ACTIVE-FLUX BASED OBSERVER FOR MOTION SENSORLESS CONTROL OF BIAXIAL EXCITATION GENERATOR/MOTOR FOR AUTOMOBILES (BEGA)

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Abstract. This paper proposes an active flux observer for motion-sensorless biaxial excitation generator for automobiles (BEGA) for wide speed operation. The active flux observer transforms BEGA, a salient-pole rotor ac machine, in a virtually non-salient pole machine model so that the rotor speed and position can be estimated in a simpler way. Simulations and experimental results are presented to verify the principles and to demonstrate the performance of the proposed observer. A rotor position and speed estimator, based on active flux estimation is proposed and tested. The performance (accuracy) of the observers has been tested with the drive system operated from very low speed down to 2 rpm, with full load and up to 2000rpm.

Key words: active flux observer, vector control, unity power factor, dc excitation, current referencer.

1. Introduction

BEGA is proposed as a solution for integrated starter-alternator system used in hybrid electric vehicles. This solution is a compromise between power, efficiency and cost. BEGA has a standard three-phase stator with uniform slots and a three-phase winding while in the rotor it has a heteropolar dc excitation winding (in \(d\)-axis) and a lower cost permanent magnets (PMs) located in the multiple flux-barriers (in \(q\)-axis). This mix between a standard permanent-assisted reluctance synchronous machine (PM-RSM) and dc excited synchronous machine is characterized by:

- Higher efficiency than conventional claw-pole alternator. The large claw-pole eddy-currents losses are eliminated. The large voltage and flux harmonics at high speeds are considerably low than in the claw-pole alternator
- The low-cost ferrite PMs placed in the multiple flux barriers are designed to "fully destroy" the \(q\)-axis stator-produced flux linkage. For PM-RSM the PMs flux interaction with \(i_d\) current give the main component of the torque; for BEGA the vector control (for \(i_d=0\) and \(i_q=0\)) the torque is produced by interaction of dc excitation current field and \(i_q\) stator current.
- A 4-quandrant dc-dc converter is required to control the dc field current regulation. The rated power of the converter is approx. 5% of machine rated power.
- The stator current for the same torque is considerably lower (even 30%) than for the PM-RSM. This has a direct impact on the rated power of the three phase inverter.
- BEGA is capable of a very large constant power speed range (CPRS). Theoretically this ratio is infinite but due to mechanical limitation and losses a ratio of 10-20 is considered practical. Very large CPRS has been demonstrated by simulations and experiments with encoder feedback [4].

A cross-section of BEGA is given in Fig. 1.

The prototype design and a comprehensive characterization with test results is presented in [1,2,3]. A vector control structure, with position and speed sensor for BEGA, is proposed and tested in [5,6]. This paper is focused on rotor position and speed estimation of BEGA, from the active flux observer, in an effort to reduce the on-line computation effort and to provide very low speed operation without any signal injection. The principles have been verified experimentally and have proven to work for very low speed operation.
2. BEGA – Mathematical model

The BEGA transient equations in d-q reference frame are:

\[ \ddot{v}_s = \frac{d\psi}{dt} + j\omega_v \psi_s \]

(1) \[ v_s = v_q + jv_d; \; \bar{v}_s = \psi_d + j\psi_q \]

(2) \[ \psi_d = L_{ds}i_d + L_{sq}i_q + \psi_M \quad \psi_q = L_{qs}i_q - \psi_M \]

(3) \[ t_e = \frac{3}{2} P_1 (\psi_d i_q - \psi_q i_d) \]

(4) \[ v_F = R_i i_d + \frac{d\psi}{dt}; \; \psi_F = L_{qs} i_d + L_{ds} i_q \]

(5)

where \( v_s, i_s \) are the stator voltage and current respectively, \( \psi_s \) is the stator flux linkage vector, \( R_i \) is the stator resistance, \( \omega_v \) is the electrical rotor speed, \( L_{ds}, L_{sq} \) are the \( d, q \) axis inductance, \( L_{ms} \) is the mutual field-armature inductance, \( \psi_M \) is the PM flux on \( q \) axis, and \( P_1 \) is the pole pair. Equation (5) characterizes the dc field (excitation) circuit, where \( v_s, i_s \) is the field voltage and current respectively; \( \psi_M \) is the field flux, and \( R_F \) are the field winding resistance and inductance, respectively. Equation (5) shows that during \( i_d \) current variation (transients) an overvoltage may occur in the dc field circuit. To avoid this overvoltage in the dc field circuit a simple protection made by a resistor and a static switch or a varistor is used.

During the unity power factor operation (with zero \( i_d \) and zero \( \psi_d \)), from (1)-(5), the steady-state dq equations of BEGA become:

\[ \bar{v}_s = R_i i_d + \omega L_{qs} i_q; \; \bar{i}_s = I_{qs} = \text{const} \]

(6) \[ t_e = \frac{3}{2} L_{qs} i_q \]

(7)

where \( L_{qs} = L_{qs}/L_{ps} \). Implicits unity power factor operation is obtained. The machine operation can be switched from motoring to generating in two ways: a) by changing the sign of \( i_q \) current, but in this case the machine does not operate at unity power factor b) by changing the sign dc. excitation current.

The vector diagram at unity power factor operation is illustrated in Fig. 2.

3. Active-flux concept for BEGA

The “active flux” concept proposed in [6] transforms all salient-pole rotor ac machines into virtually nonsalient-pole models, such that the rotor position and speed estimation becomes simpler.

For BEGA the active flux is expressed as:

\[ \bar{\psi}_d^a = \bar{\psi}_d - L_{qs} i_q = \]

\[ L_{qs} i_q + j\omega_L i_q - j\psi_M - L_q i_q + j i_q \]

\[ \bar{\psi}_q^a = L_{qs} i_q - j\psi_M + j i_q \quad \text{for} \; i_d = 0; \]

The vector diagram of eq. (10) is illustrated in Fig. 3.

The torque expression remains the same, as in eq. (3). The steady state vector diagram of BEGA (for \( id=0 \)), with in foreground, is drawn in Fig. 3.
IM was driven by an ABB ACS600 bidirectional converter. The rated power of IM was 5.5kW at n=2945 rpm, enough to load the BEGA at full load. A four quadrant dc-dc converter with \( I_{\text{dc, rated}} = 5A \), \( V_{\text{dc, rated}} = 48V \) was built for current control in the dc. field winding. An incremental encoder (Telemecanique XCC-1510PR50R, 5000ppr) was used for BEGA position and speed measurement.

![IM and BEGA diagram](image)

Fig 4 Experimental platform for BEGA control

The control algorithm has been developed in Matlab-Simulink and implemented on a dSpace 1104 Real Time System (RTI) used for rapid prototyping. The following signals were measured using dSpace acquisition board: phase currents, battery current, dc field current, phase voltages, battery voltage and BEGA rotor position.

<table>
<thead>
<tr>
<th>Tab. 1. BEGA parameters</th>
<th></th>
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<tbody>
<tr>
<td>Rated power (P_N)</td>
<td>2.35 kW</td>
</tr>
<tr>
<td>Rated phase voltage (V_0)</td>
<td>22 V (rms)</td>
</tr>
<tr>
<td>Rated phase current (I_0)</td>
<td>67 A (rms)</td>
</tr>
<tr>
<td>Rated field current (I_F)</td>
<td>5 A</td>
</tr>
<tr>
<td>Rated battery voltage (V_{batt})</td>
<td>48 V</td>
</tr>
<tr>
<td>Rated torque (T_N)</td>
<td>15 Nm</td>
</tr>
<tr>
<td>Rated speed (n_0)</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Number of pole pairs (p)</td>
<td>2</td>
</tr>
<tr>
<td>Stator phase resistance (R_s)</td>
<td>0.05 ( \Omega )</td>
</tr>
<tr>
<td>q axis inductance (L_q)</td>
<td>0.455 mH</td>
</tr>
<tr>
<td>d axis inductance (L_d)</td>
<td>1.8 mH</td>
</tr>
<tr>
<td>PM flux (( \Psi_{PM} ))</td>
<td>0.0136 Wb</td>
</tr>
<tr>
<td>Field winding resistance (R_f)</td>
<td>6.5 ( \Omega )</td>
</tr>
<tr>
<td>Field winding inductance (L_f)</td>
<td>0.380 H</td>
</tr>
<tr>
<td>Mutual field-armature inductance (L_{mf})</td>
<td>16.5 mH</td>
</tr>
<tr>
<td>Moment of inertia (J)</td>
<td>1e-3 kg( \cdot )m^2</td>
</tr>
<tr>
<td>Viscous friction coefficient (B)</td>
<td>1e-4</td>
</tr>
</tbody>
</table>

5. Proposed bega sensorless vector control system

Fig. 5 illustrates the proposed speed sensorless control system for BEGA. The commanded input is the target rotor speed (Fig. 5). The current referencer provides the target current components on q-axis \( (i_q^*) \) and target dc field \( (i_F^*) \) while the reference d-axis current \( (i_d^*) \) is set to zero. The current referencer provides the reference current combination \( (i_q^*, i_F^*) \), that ensure minimum total copper losses in the machine. More details about the current referencer can be found in [4].

The relationship used for reference q-axis current \( (i_q^*) \) calculation is given by equation (13):

\[
i_q = I_{q_k} \sqrt{\frac{1}{L_d} \left( \frac{\dot{\theta}}{\omega_d} \right)} \tag{13}
\]

where \( I_{q_k} = \frac{\psi_{PM}}{L_q} \) is the q-axis current that ensures cancellation of the total q-axis flux \( (\psi_q = 0) \). For \( i_q = I_{q_k} \) and \( i_d = 0 \) unity power factor operation of BEGA is guaranteed and the ratio torque/ampere is maximized.

Equation (14) calculates the d-axis flux component given by dc field current which, in combination with the current given by eq. (13), develops the requested torque, provided by speed controller.

\[
\psi_F^* = \frac{2 \cdot i_{q_k}^*}{3} p_i \tag{14}
\]

From the non-linear magnetization curve, stored in a look-up table, the reference dc field current \( (i_F^*) \) is extracted.

The current controllers are implemented in rotor reference frame and produce the reference stator voltage. The d-axis controller should not be calibrated for a very fast response, in order to avoid induced voltage in the dc field excitation due to fast id transients. The space vector modulation has as main inputs the stator voltage reference \( (V_\alpha, V_\beta) \), and it gives the switching command signals \( (T_1..6) \) for the voltage source inverter. For the coordinates transformation the measured electrical rotor position is used, which is furthermore used as a basis for the evaluation of the position observer performance. Also, the measured rotor speed is used in vector control structure. So the drive is encoder control and the investigation focuses on the quality of the flux, position and speed estimation.

6. State observers

6.1. The active flux observer

The observer task is to estimate the active flux in a wide speed range.

The operating principle of the proposed observer is to extract the active flux using the measured stator current, dc. field current and the estimated stator voltage. The stator voltage is estimated based on the measured dc-link (battery) voltage and the switching states.

The signal flow diagram of active flux observer is shown in Fig. 6. It is based on a combined voltage-current model from which the \( L_d i_d \) term is subtracted.

The stator flux observer combines advantages of the current-model estimator in rotor reference at low speed, with the voltage-model estimator in stator reference at medium high speed, using a dynamic compensation (PI compensator).
The values of \( k_{pc} \) and \( k_{ic} \) decide the speed range where the current model (or voltage model) prevails.

\[
x = \left( k_{pc} + \frac{k_{ic}}{S} \right) (\hat{\psi}_s - \hat{\psi}_i)
\]

(15)

where \( \hat{\psi}_s \) and \( \hat{\psi}_i \) are the stator flux estimated based on current model and respectively voltage model.

The PI compensator parameters \( k_{pc} \) and \( k_{ic} \) are defined as:

\[
k_{pc} = \omega_1 + \omega_2 \quad ; \quad k_{ic} = \omega_1 \cdot \omega_2
\]

(16)

where \([0...\omega_1] \) is the speed range where the current model based stator flux estimator prevails and \([\omega_2...\omega_{max}] \) is the speed range where the voltage model stator flux estimator prevails. Also, the PI compensator rejects the dc offset and drifts from the current acquisition [2].

The \( v_{comp} \) term is used only to compensate the voltage drop on the inverter MOSFETs (inverter non-linearities). It is expresses as follows:

\[
v_{comp(x,y,z)} = R_{ds,off} \cdot i_{(x,y,z)} + v_{th}
\]

(17)

where \( R_{ds,off} \) is drain-source resistance of the MOSFET during conduction and \( v_{th} \) is the threshold voltage of the MOSFET.

This compensation is proposed in [7] in a different form but the results are equivalent.

### 6.2. Position and speed estimator

The rotor position and speed estimator implementation is presented in Fig. 7. To extract the rotor position and speed from the active flux vector, a PLL (phase-locked-loop) state-observer is employed. The output of the PLL is the estimated position of the active flux \((\hat{\theta}_r - \gamma)\). To obtain the estimated position of the rotor, the angle \( \gamma \) is added to the estimated position of active flux.

\[
x = -\hat{\psi}_{ax} \sin(\hat{\theta}_r - \gamma) + \hat{\psi}_{ay} \cos(\hat{\theta}_r - \gamma)
\]

(18)

The angle \( \gamma \) can be very precisely estimated due to accurate knowledge of and obtained from experiments.

\[
\gamma = \begin{cases} 
\tan^{-1}(\frac{\psi_{aux}}{L_{aux} i_{aux}}) \quad & \text{for } i_{aux} > 0 \\
\tan^{-1}(\frac{\psi_{aux}}{L_{aux} i_{aux}}) + \pi \quad & \text{for } i_{aux} < 0
\end{cases}
\]

(19)

The electrical rotor speed can be estimated from the rotor electrical position using equation (20):

\[
\hat{\omega}_r = \frac{d\hat{\theta}_r}{dt} = \frac{d(\hat{\theta}_r - \gamma)}{dt} + \gamma
\]

(20)
According to equation (20) the rotor electrical speed is expressed as a sum of two components: i) active flux speed and ii) gamma speed.

The active flux speed estimation is based on derivatives of active flux components \((\tilde{\psi}_{da}^*, \tilde{\psi}_{db}^*)\) as follow:

\[
d\hat{\omega}_r = \frac{d\tilde{\psi}_{da}^*}{dt} - \frac{d\tilde{\psi}_{db}^*}{dt}
\]

\[
\tilde{\omega}_r = \left(\tilde{\psi}_{da}^*\right)\hat{\phi}_r + \left(\tilde{\psi}_{db}^*\right)\hat{\phi}_r
\]

A second solution for the speed estimation is given by equation (20):

\[
\hat{\omega}_r = \frac{\dot{\theta} - \dot{\theta}}{\Delta t}
\]

where \(\Delta t\) is the sampling time of rotor speed evaluation.

The derivative estimation (21) gives very fast estimation of speed. The drawback of this solution is that the speed estimation accuracy is strictly dependent on the accuracy of the active flux components estimation. The accuracy of active flux depends on the electromagnetic parameters and the noise and offset of the measured signals. To remove the noise from the estimated speed a first-order low pass filter is used.

\[
\hat{\omega}_r(k) = K \cdot (\hat{\omega}_r(k) - \hat{\omega}_r(k-1)) + \hat{\omega}_r(k-1)
\]

For the final approach the last solution was used due to lower noise in speed estimation. In fact the dc field derivative produces an unacceptable noise level which requires a strong low-pass filtering which furthermore gives a higher delay in the estimated speed.

7. Experimental and simulation results

A set of experiments were carried out for evaluation of the observers. The rotor speed during experiments was set to 2000, 200, 20 and 2rpm with motor loaded and unloaded. A large speed range is covered with these speed values. Due to limited space, only for extreme cases (2rpm, 2000rpm) the results will be presented.

The performance of the position and speed estimators in the high speed range is tested for a speed of 2000rpm. The experimental results are plotted in Fig. 8. The motor is accelerated from standstill to 2000rpm and then a few speed reversals take place. This way the convergence of the estimated rotor position during startup, transient and steady-state performance of the estimators can be analysed. The speed error during startup and transients slightly exceeds 50rpm, while at steady state is around 10rpm (error less than 0.5%). Less than 30ms are necessary for the position to converge to an error less than 30° (0.5rad electrical).

During speed reversal the maximum position error is below 12° electrical, while at steady-state the average position error is lower than 3°.

![Figure 8 Experimental results: startup with load, ±2000 rpm speed reversal with load. From top to bottom: (a) reference and actual rotor speed, (b) zoom in on actual and estimated rotor position at startup, (c) zoom on actual and estimated rotor position during steady-state (d) angle gamma (γ)](image)
The performance of the observer and estimators at very low speed from zero to 2 rpm and speed reversal at 2 rpm, under no-load, are presented in Fig. 9.

The phase currents and dc field current are strongly distorted due to the high pulsations of cogging torque. The higher the magnitude of dc field current the higher the cogging torque magnitude. At zero dc field current ($i_F=0$) cogging torque is insignificant.

Therefore high nonlinear cogging torque will produce highly distorted currents at very low constant speed. Even with such distortions the accuracy of the estimated position is very good (around one electrical degree).

The explanation for such a good position estimation with such distorted currents is that all phase currents distortions (reflected in active flux observer) are counterbalanced by the dc field current distortion. This demonstrates the suitability of the active flux observer for BEGA position and speed estimation. The currents distortion decreases as the load increases due to the fact that cogging torque will become a smaller percentage of the total load torque. Good experiments under full load are possible only with a passive load or with a drive that is running with motion-sensor. Experiments under load were tried using as load a sensorless induction machine drive but the experiments failed. The corresponding speed of the loaded drive was 1 rpm to the 2 rpm of BEGA. Two electric machines running sensorless at such a low speed, one being use as a load is rarely.

8. Conclusion

An accurate rotor position and speed estimator based on the active flux observer for a wide speed range (2 rpm to 2000 rpm) is proposed and validated. Remarkable is the position accuracy of the position at very low speed. The speed estimation errors are acceptable during transients while at steady state they are below 1% (of rated speed) for higher speeds. Full motion sensorless control of BEGA experiments are under way with publication due soon.

References