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

First A. Author1, *Membership*, Second B. Author2, *Membership,* and Third C. Author3, *Membership*

***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. An Overview 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 [1]–[3].

- Rank Deficient Problem: In one operation step, the parameters can be calculated as much as the number of rank of the math equation set.
- Persistent/Insufficient Excitation Problem: Input and output signals provide information to the parameter estimation process that 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 parameter estimation and 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 [4]. 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 [5], [6].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. 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

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(Authors' names and affiliation) F. A. Author1 and S. B. Author2 are with the xxx Department, University of xxx, City, State C.P. Country, on leave from the National Institute for xxx, City, Country (e-mail: author@domain.com).

T. C. Author3 is with the National Institute of xxx, City, State C.P. Country (corresponding author to provide phone: xxx-xxx-xxxx; fax: xxx-xxx-xxxx; e-mail: author@ domain.gov).

position, torque, speed, voltage or current error from controller/driver side indirectly [7].

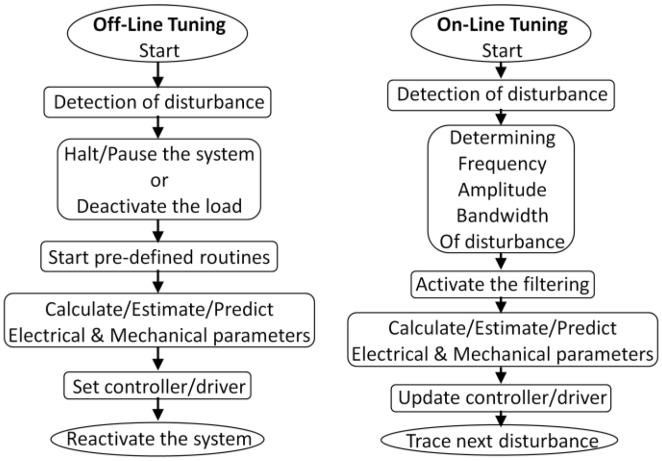


Fig. 1. Off-Line and On-Line auto-tuning flowcharts.

Also, some of them can be detect by observation (manually or algorithmic) or using some model state variables [8]. 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 [9]. 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 [10], [11]. Also, there are some filter based (band-pass) scanning approaches for detecting the disturbance with characteristics [12]. 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 [13], [14]. 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 [15]. 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) [16].

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).

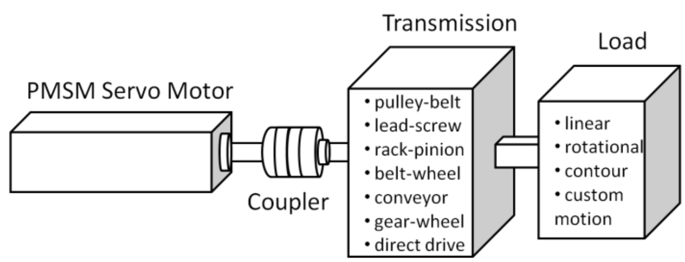
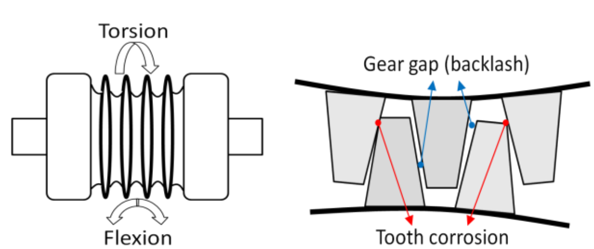
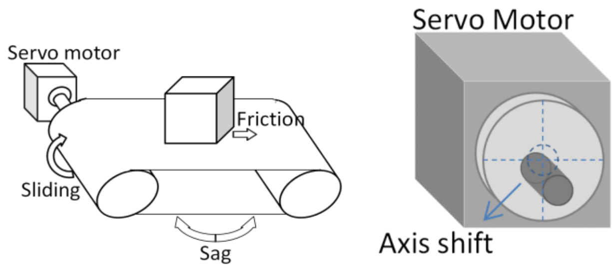


Fig. 2. Industrial servo system drive train.

These structure contains some mechanical parts are listed as rolling mill, long shafts, large inertia, bearings, elastic couplings, rail, damping elements, belt, gears (with backlash) [17] 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) [18]–[21].





(c) (d)

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

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) [22] mathematical model with respect to stationary rotating d-q frame is given in fig.4 and as follows.

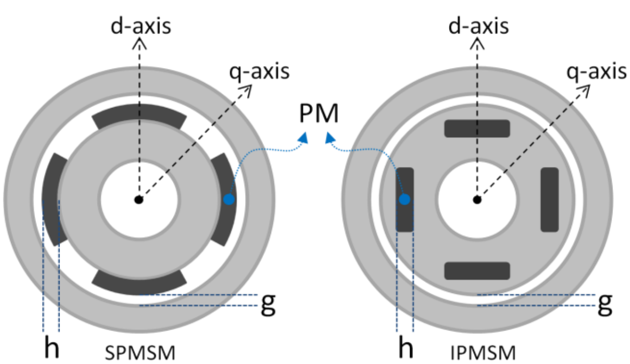


Fig. 4. SPMSM and IPMSM structure and d-q frame axes.

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

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

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.

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

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

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

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

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).

$$\dot{x} = Ax + Bu + Ee \quad (7)$$

$$y = Cx \quad (8)$$

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

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 [23]–[25].

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. 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) [11], [26], [27].

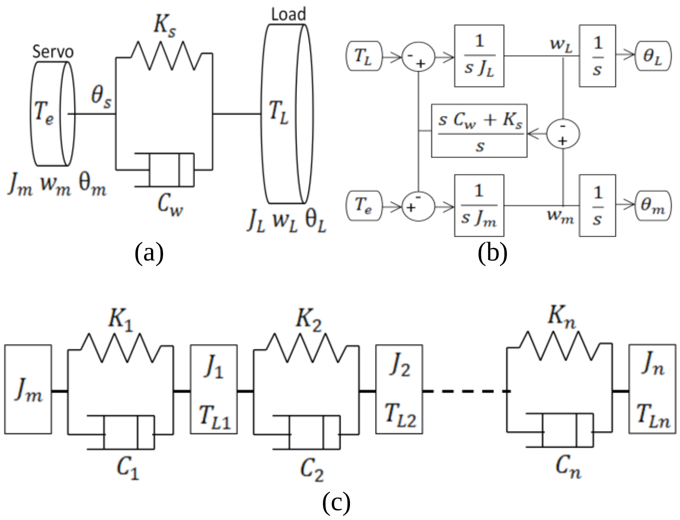


Fig. 5. Mechanical model, (a) two-mass system physical model (b) two-mass system mathematical block model (c) multi-mass model

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 [28]. 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 [29]–[31].

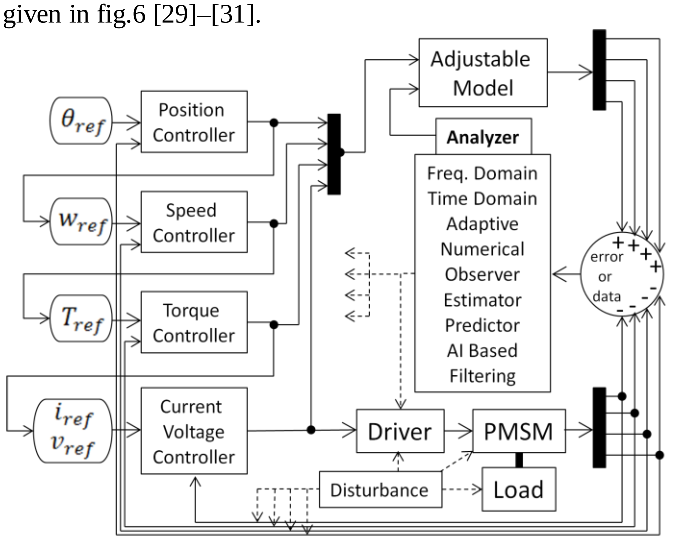


Fig. 6. Generic controller/driver approach for auto-tuning and parameter estimation in servo systems.

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 Frequency Response Function (FRF) with using 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 [32]–[34]. 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) [20]. 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) [35]. 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) [7]. 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 where detection steps run. Also, a filter block is complement of the detection system [36].

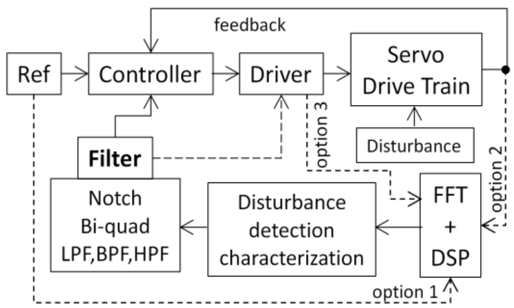
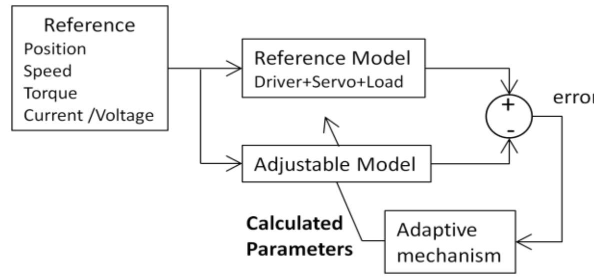


Fig. 7. FFT based disturbance detection system generic block diagram.

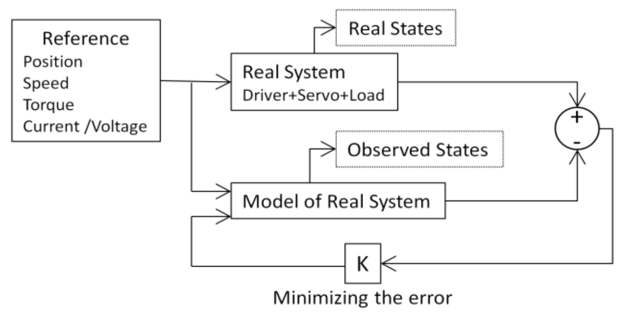
Stable results are obtained with this technique, but there is a need for hardware that can work with microprocessors and memory units with high processing capability. The parameters obtained in the frequency domain can be used directly in digital filters and can be integrated with look-up tables.

B. Model Based Estimator/Observer/Predictor

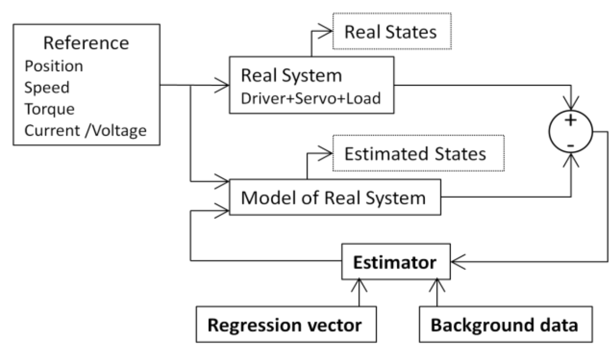
The main aim for this technique is to calculate the system parameters or control variables with using linear or nonlinear mathematical model of the plant (motor and load) in time or frequency domain. For this purpose, servo system dynamic behavior must be modeled and executed. Estimator, observer or 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 input and 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 [37]. While reduced order observers are used for calculation such basic mechanical parameters J, T_e, T_L (or K_t) [38], [39], generally, observers work with an estimator or predictor block (i.e. Kalman filter) [40]. Adaptive, sliding-mode, disturbance observers are basic ones [41], [42]. In servo system dynamics, estimators are heavily used because most of the servo systems are used in industrial applications with known limited motion profiles. Recursive Least Square (RLS) estimation and modified versions [43], maximum likelihood, Kalman based estimators are the basic applications. 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 [44], [45].



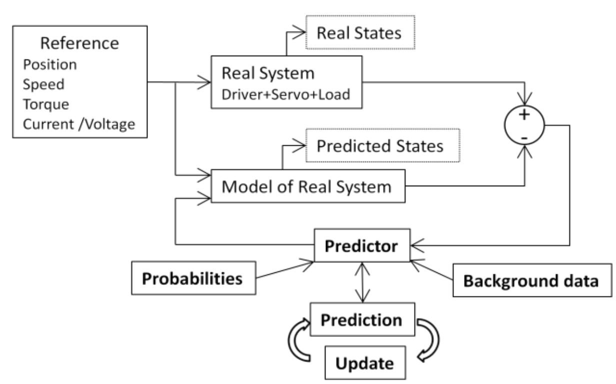
(a) MRAS generic block schematic



(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.

C. Input Configured Excitation Methods

Predefined routines are applied to the system in these parameter estimation operations that are based on excitation. The applied signal sets are selected according to the dynamics of the system (servo motor type, controller, mechanical load characteristic). The aim is to determine as many parameters of the system as possible at each excitation. Generally, this technique is used in off-line parameter estimation. The most basic application (simple single or two mass systems) is to obtain step, pulse, sine, ramp or square responses with relevant excitations. This simple method is often used to tune PID controller coefficients or to calculate the series resistance (r_s) and inductance values (L_d, L_q) of the motor windings [46]. Also, combinations of these basic signals can be used for calculating more specific parameters such as K_e, K_t, J, B [47]. These excitation types can be physical references such as speed, torque, position, or electrical signals such as phase current/voltage (or in the alpha-beta/d-q reference frames). As the structure of the servo system becomes more complex, non-linear effects [3] and delays in the system increase. This situation makes it difficult to estimate parameters with simple signal injection processes. In such cases, custom signal injection specific to the characteristics of the servo system can be made [48], [49]. For example, in a fixed-torque servo system operating in a wide speed band (60 rpm-6000rpm), it is necessary to make excitations in the limit speed components while calculating the parameters of the system. Parameters determined by low (60 rpm) or medium (3000 rpm) speed excitation may cause deviations at high speed values. This logic also is valid for torque, position, voltage/current quantities. Another approach is to use a pseudo random binary set (PRBS). This method is often used as disturbance detection (finding the center frequency of disturbance peaks). In this method, the system is stimulated with a PRBS multiplier. The aim is to generate data that helps to estimate system parameters by making random excitations in the entire frequency band. The advantage of PRBS is that it minimizes the motion so that it is convenient for mechanics with limited stroke. PRBS can be applied both, an open loop identification as a random disturbance signal and closed loop identification for unstable plants [50], [51].

D. Artificial Intelligence Based Methods

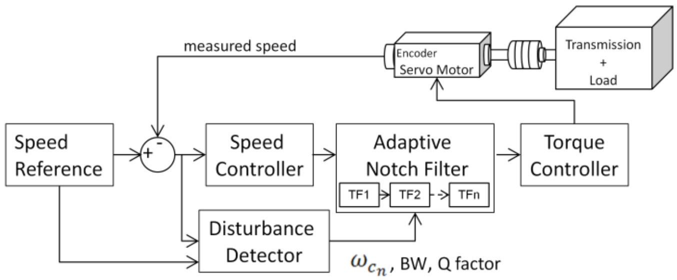
AI based methods are used for online parameter estimation or auto-tuning operations. The most common are neural network (NN), fuzzy logic, genetic algorithm (GA) and particle swarm (optimization) (PS). AI besed methods are used for online parameter estimation or auto-tuning operations. The most common are neural network (NN), Fuzzy Logic, genetic algorithm (GA), particle swarm (optimization) (PS). They use the information of servo systems such as position, motion, torque and mechanical dynamics and constrain as input. It determines the parameters of the system and tuned motion trajectory using methods such as learning, prediction, filtering and mapping [52]–[54]. Since these methods have a wide range of applications, we did not go into details in this study.

E. Other Methods

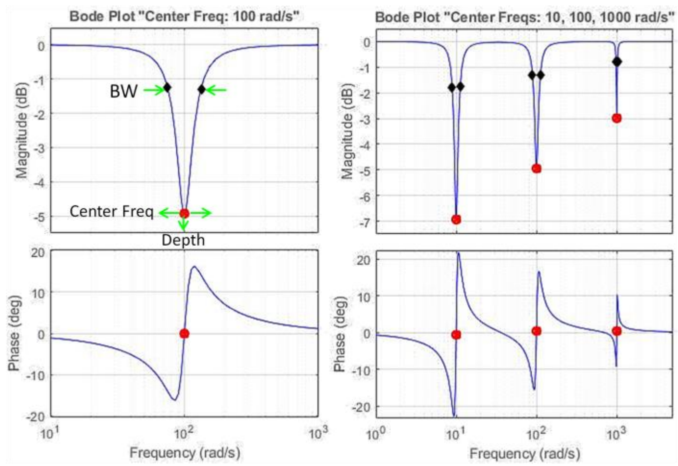
In some specific applications, uncategorized parameter estimation and auto-tune operations can be applied. In systems where thermal sensitivity is important, r_s and L_d, L_q values vary in proportional to temperature. It is possible to adjust these values by monitoring the temperature [53]. Also, temperature can be estimated parameter in the system and exact temperature of the servo motor can be estimated by using current injection or measurements [55]. One of the other different methods is to use the current ripple of the servo motor in parameter estimation. This method is similar to the input configured excitation method mentioned earlier. But in this method there is no excitation, the electrical peaks created during the routine operation of the servo motor are used [56]. Another application is finite element analysis (FEA) method that is used for off-line parameter estimation. In this technique, knowledge of the servo motor's geometry, lamination, magnet, winding specifications must known. Stored magnetic energy, vector magnetic potential and air-gap flux density as outputs provides the machine parameters with respect to relevant excitations. The challenge of this method is to integrate it into embedded systems [57].

V. FILTERS AND COMPENSATORS

In general, servo system tuning approach is detecting and fixing the distorted system. Resonances, vibrations caused by axial shifting, assembly errors, faults, environmental or drive train based disturbances are the main examples of these distortions. Each distortion has specific period, amplitude and duration. Various filter-based methods are applied to detect and compensate these situations in servo systems. There are two main filter type for operations such as band pass filter for detecting the disturbance signal and band stop (band reject) for eliminating the detected disturbance. Notch filters are the most common topologies that are using basic filtering or with adaptive designs. Also, like the distortion characteristic, there are three critical parameters for the filters as center frequency (ω_c), bandwidth (BW) and depth (Q factor). According to servo system complexity, there can be more than one distortion (vibration, resonance, periodic fault etc.) with different frequencies and amplitudes. Online adaptive notch filter (OANF), iterative tuning of notch filter and robust online adaptive notch filter (ROANF) versions are used for such issues [58]–[60]. The general structure of the notch filter embedded servo system and 2nd order specific notch filter design example is given in fig. 9. Another filtering approach of the servo system is biquad filters [61]. This filter type is used for multipurpose operations as it can be made operable like low-pass, high-pass, band-pass, band-reject by changing the coefficients. This flexibility generally provides an advantage in distortion detection and compensation, because scanning and filtering, from very small frequency (0-10 rad/s) to high frequency (10000 rad/s), can be done by setting useful topology (low-pass, band-pass, high -pass). Since the topology remains constant in the notch filter structure, the performance is insufficient in low and high frequency bands. In some applications, measurement noise, process noise, white noise, Gaussian noise etc. in inverter switching operations or phase currents/voltages that contains noise with randomness instead of a specific distortion, can be seen. Dead time compensators or Lead-Lag compensator are widely used such situations, especially driver side of the servo systems [62].



(a) Speed disturbance detection and compensation



(b) Single and three center frequencies notch filter design (for single disturbance compensation filter: $\boldsymbol{\omega_{c_{single}} = 100\, rad/s\, , depth = -5dB\, , BW = 0.25\, Log}$) , (three disturbances compensation filter: $\boldsymbol{\omega_{c_1} = 10\, rad/s\, , depth = -7dB\, , BW = 0.1\, Log}$, $\boldsymbol{\omega_{c_2} = 100\, rad/s\, , depth = -5\, dB\, , BW = 0.1\, Log}$, $\boldsymbol{\omega_{c_3} = 1000\, rad/s\, , depth = -3\, dB\, , BW = 0.02\, Log}$) , obtained by MATLAB/controlSystemDesigner(1)

Fig. 9. Adaptive notch filter block schematic and example designs

VI. System Management

Control and tune operations of industrial servo systems generally run on a DSP. The switching frequency of the servo drive and the control method (i.e. V/f, Hysteresis, FOC, DTC with parameter estimation and tuning algorithms) are effective in determining the specification of the DSP. While a single core processor is sufficient in systems that can be modeled simply (single motor – load with low level control and tuning), dual core processors run in mechanical systems that require multiple movements and more advanced on-line tuning techniques with estimators/predictors. As the nonlinearities formed in the system (sourced by inverter, gears, couplings etc.) and the complexity on the load side increase (cascaded mechanical contacts), the number of loops in the control and tuning blocks increases and this situation requires FPGA-based solutions. A summarized comparison hardware systems are given in fig. 10 [20], [29], [63], [64].

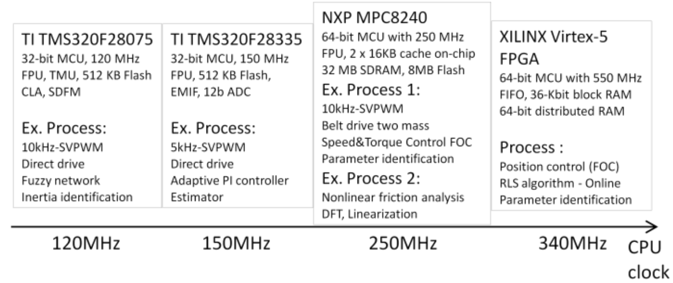


Fig. 10. Classification of hardware specifications and running applications

VII. Conclusion

In this review study, parameter estimation and auto-tune processes of industrial servo driven mechanical systems were examined. In this context, the models of the components (servo motor, controller/driver and mechanics) were modeled and reviewed. Commonly used approaches in the literature are described with examples. Some of the concept confusion found in the literature (Model based, Observer, Estimator, Predictor) are explained and classified. Studies have been systematized under six main headings. One of the two important questions drawn from this study is how feasible the designed systems are on an embedded hardware, and the other is how well the defined problems describe the real problem. In many studies, the mechanical model (two mass) used in problem definition has similar properties. In the solution part, many studies have been carried out with over specification hardware (computer interface). In future studies, the definition of the problem can be expanded by adding existing non-linear effects coming from driver side or mechanical side, and more compact embedded solutions can be offered at the solution stage.

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