T_r s} \quad (17)$$

## 3. ISG based induction machine control

The method studied previously is now used for the control of an ISG system. A complete scheme of ISG that allows torque and DC-bus voltage control has been developed, and it is shown in Fig. 3. It includes starting/generating mode state switch, which simulates the operation of ISG from starter to generator. During the starting mode, the induction machine acts as a motor to provide high torque for the starting of the engine. During the generation mode, the DC-bus voltage regulation is realised, to maintain its value as 42V, by a PI controller which generate a negative current and allows to inverse the machine torque, and the induction machine will run as a generator. Furthermore, the DC–AC converter supplies active power to the DC-load connected at the DC-side of the converter with the batteries, while the converter provides reactive power to the machine. Also, to avoid involvement of more machine parameters, the unknown variables are estimated in the $(\alpha,\beta)$ frame:

$$\Phi_{\alpha s}=\int(v_{\alpha s}-R_s i_{\alpha s})dt$$
$$\Phi_{\beta s}=\int(v_{\beta s}-R_s i_{\beta s})dt \quad (18)$$

$$\Phi_s=\sqrt{\Phi_{\alpha s}^2+\Phi_{\beta s}^2} \quad (19)$$

$$\theta_s=\arctan\left(\frac{\Phi_{\beta s}}{\Phi_{\alpha s}}\right) \quad (20)$$

$$T_{em}=p(\Phi_{\alpha s}i_{\beta s}-\Phi_{\beta s}i_{\alpha s}) \quad (21)$$

With the DC-bus voltage sensor and the actual inverter switch positions $(s_a,s_b,s_c)$, the stator voltage vector can be determined using:

$$v_{\alpha s} = \frac{V_{dc}}{\sqrt{6}}\left(2s_a - s_b - s_c\right)$$
$$v_{\beta s} = \frac{V_{dc}}{\sqrt{2}}\left(s_b - s_c\right) \qquad (22)$$

Since the controllers produce the voltage command vector, appropriate space voltage vector can be generated with SVM and fixed switching frequency can be achieved. The SVM technique is used to create a reference vector by modulating the cyclic ratios of switches in each of the six sectors shown in Fig. 4. The space voltage vector is produced by two active vectors, which limit the sector, and

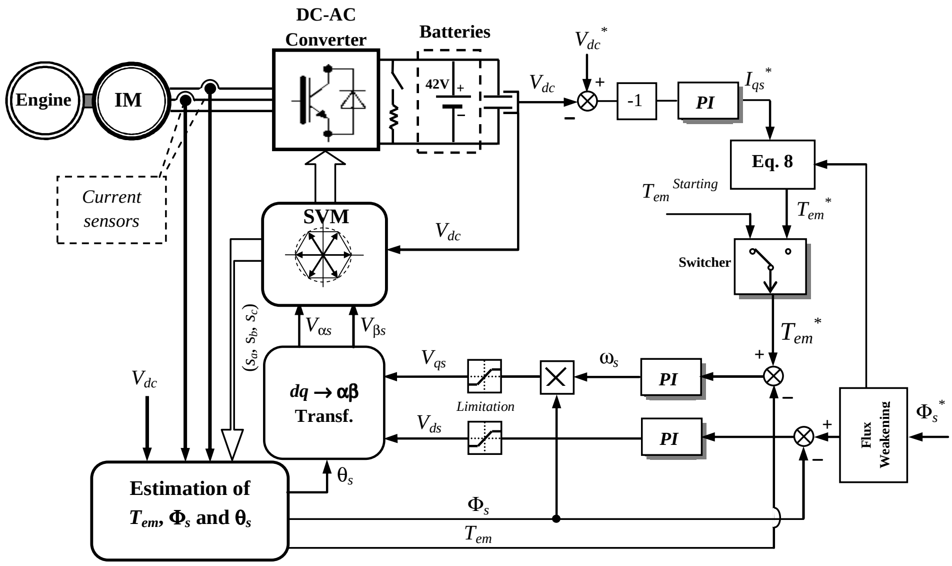


Fig. 3. Torque and flux control scheme for ISG system.

two zero vectors. For example, if the reference voltage is located between $\vec{V}_1$ and $\vec{V}_2$, it can be expressed as:

$$\vec{V}_{ref} = \frac{T_0}{T_s}\vec{V}_0 + \frac{T_1}{T_s}\vec{V}_1 + \frac{T_2}{T_s}\vec{V}_2 + \frac{T_7}{T_s}\vec{V}_7 \qquad (23)$$

where $T_0$, $T_1$, $T_2$ and $T_7$ are the time intervals of $\vec{V}_0$, $\vec{V}_1$, $\vec{V}_2$ and $\vec{V}_7$, respectively, within the sampling period $T_s$.

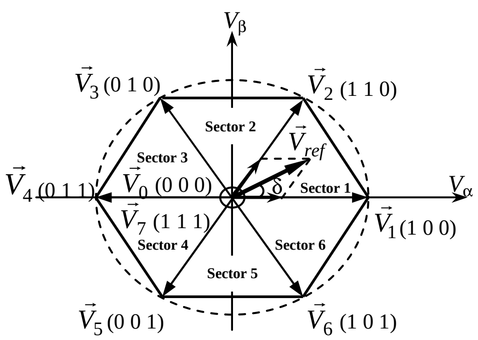


Fig. 4. Switching states of SVM

However, with the SVM method, the reference voltage should be limited to ensure that the voltage command is lower or equal to the maximum inverter voltage:

$$\left|\vec{V}_{ref}\right| \le V_{s\max} = \frac{V_{dc}}{\sqrt{3}} \qquad (24)$$

where $V_{smax}$ is the maximum available inverter voltage and $V_{dc}$ is the DC-bus voltage of the inverter.

To calculate the time intervals, it can be obtained from Fig. 4:

$$V_{ref} T_s \cos\delta = V_1 T_1 + V_2 T_2 \cos\frac{\pi}{3}$$
$$V_{ref} T_s \sin\delta = V_2 T_2 \sin\frac{\pi}{3} \qquad (25)$$

Thus, $T_1$ and $T_2$ can be expressed as:

$$T_1 = \frac{V_{ref} T_s \sin\left(\frac{\pi}{3} - \delta\right)}{V_1 \sin\frac{\pi}{3}}$$
$$T_2 = \frac{V_{ref} T_s \sin\delta}{V_2 \sin\frac{\pi}{3}} \qquad (26)$$

Hence:

$$T_0 = T_7 = \frac{T_s - T_1 - T_2}{2} \qquad (27)$$

## 4. Simulation and results

The proposed torque and flux control algorithm was simulated for the 1.1kW–50Hz–22.2V induction machine, supplied by the voltage source inverter with 42V DC-bus. The behaviour of internal combustion engine of the vehicle is simulated by employing a DC-motor drive. The engine speed is controlled after starting because the speed of the induction machine is determined by the engine. The 42V batteries are also modelled to provide a DC-voltage for starting. In order to illustrate the proposed scheme, the simulation has been carried out under the following cases: the start-up and the ISG behaviour from the motoring to generating regime, and the control at a constant and variable speed.

### *4.1. System behaviour during starting mode*

Fig. 5 shows the characteristics of the ISG at the system start-up. During this period, the starting torque is set to 6N.m and the engine is cranked by the ISG from 0 up to 500r/min. Once the speed gets 500r/min, both the engine and ISG produce accelerating torque to speed up to 1500r/min, which is the rated speed of the used induction machine. After the speed reaches 1500r/min, the DC-machine simulated engine is regulated by its own controller. At this speed level, the ISG control system changes from the motoring to generation regime instantaneously and the reference of the induction machine is switched from the torque to the output of the voltage regulator. Thus, the torque of the induction machine changes from positive to negative torque. The stator flux of the machine is kept constant with the proposed method.

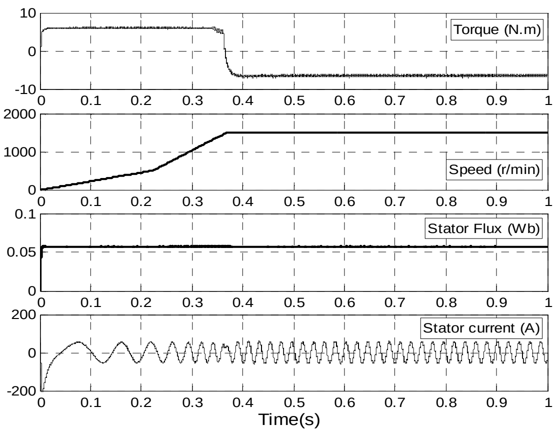


Fig. 5. ISG characteristics during starting period.

The stator current waveform in Fig. 6 demonstrates that the current ripple is very low with space vector modulation.

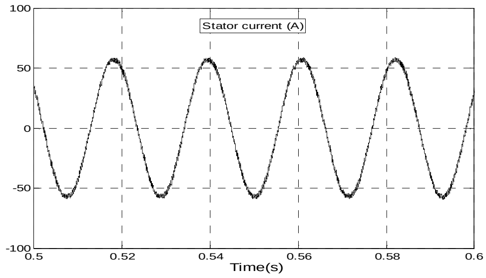


Fig. 6. Stator current waveform.

### *4.2. System behaviour during generating mode*

During the generating period, the DC-bus voltage is kept as 42V with a voltage regulator (Fig. 7). The induction machine acts as a generator and provides power to the battery and the DC-load, which can be shown for the DC-bus current waveform.

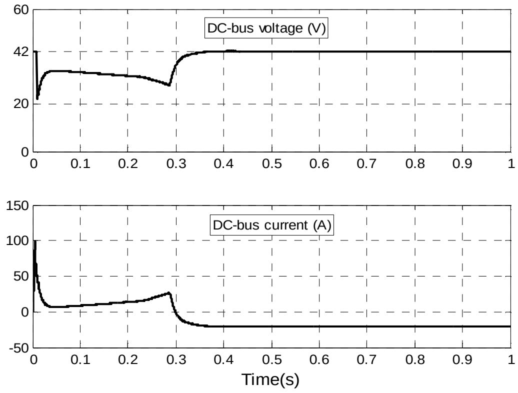


Fig. 7. DC-bus voltage and current waveforms.

The conceived system responds well also in more complex situations. The engine's speed reference is increased suddenly from 1500 to 2500r/min, as shown in Fig. 8. Also, in this condition of speed variation, the DC-bus voltage is kept constant as 42V. The induction machine's torque increase accordingly to the speed. The stator flux of the machine is weakened by the inverse proportional with the rotor speed when this one is above the base speed (1500r/min).

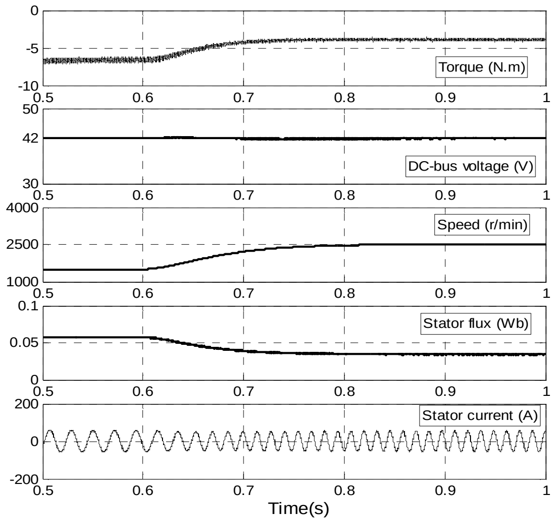

Fig. 8. System characteristics at acceleration.

The deceleration of the ISG is also tested by decreasing the engine's speed suddenly from 2500 to 1500r/min. As shown in Fig. 9, the DC-bus voltage of the ISG is kept constant as 42V. The stator flux of the machine is increased to its nominal value when the speed returns to the base speed (1500r/min).

The proposed ISG system is also tested in high-speed range. Fig. 10 shows the ISG performance at 4000r/min. Also, in this condition of speed operation, the machine's torque increase and the DC-bus voltage of the ISG is kept constant as 42V. The stator flux of the machine is weakened when the speed is above the base speed.

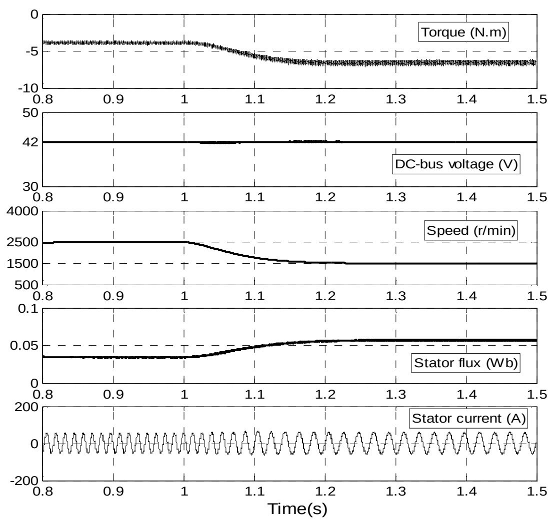

Fig. 9. System characteristics at deceleration.

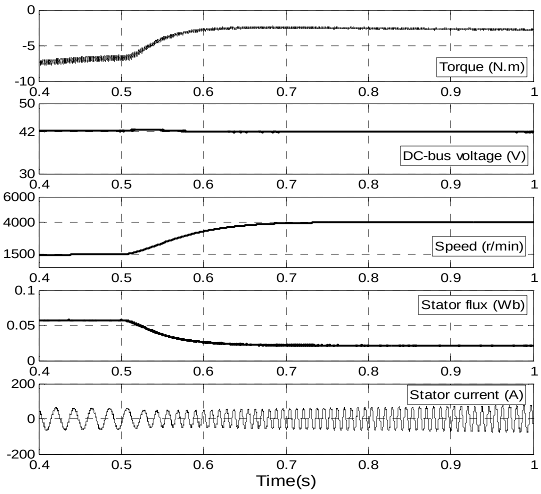

Fig. 10. System characteristics at high-speed.

## 5. Conclusion

This paper has provided a novel control scheme of the induction machine as integrated starter generator (ISG) for the future 42V hybrid electric vehicle application. The proposed control combines the basic ideas of stator vector control (SVC) and direct torque control (DTC).With SVC, the amplitude of stator flux vector is kept constant, and the relationship between the machine torque and the slip angular speed is fully developed. Thus, the electromagnetic torque can be regulated as in the case of direct torque control. Instead of the hysteresis controllers and the switching table method, PI controllers and space vector modulation are used to obtain a fixed switching frequency and low torque ripple. Also, by controlling the electromagnetic torque, the DC-bus voltage can be regulated within the 42V PowerNet specifications.

The obtained results indicate that the proposed scheme provides a practical solution for an ISG system, avoiding the drawbacks of direct torque control and rotor field oriented control schemes.

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