IN-SITU SYSTEM IDENTIFICATION FOR AN OPTIMAL CONTROL OF MAGNET POWER SUPPLIES*

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Abstract

In particle accelerators, the magnet power supply system (controller, power stage and magnet) normally has a higher system order (>5). An exact model, representing the behavior of such a system, would be very helpful for an optimal control. For the control, the engineers are mainly not interested in the analytic model, which shows the exact internal mechanisms of the physical system, but, in a model describing the I/O behavior. Moreover, since the real elements do not exactly correspond to the design values, it is desirable to model the power supply system by means of system identification from measured properties. For that, a subspace based identification method is applied. It yields the observer for the self-optimizing high dynamic control of magnet power supplies at the Paul Scherrer Institute (PSI, Switzerland). The only inputs the identification needs are the measured DC-link voltage, magnet voltage and magnet current. With that it calculates a corresponding state space model for the system. The whole process is done automatically and in situ, which is a very practical and meaningful approach to obtain the exact system information for control design.

INTRODUCTION

At PSI the SOPS (Self-Optimizing Power Supplies) project was launched in 2008. An observer based high dynamic control strategy was developed [1]. For an optimal control, it is essential to have an observer model that describes the behavior of the power supply and the magnet exactly. The observer uses standard LTI (Linear Time Invariant) time discrete state space description (see Eq.1). To obtain the observer model, i.e. A, B, C and D matrices, a subspace identification method is applied.

The basics of the subspace identification method will be introduced shortly. Following, its application on magnet power supplies will be presented. The stimulation used for the identification measurement is investigated. Other key factors, such as system order determination and system inherent delay, will be discussed as well.

$$\begin{cases} x(k+1) = A\,x(k) + B\,u(k) \\ y(k) = C\,x(k) + D\,u(k) \end{cases} \qquad (1)$$

PRINCIPLE OF SUBSPACE IDENTIFICATION

The subspace identification method is a 'black box' identification method. The only needed information is the measured input sequence $u(k)$ and output sequence $y(k)$,

k= 0, 1, …, N_m-1. All calculations are based on algebraic operations and don not involve explicit optimization criteria. The result of the identification is a time discrete state space system description, with the same I/O behavior as the measured system.

Estimation of Matrices A and C

An ordinary MOESP (Multivariable Output Error State sPace) method is used to determine the matrices A and C. For that an I/O property matrix, with a size of n' by N, is constructed (see Eq.2) from the measured I/O sequences, where $N= N_m-n'+1$. Here n' should be larger than the system order n and N should be significantly larger than n'. This matrix is the base for the further numerical calculations. The basis of the column space of the extended observability matrix $[C; CA; …; CA^{n'-1}]$ is recovered by performing first LQ factorization and then singular value decomposition (SVD) to the input/output property matrix. The system order information is an output of the SVD calculation. Finally, the matrices C and A are estimated from the extended observability matrix.

$$\begin{bmatrix} U_{0,n',N} \\ ----- \\ Y_{0,n',N} \end{bmatrix} = \begin{bmatrix} u(0) & u(1) & ... & u(N-1) \\ u(1) & u(2) & ... & u(N) \\ ... & ... & ... & ... \\ u(n'-1) & u(n') & ... & u(N_m-1) \\ ----------------- \\ y(0) & y(1) & ... & y(N-1) \\ y(1) & y(2) & ... & y(N) \\ ... & ... & ... & ... \\ y(n'-1) & y(n') & ... & y(N_m-1) \end{bmatrix} \qquad (2)$$

Estimation of Matrices B and D

An extended state space model can be constructed (see Eq.3), by making successive iterations to (1). With the estimated matrices A and C, as well as the measured I/O sequences $u(k)$ and $y(k)$, the matrices B and D can be obtained by solving these first order linear equations, basing on a least square method. For detailed information about this method, refer to [3] and [4].

$$\begin{bmatrix} y(0) \\ y(1) \\ ... \\ y(N-1) \end{bmatrix} =$$

$$\begin{bmatrix} C & | & 0 & | & u(0)^T \otimes I \\ CA & | & u(0)^T \otimes C & | & u(1)^T \otimes I \\ ... & | & ... & | & ... \\ CA^{N-1} & | & \sum_{\tau=0}^{N-2} u(\tau)^T \otimes CA^{N-2-\tau} & | & u(N-1)^T \otimes I \end{bmatrix} \begin{bmatrix} x_0 \\ B \\ D \end{bmatrix} \qquad (3)$$

MAGNET POWER SUPPLY IDENTIFICATION

Figure 1 displays the setup of the magnet power supply. There are three measured properties available: The DC-link voltage $u_{dc,m}$, the magnet voltage $u_{M,m}$, and the magnet current $i_{M,m}$. They are measured with ADCs, stored in the memory of the digital controller, and read back to the PC for further process.
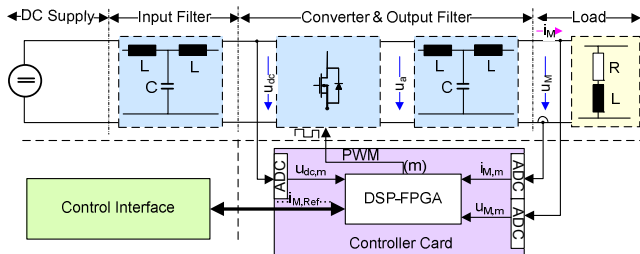

Figure 1: Power supply block diagram.

Stimulation Considerations

A proper stimulation is essential for the measurements to guarantee the quality of the subspace identification results.

There are two groups of information of interest in the system: those of the output filter and those of the load. The time constants of the output filter and the load are quite different: those of the load are usually much larger than those of the filter. The stimulation shall excite the system such that the outputs contain enough information for both filter and load identification, within the limited measuring period. In addition, from a pure mathematical view, the I/O property matrix (see Eq.2) should be well conditioned matrices, to guarantee a reliable identification result. This asks for a stimulation which gives a good frequency distribution in the output signal. Noise could be a good choice as a stimulus, but the amplitude of the noise has to be 'large enough', such that the corresponding output is not buried in the additional measurement noise.

In this application, the step changes of the PWM modulation index m, a main step together with some additional stochastic small steps, are used to excite the system. This can easily be implemented on a digital controller. The chosen stimulation yields best results for both power stage and load identification. The 'slow main step' is for the load and the 'fast stochastic steps' are for the filter identification. Each step should last 'long enough' to make sure the slowest response can be captured. To keep the system within a linear region, only small step changes shall be used.

Identification of the Power Supply System

Without any current regulation (only safety supervision), the final setup of the system is excited with the presented stimulation. As the step changes of the modulation index are made at a certain operating point, the initial values of the measurements have to be subtracted for the identification, i.e. only the differences

are considered. In addition, to model the influence of the input stage, u_a is used instead of the modulation index in the identification. Since there is no direct access to u_a, it is derived from the measurements $u_{dc,m}$ and the step changes of the modulation index Δm with $u_a(k) = \Delta m \cdot u_{dc,m}(k)$.

- Modulator, converter and output Filter:

To model modulator, converter and output filter, the sequences u_a and $u_{M,m}$ are the two inputs for the subspace identification procedure. The result is its time discrete state space description with voltage as an output.

- Magnet:

The load model is identified from the measured magnet voltage $u_{M,m}$ and current $i_{M,m}$.

- Modulator, converter, output filter and magnet:

The model of the whole system, input voltage to output current, can be obtained via a single identification, by using the sequences u_a and $i_{M,m}$ as the two inputs.

The method also allows dealing with the Multiple Input Multiple Output (MIMO) systems. For example, by taking the sequence u_a and the combined vector [$u_{M,m}$, $i_{M,m}$] as two inputs, the system model with both, voltage and current outputs, can be identified with a single identification only.

Result Demonstrations

The following results, the identification of the power stage and the load, are based on a 12V/10A corrector power supply and a corrector magnet as they are used in the SLS at PSI. The controller card is the new generation PSI Digital Power Electronic Control System (DPC) [2]. The control cycle time (sampling time) used is 10us.
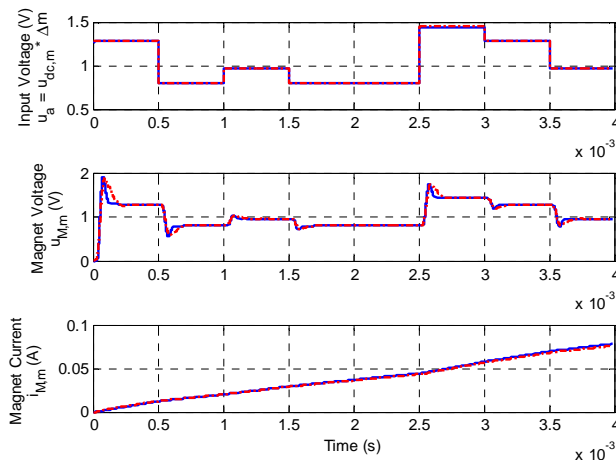

Figure 2: Measurements from the mathematical model (blue) and the real system (red).

For the development of this method, a power supply and load model is set up using the design values of the elements (mathematical models). The blue curves in Figure 2 show the measured sequences from the mathematical model. Since the mathematical model is exactly known, to show the quality of the identification, the comparison between the mathematical models and the identification results from them can be made with the frequency response of the models, as shown with the back

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and the blue curves in Figure 3. (The red curves show the behaviors of the identified models from the real system, which can deviate from the mathematical models.) Solid lines describe the power stage and dashed lines the load.
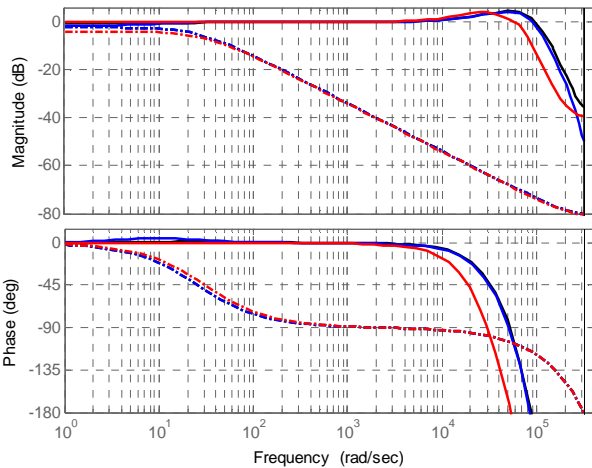

Figure 3: Behavior of the mathematical models (black) vs. that of the identified models (blue and red).

The identification of the real system is done around 50% of the nominal current. The measurements are shown with the red curve in Figure 2. Since the real system is not exactly known, the measured I/O behavior and that of the identified models are compared to show the quality of the identified models. Figure 4 shows both the measured outputs and the identified model outputs. The output voltage of the model is obtained by feeding u_a to the identified power stage. The output current from the load model is obtained by feeding $u_{M,m}$ to the identified magnet.
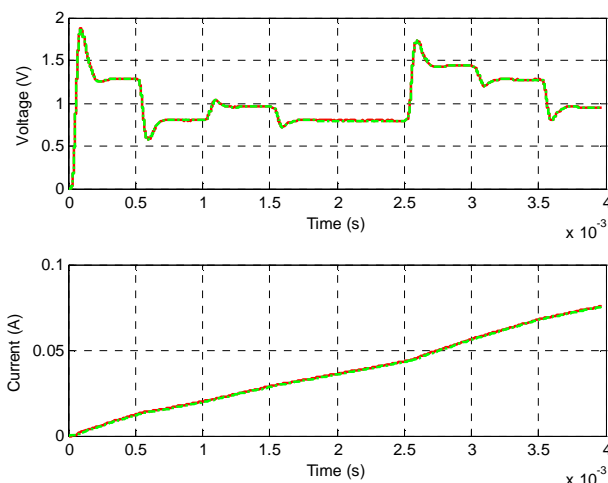

Figure 4: Measured behavior from the real system (red) vs. identified model behavior (green).

From both, Figure 3 and 4, it can be seen that the identified models correspond very well with the measured system. There is only a minor deviation at the frequency range close to the Nyquist frequency (in Figure 3 at $3.14 \cdot 10^5$ rad/s).

Discussions

Some additional points have to be taken into account to make sure the quality of the identification:

- System order:

Mathematically the system order n can be obtained via SVD calculation. The dominant singular values contain the information of the physical system and all the others, which are (should be) much smaller than the dominant ones, are from measurement delay and noise etc [4]. However, it is a difficult task to figure out the border. An alternative is that the user gives some information about the system order. It is preferable to stick to the possible order of the physical system for the sake of a better identification results.

- System inherent delay:

The measurements induce delay into the identified models. The system inherent delay can be excluded from the identified models by skipping the small samples at the beginning of the sequences. This can be done by analyzing the pole-zero pairs forming all-pass, which model the delay, from the identified models.

- Noise:

It is recommended, that the same measurement procedure be repeated several times. Averaging of the measurements reduces the noise level in the measurement data.

- *D* matrix:

Usually, there is no direct pass-through in the system, i.e. $D = 0$. But, the identification provides a matrix with all elements closed to 0. For better control results, it is recommended that the D matrix be set 0.

CONCLUSIONS

Compared to the physical system, identified models have a limited frequency range (below the Nyquist frequency) due to the time discrete structure. In addition, their internal states have no direct physical meanings. But they are easy to get and to use!

Subspace identification provides an alternative way of modeling systems in situ, without any hardware changes. The obtained models can be used in both normal control design and high dynamic model predictive control.

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