

SERIES LOAD INDUCTION HEATING INVERTER STATE ESTIMATOR USING KALMAN FILTER

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ABSTRACT

LQR and H_2 controllers require access to the states of the controlled system. The method based on description function with Fourier series results in a model with immeasurable states. For this reason, we proposed a Kalman filter based state estimator, which not only filters the input signals, but also computes the unobservable states of the system. The algorithm of the filter was implemented in LabVIEW v8.6 and tested on recorded data obtained from a 10-40 kHz series load frequency controlled induction heating inverter.

Keywords: Induction heating, Kalman state estimator

1. Introduction

Induction heating equipments are high efficiency none polluting, safe heaters. The Joule-Lenz effect of the induced eddy currents of the alternating electromagnetic field generates heat directly on the surface of the workpiece. The heating process is clean, without the release of toxic or corrosive gases. An accurate temperature control algorithm assures minimum by products (such as slag) yield.

Modern control algorithms like LQR, H_2 robust control or Lyapunov [1] based control require access to the controlled systems states for easier and better (optimal) control. Since the states of the system model used are not measurable, a Kalman state estimator is proposed.

In the present article, we present a state estimator of a frequency controlled induction heating inverter. The input variable of the inverter is the commutation frequency of the power transistors and the measured output variable is the capacitor voltage in the resonant load. Figure 1 presents the block diagram of the system.

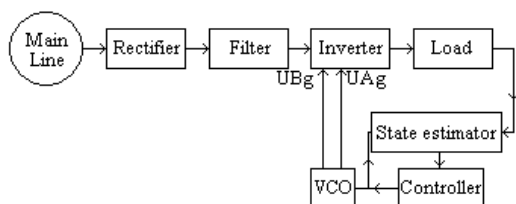


Fig. 1 – Block diagram of a frequency controlled induction heating inverter

The system is supplied by the main line. The voltage is rectified using four diodes and filtered by a filter choke and electrolytic capacitors. The obtained

voltage supplies the inverter bridge constructed of four power transistors. A voltage controlled oscillator generates the commutation frequency for the power transistors [2, 3].

2. Process description

For low power and high frequency applications, the series load induction heating inverters are preferred. They are simple in design and easy to control [4]. For this experiment, the topology presented in figure 2 was proposed.

The resonant load consists of a capacitor, a matching transformer and the heating inductor. The capacitor has a value of $7.4\mu\text{F}$ and the matching transformer (Tr) has a transformation ratio of 12:1.

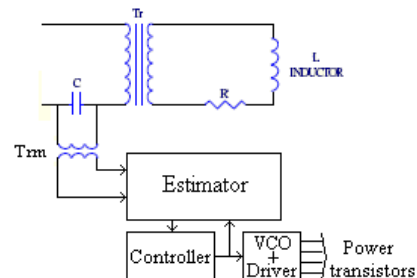


Fig. 2 – Resonant circuit with feedback and estimator

An L and R, the equivalent inductivity and resistivity, represent the heating coil. These two values were estimated using FEMM 4.2 (Magnetostatic finite element methods program) for the inductor-workpiece geometry presented in fig. 3.

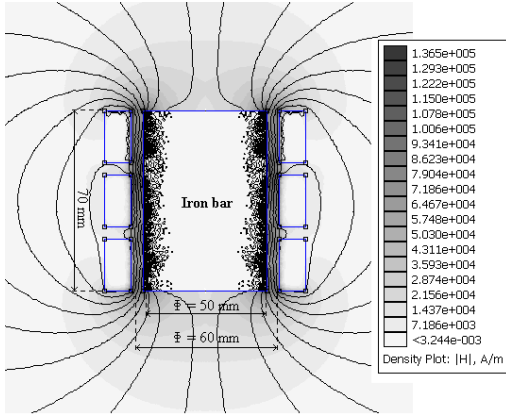


Fig. 3 – Inductor-workpiece geometry with magnetic field lines

In parallel with the load capacitor, a voltage transformer (Trm) separates galvanically and adjusts the amplitude of the supplied data to the estimator. The signal provided by this transformer contains noise due to high intensity electromagnetic fields generated by the high frequency, high intensity currents and by the switching properties of the power transistors.

The use of the Kalman filter not only provides filtering of the signal, but also allows the estimation of the unmeasurable states of the system.

3. Kalman Filter

R.E. Kalman invented Kalman filter in 1960. He proposed a recursive solution for the discrete data linear filtering problem. It is considered the optimal tracking, navigation and data prediction algorithm in many applications. Kalman filter uses the state space representation, which enables the use of the filter as a smoother, filter or predictor.

The filter minimizes the mean square error [5]

$$f(e_k) = (x_k - \hat{x}_k)^2 \quad (1)$$

Let us consider the following system:

$$\begin{aligned} x_{k+1} &= A_k x_k + B_k u_k + w_k \\ z_k &= H_k x_k + v_k \end{aligned} \quad (2)$$

Where, A: state transition matrix, B: input matrix, H: observation matrix, x: state vector, u: input vector, w: noise vector, v: measurement noise vector

The Kalman filter performs two operations: prediction and correction. When the filter is in prediction mode, it forecasts the next states taking in consideration the past states. Posterior estimation using measured data allows for the improvement of the forecast states while the filter is in correction mode. [6]

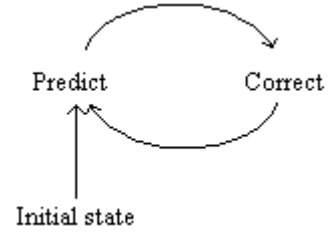


Fig. 3 – Kalman filter operations

Appropriate initial conditions for process noise covariance matrix and measurement noise covariance matrix must be chosen with care.

The Kalman filter algorithm is [7, 8]:

1. Estimate the state

$$\hat{x}_{k+1} = A_k x_k + B_k u_k \quad (3)$$

2. Estimate the covariance matrix

$$\hat{P}_{k+1} = A P_k A^T + Q \quad (4)$$

3. Compute Kalman gain:

$$K_{k+1} = \hat{P}_{k+1} H^T (H \hat{P}_{k+1} H^T + R)^{-1} \quad (5)$$

4. State vector correction

$$\hat{x}_{k+1} = x_k + K_{k+1} (z_k - H x_{k+1}) \quad (6)$$

5. Covariance error update

$$P_{k+1} = (I - K_{k+1} H) P_k \quad (7)$$

In these steps, the estimation of the next states and the covariance is made based on prior states takes place. Steps 3 through 5 implement the corrector part of the filter. First, the Kalman gain is computed (see step 3). Then the posterior estimate is calculated using the systems measured output z_k . The final step is the update of the covariance error matrix. This allows for a more accurate estimation of the next new states.

A special case is the starting of the algorithm. To be able to perform the steps 1 and 3, initial states (x_0) and the covariance matrix (P_0) have to be provided.

The advantage of this algorithm up against other filters, like Wiener filter, is the recursive nature, which makes it easier to implement.

4. State estimator of an induction heating inverter using Kalman filter

The design procedure of the filter started from the extended description function with Fourier series model developed for series load resonant inverters [9, 10]. With slight modifications for this particular application, which this paper presents, we obtained the following new nonlinear model.

$$\begin{bmatrix} \dot{u}_{cs} \\ \dot{i}_s \\ \dot{u}_{cc} \\ \dot{i}_c \end{bmatrix} = \begin{bmatrix} 0 & 1/C & \omega & 0 \\ -1/L & -R/L & 0 & \omega \\ -\omega & 0 & 0 & 1/C \\ 0 & -\omega & -1/L & -R/L \end{bmatrix} \begin{bmatrix} u_{cs} \\ i_s \\ u_{cc} \\ i_c \end{bmatrix} + \begin{bmatrix} 0 \\ 4 \\ 0 \\ 0 \end{bmatrix} \frac{\pi L}{4} U_{dc}$$

$$y = \begin{bmatrix} \sin(\omega t) & 0 & \cos(\omega t) & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_s \\ u_{cc} \\ i_c \end{bmatrix}$$

(8)

Through linearization, and taking into account that the inverter is frequency controlled, the following model resulted. The values of U_{cs} , I_s , U_{cc} , I_c , were obtained using Cramer's rule.

$$\begin{bmatrix} \dot{u}_{cs} \\ \dot{i}_s \\ \dot{u}_{cc} \\ \dot{i}_c \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1/C & \omega & 0 \\ -1/L & -R/L & 0 & \omega \\ -\omega & 0 & 0 & 1/C \\ 0 & -\omega & -1/L & -R/L \end{bmatrix}}_A \begin{bmatrix} u_{cs} \\ i_s \\ u_{cc} \\ i_c \end{bmatrix} + \underbrace{\begin{bmatrix} U_{cc} \\ I_c \\ -U_{cs} \\ -i_s \end{bmatrix}}_B \hat{\omega}$$

$$y = \underbrace{\begin{bmatrix} U_{cs}/\sqrt{U_{cs}^2 + U_{cc}^2} & 0 & U_{cc}/\sqrt{U_{cs}^2 + U_{cc}^2} & 0 \end{bmatrix}}_C$$

(9)

where: R , L and C are the resistor's, inductor's and capacitor's values from the load circuit, ω – inverter's switching pulsation, U_{cs} – capacitor voltage first harmonic sine amplitude, U_{cc} – capacitor voltage first harmonic cosine amplitude, I_s – load current first harmonic sine amplitude, I_c – load current first harmonic cosine amplitude.

To construct the estimator, we used the circuit presented in figure 2. The voltage transformer has a 10:1 transformation ratio. The signal provided by the transformer was converted to DC signal using a RMS-DC converter. This converter was made using AD736 specialized integrated circuit. Its output together with the VCO driving signal was recorded using an ADS1062CA digital oscilloscope. Figure 5 presents these recorded signals. After filtering, these signals are fed to the estimator presented in figure 6.

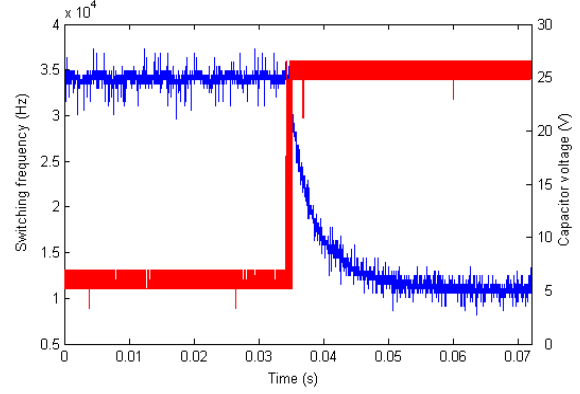


Fig. 5 – Recorded input-output signals

The program of the estimator was developed in LABVIEW v8.6, based on the Kalman Filter algorithm presented in part 3. To implement the estimator a "Flat Sequence Structure" was used[11]. Each "sequence" from the structure implements an equations from the algorithm. The algorithm begins with the pressing of the start button. The first input data is read (u_{mas} , y_{mas}). The first sequence calculates the state estimate using u_{mas} and the initial states, x_{est} . In the next iterations, the initial states are provided by the fourth sequence.

The second sequence calculates the covariance matrix using the previous value of P_k . For matrix multiplication, the $A \times B.vi$ block was used [12].

The third sequence computes the Kalman gain. It receives as input variable matrix H_k and the covariance matrix. A sequential selection is necessary to assure the correct order of execution of the mathematical calculations.

In order to compute the Kalman gain, the previous two sequences, state estimate and covariance matrix, must provide outputs.

The fourth sequence calculates the state vector correction. It receives as input: P_{est} , K and y_{mas} , and provides the next initial states for the first sequence.

The last sequence calculates the covariance error update, which is fed back to the second sequence.

The program generates a state vector of four elements:

- The first element represents the amplitude of the sine function of Fourier expansions for capacitor

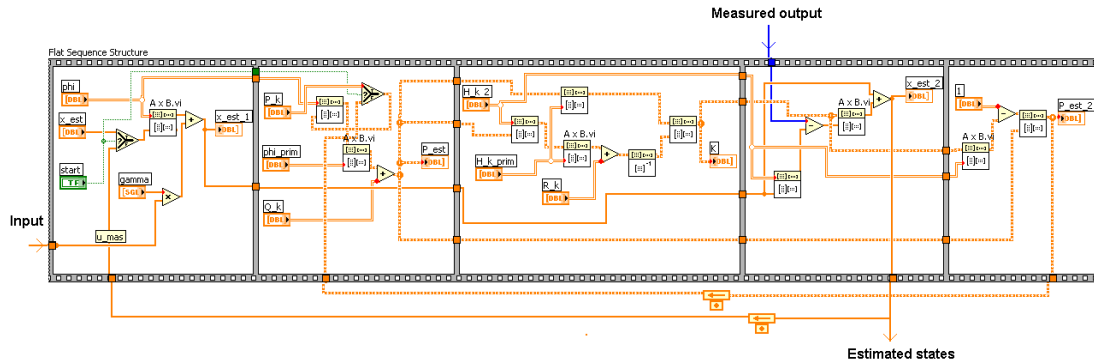


Fig. 6 State estimator practical realization

voltage (u_c);

- the second element represents the sine amplitude of load current;
- the third element represent the cosine amplitude of capacitor voltage
- the fourth element represents the cosine amplitude of load current.

Figure 7 presents the four states and the estimated system outputs. For representation Matlab plot was used. At approximately 35msec, the input signal receives a 25 kHz step. The appropriate states begin 20msec transient to the next work point. After the transient period, the following states were obtained $\tilde{x} = [-7.4 \quad 0.2 \quad -20.3 \quad -0.07]^T$

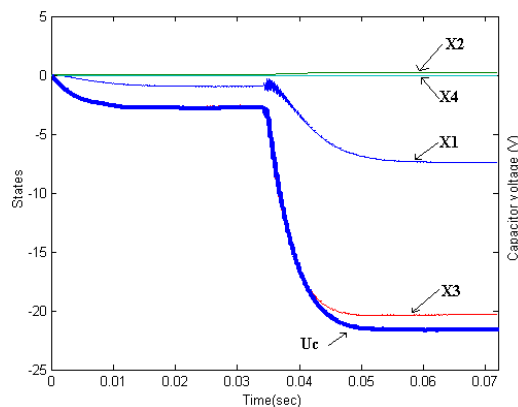


Fig. 7 – Recorded input-output signals

5. Conclusions

Observing figure 7, we can conclude that by using the Kalman filter, the systems unmeasurable states are estimable. The advantage of the algorithm is its simplicity. It runs sequentially which makes it attractive for embedded applications.

For further work, we propose to use a PXI (PCI extensions for Instrumentation), which can run LabVIEW programs and is equipped with high sampling rate analog-to-digital and digital-to-analog converters. The goal of this study is the implementation and testing of Kalman filters for LQR and H_2 controllers, which require access to the system's states.

6. Acknowledgement

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