Review on Industrial Permanent Magnet Synchronous Machine Servo Systems: Parameter Estimation and Auto-tuning Concepts

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***Abstract*— One of the result of the advanced industrial technology, industrial servo drive systems need advanced skills for managing the system and motion. Industrial servo systems have challenging mechanical characteristic for sensitive control and accurate stability of driver systems. These mechanical issues occur with respect to drive train of servo systems such as mechanical assembly, motion elements, motion types and load characteristics. In this context, on the driver and control side, there are several approach and solution of tuning methods for mentioned mechanical issues and system deviations. In this paper, problematic issues and offered solutions about parameter estimation and auto-tune process in the current literature for servo drive systems are defined and systematized.**

***Index Terms*—Servo Drive Mechanics, Mechanical Servo Issues, Filtering in Servo, Servo Control**

I. Introduction

A WELL tuned servo system is robust and has the fastest possible response with (negligible or) no overshoot and steady state error. But, a well tuned servo system can lose its accurate response with disturbances that come from the mechanical dynamics of operated drive train. Drive train of a servo system contains controller-driver, motor and load. Controller-driver can be defined as white box, motor can be defined as grey box and load can be defined as black box. In this concept, tuning of the whole system can be done by controller-driver via motor with reflection from load to motor shaft. The main principle in tuning a servo system is detecting the unwanted situations from motor and controller side and to suppress them. For this purpose, we have to define the unwanted situations with using mathematical models and their effects on the parameters (both electrical and mechanical) of the system for starting the tuning process. After defining the mathematical model, the system must overcome the situations that will cause problems in the parameter estimation process described below.

- Rank Deficient Problem: In one operation step, the parameters can be calculated as much as the rank number of the math equation set.
- Persistent Excitation Problem: Input and output signals that provide information to the parameter estimation process must contain sufficient data signal and must be fast enough to ensure continuity.
- Rotor Position and Nonlinearity Problem: Aligning the magnetic axes of magnets with phases in PMSM-based systems is critical for the correct operation of the dynamic equations of the machine (rotor position information in the software). In addition, nonlinear current or voltage characteristics caused by the inverter on the driver's side should be taken into account in parameter estimation processes.

There are two strategies for operating the tuning process as known Off-line and On-line. Off-line tuning the servo system means that defining process is done under the zero or no-load (dummy) motions []. This type tuning can be done by using some previous information (commission) or without any information (self-commission) about any part of the system. The other type On-line tuning the servo system means that defining process is done during the loaded motions. This type tuning is more complicated than Off-line tuning because it needs dynamic measurements and decision mechanism in parallel with the work done by servo system [].The generalized flow charts of both strategies are shown in fig 1. Possible useful methods are demonstrated for each step. Detection of the unwanted situations (disturbances) is the first step of both strategies.

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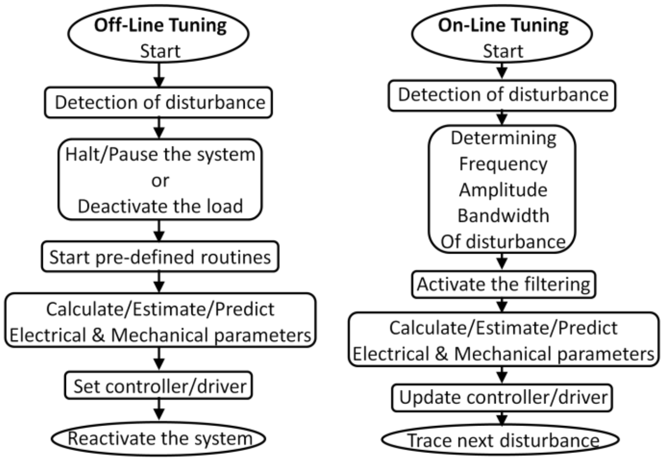


Fig. 1. Off-Line and On-Line auto-tuning flowcharts.

In real servo systems, these disturbances act as vibration, friction and mismatch []. These disturbances create detectable mechanical characteristics effects on the motor shaft that can appear as position, torque, speed, voltage or current error from controller/driver side indirectly []. Also, some of them can be detect by observation (manually or algorithmic) or using some model state variables []. After detection of the disturbance process, off-line tuning process halt or pause the system (motion is stopped) or system is unloaded (dummy motions). Then the system tries to understand the disturbances with using pre-defined routines that can be voltage/current injections, to try specific motion profiles, torque measurements, movements pushing the boundaries, specific position tracking or regular movements as same as loaded condition []. After this process system calculates or estimates the critical parameters, which are electrical, mechanical, model based or state variables, with using measured data from pre-defined routines. New parameters are integrated the controller/driver system and if need controller/driver parameters are updated with respect to new dynamics. System is reactivated []. When we look the On-line tuning process, it keeps going the regular motion (with load) with calculating the disturbance properties, which are mainly frequency, amplitude and bandwidth, as a parallel process. In this process, since the under load system is not suitable for injection signal or specific profiles, existing under load signals are used for calculation or estimation. Because of this challenge, as a parallel process, Fourier Transform based signal process, model based estimator, observer, predictor, iteration algorithms, adaptive mechanism, filtering techniques are used for determining the disturbance properties []. Also, there are some filter based (band-pass) scanning approaches for detecting the disturbance with characteristics []. After detection of disturbance properties, a filtering operation, which is mostly notch filters (in some applications low-pass and high pass topologies are used), is used for suppressing the detected disturbance during regular operation (under load) of servo systems. Some of the designers try to combine detection of the properties of the disturbance and suppression operation in same step. In this case, one of the approaches is observer/estimator strategy. In this approach an observer/estimator structure, which contains state-space equations (position, speed, voltage/current) and time dependent data collected from system, traces the system dynamics and evaluate the near future data from past data with using trajectory. Kalman Filter based estimators are commonly used for this approach []. Another commonly used approach, which is known as Model Referenced Adaptive System (MRAS) is creating and controlling/driving a model in parallel with the actual system and comparing or evaluating the data from model and actual system for tuning the system []. MRAS based other adaptive systems also derived []. Some of the systems contain Fuzzy logic, Artificial Intelligent (AI) based structures, Neural Network (NN) strategies and Swarm Intelligence (SI) based self-organized systems but they need much more computing capability and have implementation hardness because of the hardware limits (FPGA is one of the solution such designs) [].

II. MECHANICAL ISSUES

Most of the servo systems have a specific mechanical architecture and load properties as known drive train. A servo drive train can be characterized three different motion profiles as linear motion, circular motion and contour motion. Providing these motion, there are several mechanical auxiliaries such as, pulley-belt, lead-screw, rack-pinion, belt-wheel, conveyor and gear-wheel structures (fig.2).

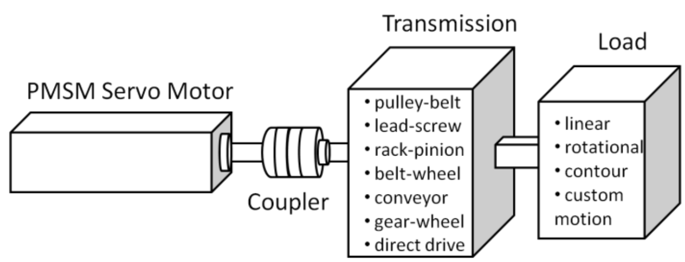
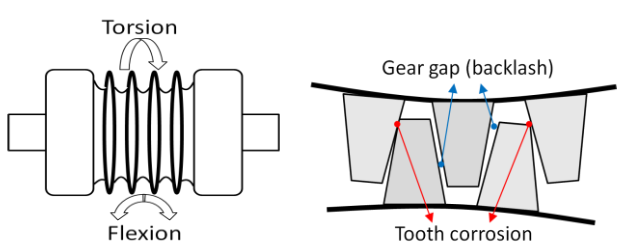


Fig. 2. Industrial servo system drive train.

These structure contains some mechanical parts are listed as rolling mill, long shafts, large inertia, bearings, elastic couplings, rail, damping elements, belt, gears etc. return vibration (resonance or randomly), friction or sliding on the transmission and then these effects are seen by motor side as reflected inertia, viscous friction and torque (from controller/driver side as position, speed, voltage/current error).



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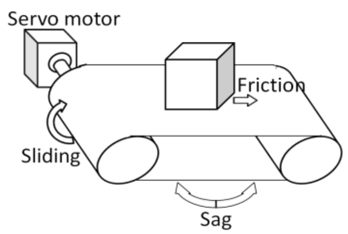


(c)

Fig. 3. Vibration and friction sources in servo drive train. (a) Elastic coupling, (b) Gear transmissions, (c) Conveyor transmission.

These type mechanical issues must be compensated as possible as by controller/driver structure with using a detection-filtering method. For this purpose electrical and mechanical parameters of the system and auxiliary variables, which are used for modeling or defining the reflections must be defined in controller side as shown in Table 1.

TABLE I
SERVO SYSTEM MAIN PARAMETERS AND VARIABLES

Variables	**Electrical Parameters**	**Mechanical Parameters**
P: Pole number	r_s : Series resistance	T_e : Electromech. torque
w_r: Speed elect.	L_d : d-axis inductance	T_L : Load torque
θ_r: Angle elect.	L_q : q-axis inductance	K_t : Torque constant
s: Laplace operator	K_e : Back EMF const.	J : Rotor and load inertia
v_{do}, v_{qo}:Back EMF, Cross coupling volt.	λ_m : PM flux linkage	B: Viscous friction coeff.

III. Modeling

A. Motor Model

Modeling of the servo drive train have critical role in tuning operation because the real system behavior have to run in the controller side. Modeling can be categorized in three main parts as mechanical model, machine model, controller/driver model. For this purpose, PMSM machine (there are two types as SPMSM and IPMSM) mathematical model with respect to stationary rotating d-q frame is given in fig.4 and as follows.

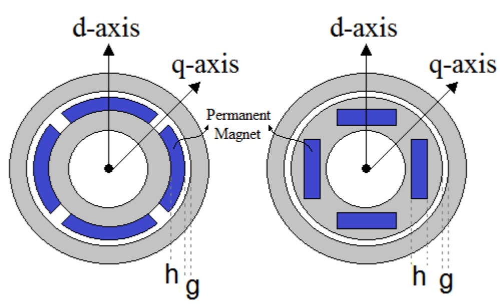


Fig. 4. SPMSM and IPMSM structure and d-q frame axes.

For SPMSM: $$L_d = L_q = \frac{\mu_0 N^2 A}{2(g+h)} \tag{1}$$

For IPMSM: $$L_d = \frac{\mu_0 N^2 A}{2(g+h)}, L_q = \frac{\mu_0 N^2 A}{2(g)} \tag{2}$$

d-q axis voltage/current (v_d, i_d, v_q, i_q), speed and torque expressions with respect to rotating d-q frame are given below.

$$\frac{di_q}{dt} = \frac{1}{L_q}\left(v_q - r_s i_q - \frac{P}{2}\lambda_m w_r - L_d w_r i_d\right) \tag{3}$$

$$\frac{di_d}{dt} = \frac{1}{L_d}\left(v_d - r_s i_d + L_q w_r i_q\right) \tag{4}$$

$$\frac{dw_r}{dt} = \frac{P}{2J}\left(T_e - \frac{2B}{P} w_r - T_L\right) \tag{5}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_m i_q + \left(L_d - L_q\right) i_d i_q\right) \tag{6}$$

Equations (3-6) represent a PMSM machine mathematical model and variables in these equations are referred by Table 1. The state-space representation is also critical for the designing control structure. Generally, the drive method is field oriented control (FOC) for the PMSM based servo systems. i_d current is kept zero to provide stator current vector kept along $q - axis$ direction (T_e is linearly proportional to the $q - axis$ current in closed loop control). Also, for the simplicity we can select SPMSM ($L = L_d = L_q$). With these simplifications, we can describe the state-space representation of the SPMSM as shown eqs. (7-9).

$$\dot{x} = Ax + Bu + Ee \tag{7}$$

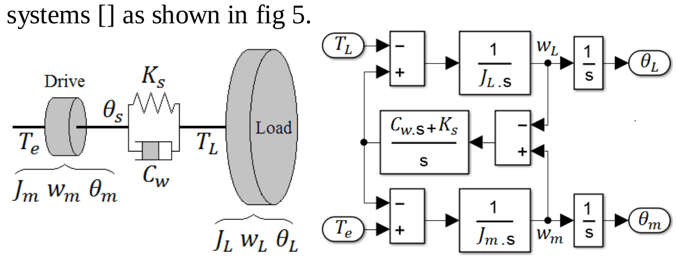
$$y = Cx \tag{8}$$

$$A = \begin{bmatrix} -\frac{r_s}{L} & -\frac{\lambda_m P}{2L} & 0 \\ \frac{\frac{3}{2}P\lambda_m}{J} & -\frac{B}{J} & 0 \\ 0 & 1 & 0 \end{bmatrix} B = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} E = \begin{bmatrix} 0 \\ -\frac{P}{2J} \\ 0 \end{bmatrix} C = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}^T \tag{9}$$

Where, the state $x = [i_q \quad w_r \quad \theta_r]^T$, input $u = v_q$ and disturbance $e = T_L$. In this case, the rank of the system is equal to 1. This means that, only 1 parameter can be calculated in each operating cycle (Rank Deficient Problem). Systems operated with i_d current, that is slightly larger than zero, it is to make the rank number 2 and solve 2 parameters in one process step.

B. Mechanical Model

Experimental mechanical implementation of the servo systems are created by using two ways as using flywheels [] or two or three mechanically coupled motors system (one of them represent motor, other one acts as load). In general, they are called two-mass (motor-load) or multi-mass (motor - coupling1 - load1 - coupling2 - load2 – coupling n - load n) systems [] as shown in fig 5.



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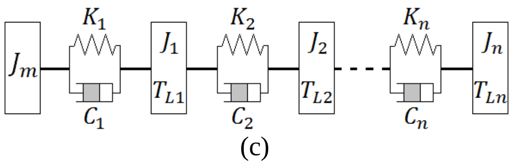


Fig. 5. Mechanical model, (a) two-mass system physical model (b) two-mass system mathematical block model (c) multi-mass model

In two mass model approach, there are two sides that are connected with a coupling or any connector. Each sides (driver and load) have dependent torque (T), inertia (J), speed (w) and position (θ). The dependence is comes from coupling that has two critical parameters as stiffness (K_s) and damping (C_w).

C. Controller/Driver Model

In controller side, most of the servo drive systems use Field Oriented Control (FOC) in rotating d-q frame. Position, speed and current/voltage control loops are located sequentially and they are controlled by PID []. Some specific applications (torque dominant) use Direct Torque Control (DTC) technique if there is no need any sensitive speed or position control need []. Another control action for these systems is Model based control systems. These type controller works with a mathematical model of a plant (only motor or motor with load) and a predictor, estimator or adaptive structure []. In driver side, three phase inverter with sine PWM or Space Vector PWM techniques are commonly used. Also, specific vector tables for DTC or look-up tables for model based control systems are used. Generic structure about control strategies are given in fig.6.

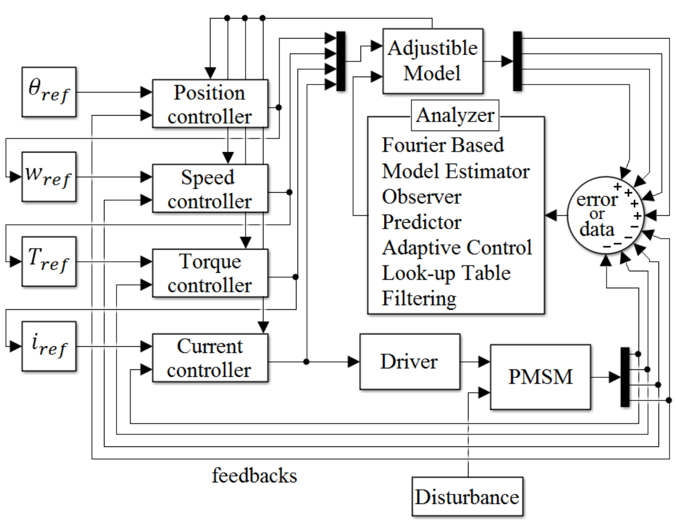


Fig. 6. Generic controller/driver approach for auto-tuning and parameter estimation in servo systems.

IV. Disturbance Detection

The main idea of auto-tuning process is detecting the disturbance signal from feedbacks or measured data of the servo system. An unknown electrical signal has three main characteristic such as frequency, amplitude and bandwidth (or duration of disturbance). Also another critical data about disturbance is formation, which can be form of specific function, periodic or non-periodic. In addition, non-periodic formations can be categorized as follows, pure random, limited random, changing in certain order or dependent to any system's variable (electrical or mechanical).

A. Frequency Domain Analysis Based Techniques

The main works of frequency analysis techniques concentrate around Fourier based analysis. In Fourier transformation based techniques, detection system contains two main parts as signal analyzer in frequency domain and filter. This technique needs excessive computing ability (high process DSP). The work flow of this technique contains three basic processes. The first one is collecting the position, speed, current/voltage or torque error data (whichever system is controlled) and these data is saved in a memory element. After that Fourier analysis of collected data is done. At this step classical FFT or DFT computation takes much more time in real time systems. Overcome this challenge, designers determine a resolution for FFT computing according to overall servo system needs. For this purpose, shifted DFT (SDFT) (DFT computing is done when the frequency window is shifted with fixed length) or DWT techniques are in use. Similar approach is used in sweep frequency response analysis (SFRA). In this approach, plant (servo motor and load) is excited by sine wave with consecutive frequency intervals (generally, 5-10 Hz increment is selected and plant is excited after that, results are evaluates in frequency domain with DFT analysis) [A Friction Model-Based Frequency Response Analysis for Frictional Servo Systems Yoshihiro Maeda]. Another technique in same manner is obtaining transfer function (Empirical transfer function estimate, ETFE) of the plant in frequency domain with using DFT. After that processed data can be grouped with using average based methods for data compression (for creating a kind of resolution) or impulse responses can be evaluated (like SFRA). The main logic is decrease the computing time with decreasing the detection frequency resolution of system (2048 point data with Advantech 610H industrial control computer takes 3ms for traditional DFT, 0.1ms for SDFT) [jian kang online detection and suppression]. The second step is, collected and transformed data are sorted (or grouped) with respect to amplitude or center frequency. In this stage, it is known that motor and load controller variables (position speed, current/voltage, torque) are oscillating at resonance frequency. So, in sorted data, the most dominant frequency (or the biggest amplitude) refers to resonance frequency of the system and other ones are vibrations or frictions sourced. The last step is filtering the significant frequencies with side lobes. The coefficients of filter (According to specifications, system has one or more than one filter action such as notch with multi channel, low-pass, high-pass, band-pass) are set. After activating the filtering, disturbance of the system eliminated and controller reference signals are purified. Fig. 7 shows that generic block diagram and FFT analyzer with DSP block (encircled) where detection steps run. Also, a filter block is complement of the detection system.

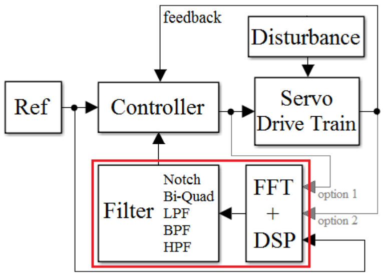


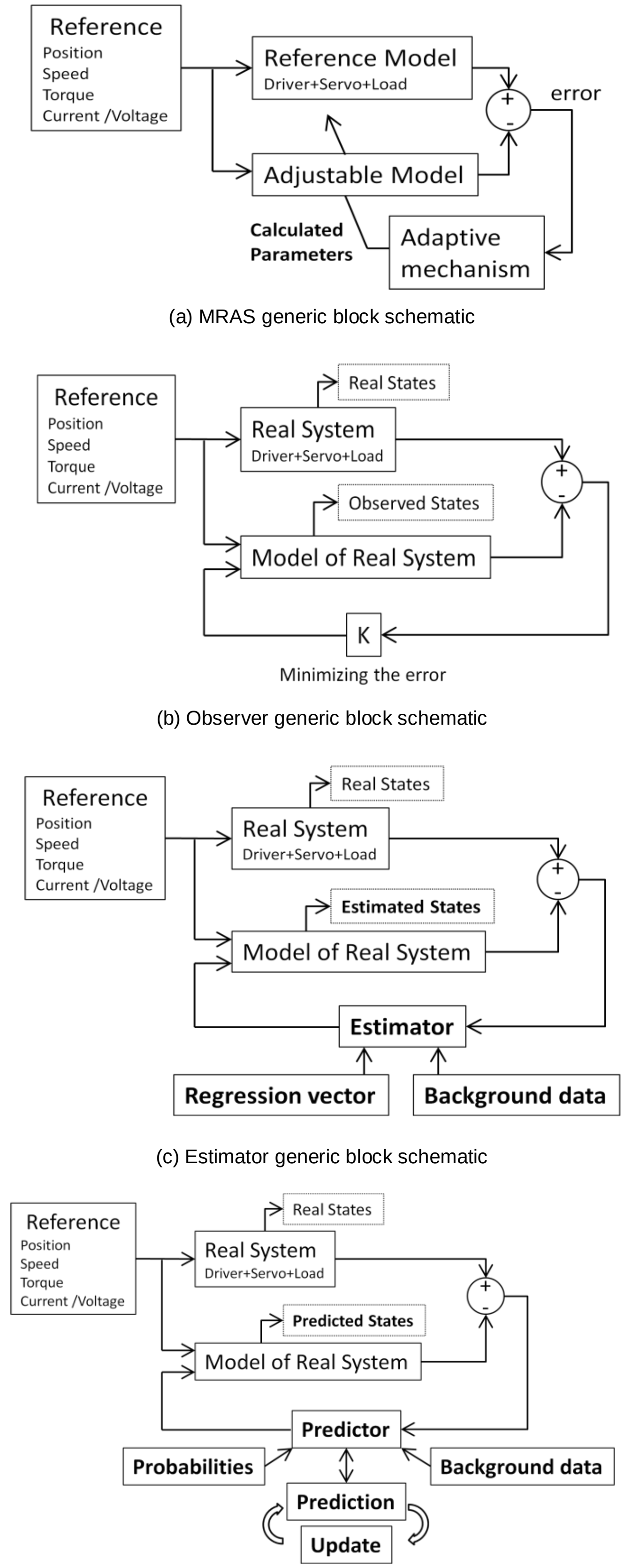
Fig. 7. FFT based disturbance detection system generic block diagram.

Stable results are obtained with this technique, but there is a need for hardware that can work with microprocessors and memory units with high processing capability. The parameters obtained in the frequency domain can be used directly in digital filters and can be integrated with look-up tables.

B. Model Based Estimator/Observer/Predictor

MRAS(Online adaptive parameter identification of PMSM based on the dead-time compensation)

The main aim for this technique is to calculate the system parameters or control variables with using linear or nonlinear mathematical model of the plant (motor and load) in time or frequency domain. For this purpose, servo system dynamic behavior must be modeled and executed. Estimator, observer or predictor uses measured data from physical plant and model data and evaluates with statistical methods and system specific calculations. The basic difference between estimators and predictors is feature of produced data. Estimators creates the output data with respect to created trajectory from background information (which is called in models as regression vector), on the other hand predictors creates data that may contain limited randomness and background data. In observers, the operation is based on data or error tracking or comparison of model data and real data. Generally observers work with an estimator or predictor block (i.e. Kalman filter). In servo system dynamics, estimators are heavily used because most of the servo systems are used in industrial applications with known limited motion profiles. More advanced servo systems (i.e. underwater systems, military purposed usage) contain observer with predictor controller. MRAS can be evaluated in a separate category. An adjustable model running parallel to the reference model is updated iteratively. This process performs parameter calculation by passing the difference (error) of the signals coming from the reference model and the signals produced by the adjustable model through an adaptive process block. It tries to compare and equalize these parameters with the reference system. The single structures of the mentioned parameter determination techniques are given in fig. 8.



(a) MRAS generic block schematic

(b) Observer generic block schematic

(c) Estimator generic block schematic

(d) Predictor generic block schematic

Fig. 8. The control blocks for determining the parameters in servo systems (a)MRAS (b) Observer (c) Estimator (d) Predictor.

A classical linear model of a system can be generalized in a form as given in eq(7).

$$y(x) = \boldsymbol{\alpha} u(x) + \boldsymbol{\beta} e(x) \tag{7}$$

$y(x)$ is the output, $u(x)$ is the input and $e(x)$ is the noise, disturbance or error of the system. Dynamic behavior of the system is embedded in $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ expressions (may be polynomials or state space matrices). Expanded version of eq(7) is given in eq(8-9) that is the generalized version of a linear system mathematical representation with polynomials. All linear models (AR: '$A, B, C, D = 1$', ARX: '$C, D, B = 1$', ARMA: '$A, B, D = 1$', ARMAX '$D, B = 1$', OE: '$K, C, D = 1$') can be derived from this generalized linear equation.

$$y(x) = \frac{A(z)}{K(z)B(z)} u(x) + \frac{C(z)}{K(z)D(z)} e(x) \tag{8}$$

$$\begin{aligned} y(x) \\ = \frac{a_1 z + a_2 z \ldots + a_{an} z}{(1 + k_1 z + k_2 z \ldots k_{kn} z)(1 + b_1 z + b_2 z \ldots b_{bn} z)} u(x) \\ + \frac{(1 + c_1 z + c_2 z \ldots c_{cn} z)}{(1 + k_1 z + k_2 z \ldots k_{kn} z)(1 + d_1 z + d_2 z \ldots d_{dn} z)} e(x) \end{aligned} \tag{9}$$

C. *Input Configured Excitation Methods*

(A fast online full parameter estimation of a PMSM with sinusoidal signal injection)

D. *Artificial Intelligence Based Methods*

E. *Other Methods*

Current ripple (Using the Stator Current Ripple Model for Real-Time Estimation of Full Parameters of a Permanent Magnet Synchronous Motor)

(Online multiparameter estimation of nonsalient-pole PM synchronous machines with temperature variation tracking)

V. Filters and Compansators

(A New LMS Algorithm Based Deadtime Compensation Method for PMSM FOC Drives)

T twin notch, notch, band pass,

VI. System Management

If you are

VII. Conclusion

VIII. Conclusion

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

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