Frequency-current control. Modeling. Optimization

P G Mikhailov¹*, O V Ermilina³, D A Budagovsky² and L Basarbay³

¹Penza state technological University 1а/11, Baydukova/Gagarina str., Penza, 440039, Russia;
²Penza state University, 40, Krasnaya str, Penza, 440026 Russia,
³Satbayev University , 22а Satpaeva str., Almaty, Kazahstan

*pit_mix@mail.ru

Abstract. To increase frequency-current-controlled asynchronous engine performance and to improve its startup and shutdown response abstract models and circuit implementations were developed. Adding feedbacks on various grades allowed to optimize rotor speed control for various engine operating modes. Suggested circuit implementations and microprocessor and software integration allowed to reduce noise, to calculate speed and to reduce startup currents. An extreme control implementation was suggested. MATLAB Simulink models were developed allowing to optimize automated control system configuration.

1. Introduction
Frequency-current-controlled asynchronous engine (where frequency-current control is accepted due to engine performance features [1]) application is common for high overload capacity drives.

Electric engine and machine tool automation department (Ural State Engineering University) science articles prove that asynchronous engine powered from frequency converters using independent voltage and current controllers, as well as from direct-linked converters, has great levels for the most important quality indicators [3; 4].

2. Research goals
To prove that statement according to considered problem we will analyze the matter chart equation for frequency-current-controlled asynchronous engine [2; 3]:

\[ M = \frac{mI_s^2L_m^2}{L_2(s + sk)} \]

(1)

where m is phase count. I – single-phased current, s – slide, sk – critical slide, L_m, L_2 – magnetic circuit and rotor inductances. Critical slide equals to:

\[ sk = \frac{R_2^2}{\omega_0L_2} \]

(2)

where R_2 – rotor resistance, \( \omega_0 \) – rotor current frequency.
It’s obvious that stator current is constant when control is frequency-current and in this case engine torque reaches its maximum level. This maximizes the expression value. That is especially important for traction engine because specified traction torque can be reached on least possible stator current [4]. Figure 1 represents calculated mechanical charts for frequency-current-controlled asynchronous engine while operating on critical slide on fan load.

![Figure 1. Mechanical charts for frequency-current-controlled asynchronous engine while operating on critical slide on fan load.](image)

For considered cases, power frequency $\omega_0$ is equal to:

$$\omega_0 = \omega + \omega_0 s.$$  \hspace{1cm} (3)

where $\omega$ – rotor current frequency, $s$ – slide.

In order to operate on critical slide, voltage frequency $\omega_0$ must be chosen according to this statement: $\Delta \omega = \omega_0 s$.

3. Search for solution

Engine operating point where slide is equal or greater than critical is theoretically considered as unstable-balanced point. An open dimension control system in unable to stabilize its performance on critical slide according to (3) due to uncontrollable vibrations.

Therefore, a closed control system with subordinate basic dimension control was suggested to use. Stator current $I_1$ and rotation speed $\omega_3$ were chosen as basic dimensions. Figure 2 represents a block diagram for such control system.

![Figure 2. A block diagram for constant-powered frequency-current-controlled asynchronous engine operating on critical slide.](image)

Block diagram legend: $\omega_3$ is specified engine rotation speed, $\Delta \omega$ – additive speed [5], RS and RC are speed and current controllers, U and $\omega_0$ – power voltage and frequency, FC and AD – frequency converter and asynchronous engine.
An abstract model for this engine was designed using Simulink and its operation was simulated. This abstract model was implemented as abstract model for perfect double-phased electromechanical converter which is known as general electric engine [6].

\[
\begin{align*}
\frac{d\Psi_1}{dt} &= U_1 - R_1 I_1 - j\omega_k \Psi_1; \\
\frac{d\Psi_2}{dt} &= U_2 - R_2 I_2 - j(\omega_k - \omega) \Psi_2; \\
M &= p_L L_m (I_1 \times I_2).
\end{align*}
\] (4)

Stator \(\Psi_1\) and rotor \(\Psi_2\) flow vectors are equal to:

\[
\begin{align*}
\Psi_1 &= L_1 I_1 + L_m I_2; \\
\Psi_2 &= L_2 I_1 + L_m I_2,
\end{align*}
\] (5)

where \(L_1, L_2, L_m\) are rotor, stator and magnetic circuit inductances; \(R_1, R_2\) – active rotor and stator resistances; \(U_1, U_2\) – stator and rotor voltage vectors; \(I_1, I_2\) – stator and rotor current vectors; \(\omega_k, \omega\) – dimension system rotation speed as function to stator and rotor speed. \(M\) is engine torque; \(p_n\) – pole couple count.

4. Simulation

To simulate, a AJR112MA8-class asynchronous engine was used. Its specifications are listed in table 1.

Table 2 represents idle and short-circuit mode specifications for equivalent circuit.

| Engine class | Power (kW) | Rotation speed (rev/minute) | Stator current (A) | Performance (%) | Power multiplier I_{st} / I_{op} | Weight (IM1081) (kg) |
|--------------|------------|----------------------------|-------------------|----------------|-----------------------------------|---------------------|
| AJR90L4      | 2.2        | 1500                       | 5                 | 81             | 0.83                              | 6.5                 |

Table 2. AJR112MA8 engine equivalent circuit specifications.

| Stator resistance (Ω) | Rotor resistance (Ω) | Stator inductance (mH) | Rotor inductance (mH) | Magnetic circuit inductance (mH) | Reduced torque (kgm²) |
|-----------------------|----------------------|------------------------|-----------------------|----------------------------------|------------------------|
| 2.7                   | 2.69                 | 367                    | 378                   | 362                              | 0.02                   |

Figure 3 a represents an abstract model for constant-powered frequency-current-controlled asynchronous engine operating on critical slide; figure 3 b – stator current computing subsystem [8].

Data displayed on Scopes correspond to operating modes while engine operates on standard mode. Scope 1 displays rotation speed (Rad/second), Scope 2 – engine torque (Nm), Scope 3 – stator current (amperes), Scope 4 – power mode (watts).

Standard mode renders AJR90L4 class engine critical slide equal to \(S_k = 0.0227\) and \(\Delta\omega_k = \Delta\omega = 7\) rad/s. Designed abstract model allowed to determine stator current function \(\Delta\omega_k = 8\Delta\omega\). Chart for this function is shown in figure 4.
This system is stochastic because it handles high levels of noise. Due to latter, it’s recommended to use noise-proof ways to search extreme locations. This problem can be solved with inertial object static function chart extremum-searching program based on recurrent least square method (RLSM).

We suggest to merge identification and RLSM-based step-by-step program advantages. First, this method can handle very high noise levels (e. g. has high noise-proof level). And, secondly, it guarantees reliable estimation convergence while computational complexity stays rather low. This guarantees high stability and speed for extremal control based on this program.

Consider a system consisting of a control object and an extremum search controller (ESR; figure 5). Control object is implemented as series of non-linear unit and inertial linear unit which transfer function is W(s). Figure 5 legend: u is input (control), y – output (target function which extremum is required), x – non-linear unit input, v – non-linear unit output, e – random noise implemented as random white noise [9-11].
Let’s assume that non-linear unit function \( u = f(x) \) is a priori unknown. Inertial unit can be implemented as grade \( n \) differential equation like this:

\[
y(k) = \sum_{i=0}^{n} a_i y(k-i) + \sum_{j=1}^{m} b_j u(k-j) + e(k),
\]

where \( k = 0, 1, 2, \ldots, N \) is sample time, \( y(k) \) – model output (time chart) on \( k \)-th step; \( a_i \) – autoregression multipliers, where \( i = 1, \ldots, n \); \( n \) is autoregression argument count; \( b_j \) – moving average multipliers, where \( j = 1, \ldots, m \); \( m \) – moving average multiplier count, \( u(k) \) - input, \( e(k) \) – perturbation.

Each computing procedure step requires to support the extreme value for target function \( y(k) \) implementing following extreme control algorithm:

1. Analyze extreme object inputs \( u(k) \) and outputs \( y(k) \);
2. Find autoregression \( a_i \) and moving slide \( b_j \) multipliers using RLSM;
3. Using found \( a_i \) and \( b_j \) compute the object transfer gain.
4. Find control input \( u(k) \) which provides zero value for transfer gain using direct zero-finding methods. Transfer gain can be computed using RLSM which always guarantees estimation convergence and has pretty low computational complexity.

RLSM can be described as following:

\[
\begin{pmatrix}
\hat{\theta}(k+1) = \hat{\theta}(k) + \gamma(k)e(k+1);
\gamma(k) = \mu(k+1)\Psi(k+1);
\end{pmatrix}
\]

\[
e(k+1) = y(k+1) - \Psi^T(k+1)\hat{\theta}(k),
\]

where \( \hat{\theta}(k-1) \) is model parameter vector: \( \hat{\theta}(k-1) = [a_1, \ldots, a_n, b_1, \ldots, b_m] \)
data vector: \( \Psi^T(k) = [-y(k-1), \ldots, y(k-n), u(k-1), \ldots, u(k-m)] \)
correction vector: \( \mu(k+1) = \frac{1}{1 + \Psi^T(k+1)\Psi(k+1)} \)
weight matrix: \( \Psi(k) = \frac{1}{\Psi^T(k)\Psi(k)} \)
weight matrix calculated in the next step: \( \Psi(k+1) = [I - \gamma(k)\Psi^T(k+1)]\Psi(k) \)
initial values of variables: \( \hat{\theta}(0) = 0; \Psi(0) = \alpha I \)
where \( \alpha \) is a pretty large number, \( I \) – identity matrix.

Figure 6 represents control system abstract model for engine indirectly oriented in electromagnetic field. Figure 7 represents output data for critical engine operating mode (startup and shutdown) simulation based on developed Simulink model.
**Figure 6.** Control system abstract model for engine indirectly oriented in electromagnetic field.

**Figure 7.** Engine torque (a) and rotation speed (b) when input voltage equals 60 V.

5. **Conclusions**
   The charts prove that the proposed block diagram for a frequency-current-controlled asynchronous engine (Figure 1) ensures stable operation during critical slip and at the same time achieves a minimum current consumption of the stator.

Since the parameters of an asynchronous engine are unstable and might vary during operation, it is recommended to use the extreme regulation for this append in order to compute the required speed increase $\Delta \omega$ for this value while stator’s power consumption stays pretty low.

In this case, the extreme current control is complex because it’s related to faint extreme functions and, as a result, a high noise impact. In order to resolve this, a RLSM-based noise-proof extreme control algorithm was implemented.

**References**

[1] Bazzi M and Krein P T 2010 *IEEE Energy Conversion Congr. and Expo.* pp. 3345-51.
[2] Bazzi M and Krein P T 2009 *IEEE Elect. Ship Technologies Symp.* pp. 98-106.
[3] Concari L, Barater D, Buticchi G and Concari C 2016 *IEEE Trans. Ind. Appl.*, 52, 4010–19.
[4] Gerada D, Mebarki A, Brown N L and Bradley K J 2011 *IEEE Trans. Ind. Electr.*, 58, 4039–47.
[5] Madonna V, Giangrande P and Galea M 2018, *IEEE Trans. Transp. Electr.* 4, 646–59.
[6] Lane M. 2015 *Springer*, p. 801-10
[7] Polyakov V N 2007 *Conf. Yekaterinburg: GOU VTO UGTU-UPI* pp. 161-64.
[8] Youssef M Z 2015 *IEEE Trans. Industr Electr*, vol. 62, no. 5, pp. 3277–84.
[9] Jain S, Karampuri R and Somasekhar V T 2016 *IEEE Trans. Industr Electr*, vol. 63, no. 2, pp. 956–65.
[10] Lee W, Schubert E, Bobba D and Sarlioglu B 2017 *IEEE Trans. Transp. Electrif.*, 3, 36–47
[11] Kroeger K P, Sanghun C and Bazzi A M 2010 *Power and Energy Conf. at Illinois*, pp. 7-11.