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Vector Control of Double Excited Synchronous Machine as Integrated Starter–Alternator

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Original scientific paper

The paper proposes a double excited synchronous machine as integrated starter–alternator for future automobiles applications. Particularly, the biaxial excitation synchronous machine (BESM) is proposed for its high efficiency and wide constant power speed range. As the integrated starter–alternator system combines both starter and generator functions in a single electric machine, an alternative vector control strategy for BESM is developed and detailed to allow operation in the two modes at unity power factor operation by setting d-axis current to be zero and q-axis current to be constant and equal to its value that cancel the q-axis flux. In such conditions, the BESM torque can be controlled by the dc-excitation current and the required dc-bus voltage can be regulated within the 42V PowerNet specifications. To overcome the slowness dc-excitation current response, which is due to higher dc-field excitation time constant, and to increase the torque response quickness, the control of the magnetising current is proposed instead of the d-axis current. Implementation and simulation results validate the proposed scheme and provide a practical solution for an integrated starter–alternator.

Key words: Biaxial excitation synchronous machine, Vector control, Integrated starter–alternator, 42V PowerNet

Vektorsko upravljanje dvostruko pobuđenim sinkronim strojem kao integriranim starterom-alternatorom. U radu je predložena upotreba dvostruko pobuđenog sinkronog stroja kao integriranog startera-alternatora, za buduće primjene u automobilskoj industriji. Preciznije, predložena je upotreba biaksijalno pobuđenog sinkronog stroja (BESM) zbog visoke korisnosti i širokog raspona područja konstantne snage. Kao integrirani starter-alternator, sustav kombinira funkcije i startera i generatora u jednom električnom stroju. Razvijen je i detaljno opisan alternativni pristup vektorskom upravljanju BESM-om za omogućavanje rada u dva moda uz jedinični faktor snage postavljanjem d-osi struje u nulu i q-osi struje na konstantnu vrijednost koja poništava tok u q-osi. U ovakvim uvjetima, BESM momentom moguće je upravljati istosmjernom uzbudnom strujom i traženi napon dc-sabirnice moguće je regulirati unutar 42V PowerNet specifikacija. Za prevladavanje sporog odziva na istosmjernu uzbudnu struju koji nastaje zbog veće vremenske konstante magnetskog polja uzbude, a s ciljem ubrzanja odziva momenta, predloženo je upravljanje strujom magnetizacije umjesto strujom u d-osi. Implementacijski i simulacijski rezultati potvrđuju predloženi pristup i pružaju praktično rješenje za integrirani starter-alternator.

Ključne riječi: Biaksijalno pobuđeni sinkroni stroj, vektorsko upravljanje, integrirani starter-alternator, 42V PowerNet

1 INTRODUCTION

Recently, integrated starter–alternator (ISA) 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 (HEVs). The ISA 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 [1-4]. This innovative solution has been proposed as solution to implement the new PowerNet architecture in vehicles, an increase of the electrical bus voltage from 14V to 42V [5-7], and to replace the conventional Lundell alternator which is not able to meet the requirements of high power and voltage transients. In this context, the machine selection and design are being investigated intensively. The machine designed for an ISA 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 ISA machine operates in generation state to supply a constant voltage for charging the battery of vehicle. To meet the aforementioned conditions, various machines have been proposed for ISA application [8-13].

However, with the review of electrical machine technologies including induction machines (IMs), surface and interior permanent magnet synchronous machines (SPMSMs and IPMSMs), switched reluctance machines (SRMs) and reluctance brushless machines (RMs), it was established that hybrid machine topologies are particularly attractive in HEV applications, in terms of torque and power density, operating speed range, over load capability and efficiency [12,13]. Among them, the double excited synchronous machines have been proposed. The double excitation refers to the fact that in the excitation circuit there is the permanent magnets as the main component of the flux source and an auxiliary excitation winding, which may be either in series [14] or in parallel [15]. Also, they can be classified according to the auxiliary winding location and rotor design [14-19]. In our case, the attention was concentrated on the biaxial excitation synchronous machine (BESM) [16,17], which has a standard stator with three phase winding and a salient-pole excited heteropolar rotor with multiple flux barriers filled with permanent magnets. The dc-excitation winding produce the main electromagnetic field in the machine, and the permanent magnets produce a field which is meant to fully cancel the armature reaction field at peak torque. Consequently, the selected machine combines two abilities: the wide constant power speed range of an IPMSM and the lower peak stator current for peak stall torque of a claw-pole machine.

In addition to the machine selection, the control strategy is one of the most important aspects of any vehicular drive system including the ISA. Therefore, field oriented control (FOC) and direct torque control (DTC) of AC machines appears to have drawn much interest, and it was natural to extend to the ISA application. However, it was developed less for BESM. Both FOC and DTC have been proposed for double excited synchronous machine [20], but for motoring mode only. FOC technique has been applied for biaxial excitation generator for automobile, and tested in motoring and generating modes of operation [21-23], but not for an ISA system, and their proposed current referencer is based on the torque/speed characteristic, derived from finite element analysis, which depends on the studied machine and cannot be carried out online for real time control.

The main objective of this paper is the vector control of a BESM for ISA application. With the proposed scheme, the machine torque is controlled by the dc-field current when the q-axis stator current is kept constant. To overcome the slowness dc-excitation current response, which is due to higher dc-field excitation time constant, and to increase the torque response quickness, the control of the magnetising current is proposed, instead of controlling the d-axis current as proposed in [21-23] with non-zero reference during transients and which leads to a coupling of the axes. Also, unity power factor operation strategy is proposed, based on the setting of the d-axis stator current as zero and the q-axis stator current as equal to its value that cancel the q-axis stator flux. For high speed operation, the field flux is weakened by the inverse proportional with the rotor speed when this one is above the base speed. Furthermore, by controlling the dc-excitation current, the dc-bus voltage of the battery can be regulated to meet the specification of the 42V hybrid electric vehicle.

The paper is organised as follows: in section 2, the dynamic model of the BESM is detailed and the proposed vector control strategy is developed. The ISA based BESM control during unity power factor operation is described in Section 3. The effectiveness of the proposed approach is examined in Section 4.

2 PROPOSED BESM VECTOR CONTROL

2.1 BESM dynamic model

The dynamic model of a biaxial excitation synchronous machine (BESM) can be expressed in the rotor (d, q) reference frame as:

$$\left\{\begin{array}{l} v_d = R_s i_d + \frac{d\Psi_d}{dt} - p\Omega\Psi_q \\ v_q = R_s i_q + \frac{d\Psi_q}{dt} + p\Omega\Psi_d \\ v_f = R_f i_f + \frac{d\Psi_f}{dt} \end{array}\right. , \tag{1}$$

$$\left\{\begin{array}{l} \Psi_d = L_d i_d + L_{sf} i_f \\ \Psi_q = L_q i_q - \Phi_{PM} \\ \Psi_f = L_f i_f + L_{sf} i_d \end{array}\right. , \tag{2}$$

$$\begin{aligned} T_{em} &= p\left(\Psi_d i_q - \Psi_q i_d\right) \\ &= p\left(L_{sf} i_q i_f + \left(L_d - L_q\right) i_d i_q + \Phi_{PM} i_d\right), \end{aligned} \tag{3}$$

where v_d and v_q are the d-q-axes stator voltages, i_d and i_q are the d-q-axes stator currents, v_f and i_f are the field winding voltage and current, (Ψ_d, Ψ_q) are the stator fluxes, Ψ_f is the field flux, Φ_{PM} is the PMs flux, T_{em} is the electromagnetic torque, Ω is the mechanical speed. R_s, L_d and L_q are the stator resistance and d-q-axes inductances respectively, R_f and L_f are the field winding resistance and inductance, L_{sf} is the mutual stator-field inductance and p is the number of pole pairs.

From d-axis stator voltage equation, let us define the variable e_μ as:

$$\begin{array}{rcl} e_\mu & = & v_d - R_s i_d + p\Omega\left(L_q i_q - \Phi_{PM}\right) \\ & = & L_d \frac{d}{dt}\left(i_d + \frac{L_{sf}}{L_d} i_f\right). \end{array} \tag{4}$$

Thus, the magnetising current can be expressed as:

$$\frac{di_\mu}{dt} = \frac{d}{dt}\left(i_d + \frac{L_{sf}}{L_d} i_f\right) = \frac{1}{L_d} e_\mu. \tag{5}$$

Hence, according to (1)–(5) and considering currents as state variables, the state equations of BESM can be expressed as:

$$\begin{cases} \frac{di_\mu}{dt} = \frac{1}{L_d}\left(-R_s i_\mu + \gamma R_s i_f + p\Omega(L_q i_q - \Phi_{PM}) + v_d\right) \\ \frac{di_q}{dt} = \frac{1}{L_q}\left(-R_s i_q - pL_d\Omega i_\mu + v_q\right) \\ \frac{di_f}{dt} = \frac{1}{\sigma L_f}\left(-R_f i_f - \gamma e_\mu + v_f\right), \end{cases} \tag{6}$$

where $\gamma = \frac{L_{sf}}{L_d}$, and $\sigma = 1 - \frac{L_{sf}^2}{L_d L_f}$ is the total leakage constant.

2.2 Vector control strategy

The machine torque of a BESM can be controlled like that of a dc-machine by setting *d*-axis stator current to be zero (i_d = 0). Thus, the electromagnetic torque expression can be simplified to:

$$T_{em} = pL_{sf} i_q i_f. \tag{7}$$

According to (7), it is obvious that the electromagnetic torque can be controlled by the *q*-axis stator current or the dc-excitation current. However, since the dc-excitation winding produce the electromagnetic field, the permanent magnets, placed along *q*-axis, should produce a field which is meant to fully cancel, at peak torque, the armature reaction field along the same *q*-axis ($\Psi_q = 0$). So, the reference *q*-axis stator current can be imposed constant as:

$$I_q^* = \frac{\Phi_{PM}}{L_q}, \tag{8}$$

and the reference torque and reference dc-excitation current as:

$$T_{em}^* = pL_{sf}\frac{\Phi_{PM}}{L_q} I_f^*, \tag{9}$$

$$I_f^* = \frac{L_q}{pL_{sf}\Phi_{PM}} T_{em}^*, \tag{10}$$

then, with $i_d = 0$, the reference magnetising current can be imposed as:

$$I_\mu^* = \frac{L_{sf}}{L_d} I_f^* = \frac{L_q}{pL_d\Phi_{PM}} T_{em}^*. \tag{11}$$

However, to set the three currents to its reference values, the system should be decoupled, and the required *d*-*q* stator voltages and dc-excitation voltage should be produced. Thus, with proportional-integral (PI) controllers, the command voltages can be generated:

$$\begin{cases} V_d^* = \left(\frac{K_p^{i_\mu} s + K_i^{i_\mu}}{s}\right)\left(I_\mu^* - i_\mu\right) + E_d \\ V_q^* = \left(\frac{K_p^{i_q} s + K_i^{i_q}}{s}\right)\left(I_q^* - i_q\right) + E_q \\ V_f^* = \left(\frac{K_p^{i_f} s + K_i^{i_f}}{s}\right)\left(I_f^* - i_f\right) + E_f \end{cases}, \tag{12}$$

where $E_d = -\gamma R_s i_f - p\Omega\Psi_q$, $E_q = p\Omega\Psi_d$, $E_f = \gamma e_\mu$ are the current disturbances and are added to the command signals for decoupling. The pairs ($K_p^{i_\mu}$, $K_i^{i_\mu}$), ($K_p^{i_q}$,$K_i^{i_q}$) and ($K_p^{i_f}$,$K_i^{i_f}$) are the proportional and integral gains of the PI controllers, and can be chosen to compensate the time constants L_d/R_s, L_q/R_s and L_f/R_f. Therefore, the PI parameters will be:

$$\begin{cases} K_p^{i_\mu} = K_1 L_d \ ; \ K_i^{i_\mu} = K_1 R_s \\ K_p^{i_q} = K_2 L_q \ ; \ K_i^{i_q} = K_2 R_s \\ K_p^{i_f} = K_3 \sigma L_f \ ; \ K_i^{i_f} = K_3 R_f \end{cases}, \tag{13}$$

where K_1, K_2 and K_3 are constant gains, and can be tuned according to the desired dynamics.

Hence, the machine torque can be regulated by controlling the dc-excitation current, and the machine operation can be switched from motoring to generating operation by changing the sign of the dc-excitation current.

On the other hand, the estimated active and reactive powers (*P* and *Q*) as well as the power factor angle (φ) can be expressed at machine terminals based on the *d*-*q* machine model as:

$$\begin{cases} P = v_d i_d + v_q i_q \\ Q = v_d i_q - v_q i_d \end{cases}, \tag{14}$$

$$\varphi = \cos^{-1}\left(\frac{P}{\sqrt{P^2 + Q^2}}\right), \tag{15}$$

by setting $i_d = 0$ and $\Psi_q = 0$, estimated active and reactive powers expressions can be simplified to:

$$\begin{cases} P = R_s i_q^2 + pL_{sf}\Omega i_f i_q \\ Q = L_{sf} i_q \frac{di_f}{dt} \end{cases}. \tag{16}$$

Since the dc-excitation current and *q*-axis stator current are set to be constant in steady state, (16) can be more simplified and implicit unity power factor operation can be obtained.

3 ISA BASED BESM VECTOR CONTROL

The proposed BESM vector control strategy is now used for the control of an ISA system. A complete scheme that allows torque and dc-bus voltage control has been developed, and it is shown in Fig. 1. It includes starting/generating state switch, in order to simulate the two operating modes of ISA. During the starting mode, the BESM acts as a motor to provide high torque for the starting of the engine. During the generating mode, the dc-bus voltage is kept constant as 42V by a PI controller, which generates a negative reference dc-excitation current and allows torque reversal so that the BESM runs as generator.

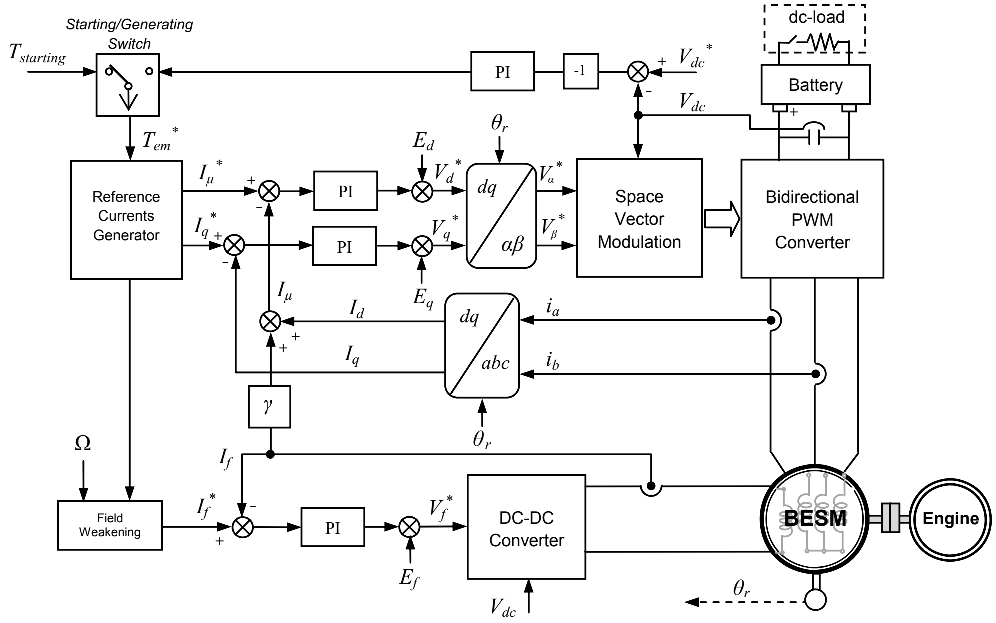

Fig. 1. BESM vector control scheme for ISA system

Furthermore, the DC–AC converter and BESM 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. The speed and the rotor position were obtained from an incremental encoder. Voltage sensor is used to detect the dc-bus voltage, and three current sensors are used to control the stator currents and dc-excitation current by PI controllers.

4 RESULTS AND DISCUSSION

The proposed scheme for torque control of ISA system has been implemented using Matlab/Simulink. The tests are for the 2.35kW–50Hz–22.2V biaxial excitation synchronous machine with parameters listed in Table 1.

Table 1. Parameters of the BESM

4-poles	L_d = 1.8 mH
R_s = 0.05 Ω	L_q = 0.455 mH
R_f = 6.5 Ω	L_f = 0.3 H
Φ_{PM} = 0.0136 Wb	L_{sf} = 16.5 mH

The power converter is a three-phase DC–AC voltage source bidirectional converter, which is supplied with 36V batteries. The BESM is mechanically coupled with a dc-machine, which simulates the engine. The engine speed is controlled after starting when the BESM runs as generator. In order to illustrate the proposed scheme, the simulation has been carried out under the following conditions.

4.1 System behaviour during starting mode

During starting mode, the dc-machine simulated engine is cranked by the BESM from 0 up to 500 r/min with a starting torque set to 6 Nm. Once the speed gets 500 r/min, both the engine and BESM produce accelerating torque to speed up to 1500 r/min, which is the rated speed of the used machine. After the speed reaches 1500 r/min, the dc-machine simulated engine is regulated by its own controller. At this speed level, the ISA control system changes from motoring to generating mode instantaneously and the reference is switched from the torque to the output of the dc-bus voltage regulator. Thus, the dc-excitation current change from positive to negative value and allow BESM's torque reversal. The BESM now begins to act as a generator to provide power to the battery and dc-load. The simulation results are shown in Fig. 2.

As shown in Fig. 3 and Fig. 4, the q-axis current is kept constant and the q-axis stator flux is set to zero with the proposed vector control. The d-axis current is nonzero during transients, which increase the torque response quickness, and zero in steady state when the magnetising current is set to its reference value.

Figure 5, on the other hand, shows that the ISA system operates with unity power factor for both motoring and generating modes, which justifies the efficiency of the proposed vector control strategy.

4.2 Steady state response during generating mode

The steady state performance is shown in Fig. 6. The dc-bus voltage is kept constant as 42V when the BESM

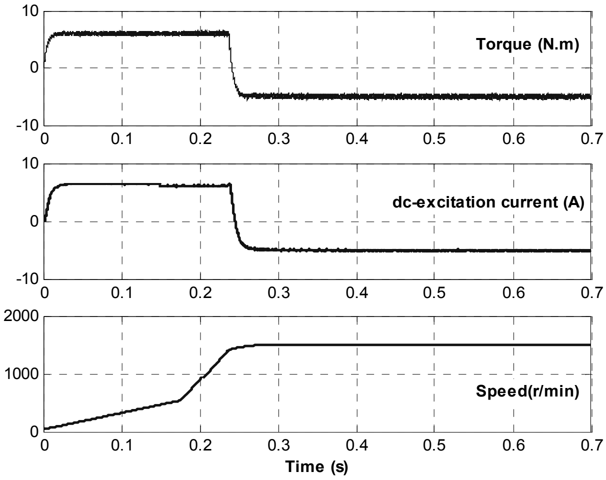

Fig. 2. Starting transients of the proposed ISA system: responses of torque, dc-excitation current and speed

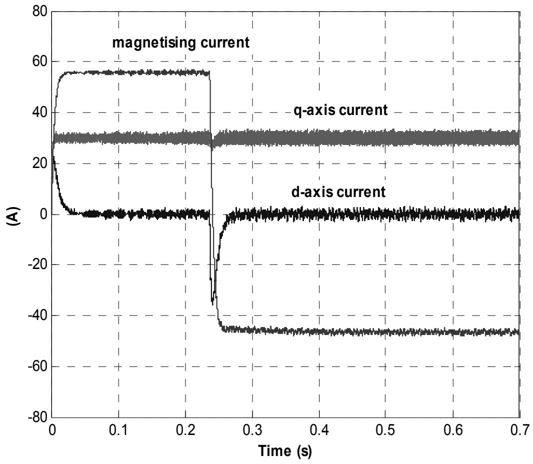

Fig. 3. Transient responses of the magnetising current and d-q-axes currents during starting period

acts as a generator and provides power to the battery and the dc-load. Furthermore, the q-axis current is still constant.

4.3 Dynamic response during generating mode

In this section, the dynamic performance of the proposed ISA is studied under the following cases: load dump and engine speed acceleration or deceleration.

4.3.1 Load dump

During generating mode, the dc-load of the ISA is removed suddenly when the speed is 1500 r/min. As shown in Fig. 7, the dc-bus voltage is well controlled within the 42V PowerNet specifications. The BESM's torque is

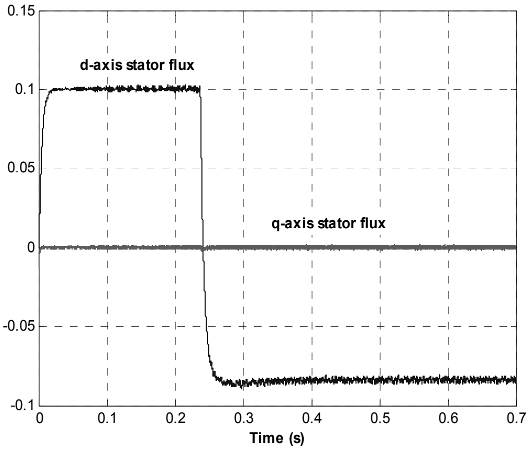

Fig. 4. Transient responses of the d-q-axes stator flux during starting period

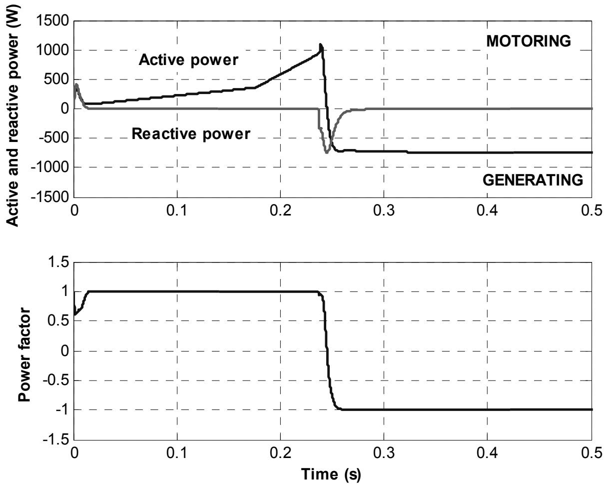

Fig. 5. Active power, reactive power and power factor during motoring and generating modes of operation with the proposed ISA

changed from –5 to about –4 Nm during load dumping. The machine torque varies slowly because of the charging of the battery. Also, in this test condition, the q-axis current is kept constant.

4.3.2 Speed acceleration/deceleration

The engine's speed reference is increased from 1500 to 2500 r/min while the BESM is generated with a full dc-load. As shown in Fig. 8, the dc-bus voltage is kept constant as 42V. The BESM's torque is great than –5 Nm due to the increase of speed. The dc-excitation current is increased by weakening the field flux when the rotor speed is above the base speed (1500 r/min).

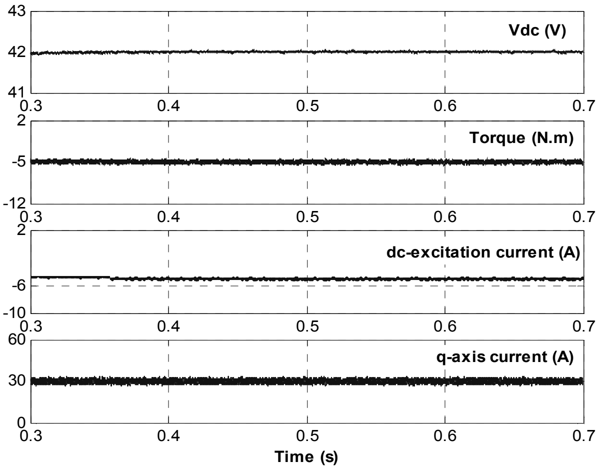

Fig. 6. ISA steady state characteristics during generating period

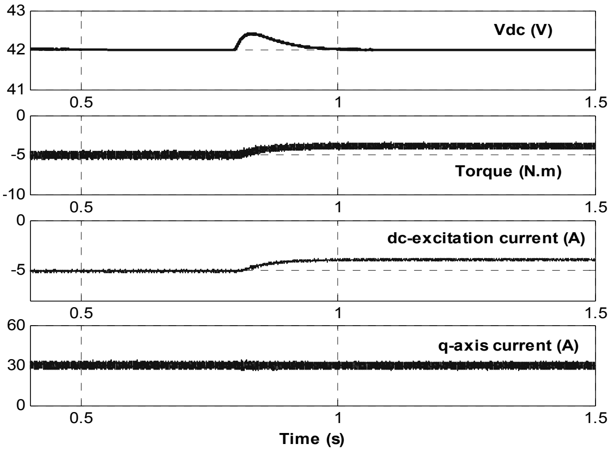

Fig. 7. Load dump of ISA during generating mode

The deceleration of the ISA system is also tested by decreasing the engine's speed from 2500 to 1500 r/min while the BESM is generated with a full dc-load. As shown in Fig. 9, the dc-bus voltage is kept constant as 42V. The dc-excitation current is decreased to its nominal value when the speed returns to the base speed (1500 r/min).

4.3.3 High speed operation

The proposed ISA system is also tested in high-speed range. Fig. 10 shows the ISA performance at 4000 r/min. The BESM's torque change from –5 Nm to about –2 Nm due to the high-speed operation. Also, in this condition of speed operation, the dc-bus voltage of the ISA is kept constant as 42V. The field flux of the machine is weakened when the speed is above the base speed (1500 r/min).

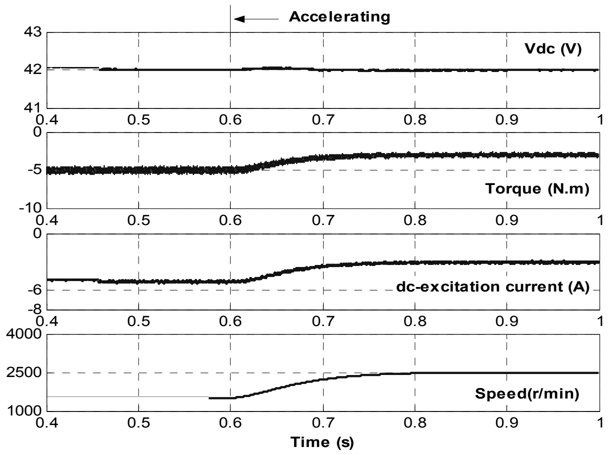

Fig. 8. ISA performance at acceleration (from 1500 r/min to 2500 r/min)

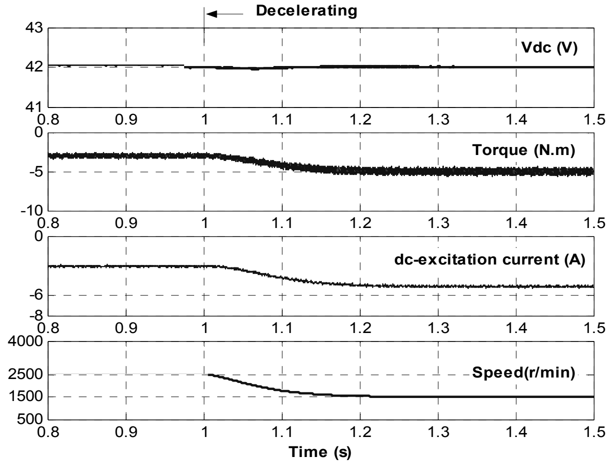

Fig. 9. ISA performance at deceleration (from 2500 r/min to 1500 r/min)

5 CONCLUSION

In this research work, a double excited synchronous machine has been proposed as integrated starter–alternator (ISA) for the future 42V hybrid electric vehicle applications. Particularly, the Biaxial Excitation Synchronous Machine (BESM) is proposed for its high efficiency and wide constant power speed range. For ISA control during motoring and generating modes, a vector control scheme is developed for BESM operation at unity power factor. Furthermore, by controlling the field winding current, 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 ISA system.

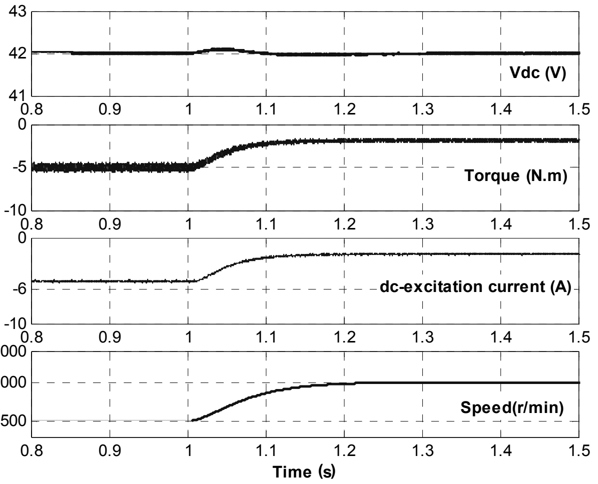

Fig. 10. ISA performance at high speed

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