Disturbance/Uncertainty Estimation and Attenuation Techniques in PMSM Drives—A Survey

Jun Yang, *Member, IEEE*, Wen-Hua Chen, *Senior Member, IEEE*, Shihua Li, *Senior Member, IEEE*, Lei Guo, and Yunda Yan, *Student Member, IEEE*

Abstract—**This paper gives a comprehensive overview on disturbance/uncertainty estimation and attenuation (DUEA) techniques in permanent-magnet synchronous motor (PMSM) drives. Various disturbances and uncertainties in PMSM and also other alternating current (ac) motor drives are first reviewed which shows they have different behaviors and appear in different control loops of the system. The existing DUEA and other relevant control methods in handling disturbances and uncertainties widely used in PMSM drives, and their latest developments are then discussed and summarized. It also provides in-depth analysis of the relationship between these advanced control methods in the context of PMSM systems. When dealing with uncertainties, it is shown that DUEA has a different but complementary mechanism to widely used robust control and adaptive control. The similarities and differences in disturbance attenuation of DUEA and other promising methods such as internal model control and output regulation theory have been analyzed in detail. The wide applications of these methods in different ac motor drives (in particular in PMSM drives) are categorized and summarized. Finally, the paper ends with the discussion on future directions in this area.**

Index Terms—**Adaptive control, disturbances, estimation, permanent-magnet synchronous motor (PMSM) drives, robust control, robustness, uncertainties.**

I. INTRODUCTION

WITH the increasing demands of higher precision machine drives, ac machine drives, which are widely considered as a substitute of direct current (dc) machine drives,

are deemed as the most prevailing components of modern motion control systems due to many distinctive features they offer. Among various ac machine drives, the permanent-magnet synchronous motor (PMSM) has been receiving abundant attention because of its advantageous features including high efficiency, high-power density, large torque-to-inertia ratio, low noise, and free maintenance [1]–[4]. As such, PMSM drives have been extensively applied to a variety of industrial sectors, such as robotics, machine tools, electrical vehicles, power generations, and aerospace [3].

Despite many advantages described above, high precision control of PMSM drives is rather challenging because the motion dynamics of PMSM are complicated and intrinsically nonlinear, and, in addition, subject to various sources of disturbances and uncertainties [5]–[7]. Aiming to achieve desired servo control performance, apart from classical proportional-integral-derivative (PID) controllers, plenty of advanced control algorithms have been put forward for ac machine drives, for example, model predictive control [4], [8], [9], robust and adaptive control [10]–[16], internal model control (IMC)[17], output regulation [2], disturbance observer-based control (DOBC) [3], [4], [18]–[27] and active disturbance rejection control (ADRC) [9], [28]–[30], to name but a few.

It has been widely recognized that a crucial task of controller design for PMSM systems is to reject various external disturbances and improve robustness in the presence of a wide range of uncertainties. The disturbances/uncertainties in ac machine drives, which usually exhibit different features, are generated from a wide range of sources including the changes of load, operational environments, and the mechanical or electrical parts in the motor systems. In order to design a successful control algorithm and achieve desirable control performance, it is important to have a comprehensive understanding of the features of the disturbances/uncertainties in ac servo systems first. Consequently, the *first focus* of this paper is to provide a comprehensive overview of various kinds of disturbances/uncertainties in typical types of ac machine drives including PMSM, induction motor (IM) and brushless direct current motor (BLDCM). Among many advanced control strategies in dealing with disturbances and uncertainties, disturbance/uncertainty estimation and attenuation (DUEA) techniques have received considerable attention in ac machine drives during the past several decades. Here, DUEA represents a category of algorithms/methods

TABLE I
DIFFERENCES AND SIMILARITIES BETWEEN PMSM, IM, AND BLDCM BASED ON FIELD-ORIENTED CONROL

| Motor Type	Motor Body		Disturbances/Uncertainties		Control	
	Rotor Type	Dynamic Models	Caused by Motor Body Structure	Others	Rotor Flux Position Measurement	Control Algorithms
IM	Aluminum/ cuprum windings ([1]wound-rotor [2]squirrel cage)	4th order	Skewed Slot Torque		Direct/Indirect	
PMSM	PM material	3rd order	[1]Cogging Torque/[2]Flux Harmonics	Similar	Direct	Similar
BLDCM			[1]Cogging Torque/[2]Commutation Torque/[3]Nonideal Trapezoidal Back Electromotive Force			
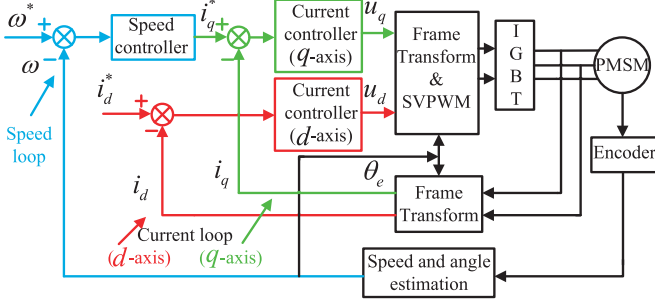
Fig. 1. Schematic diagram of PMSM based on vector control.

sharing a similar fundamental idea; that is, an observation mechanism is designed to estimate disturbances/uncertainties and corresponding compensation is then implemented by making use of the estimate [31]. Both DOBC and ADRC mentioned earlier belong to the category of DUEA. Since DUEA exhibits promising performance in handling disturbances and uncertainties [32], and it is not as well known as other methods for handling disturbances and uncertainties such as IMC and robust control, the *second focus* of this paper is to give a brief survey on the applications of DUEA and related techniques in PMSM drives.

It is also noticed that understanding the relationships between different DUEA methods and other well established control methods in handling disturbances and uncertainties particularly in the context of motion control is of significant importance. It not only provides insight into the differences and similarities of those methods, but also, more importantly, guides researchers and engineers to identify and select most appropriate methods for applications in their hands. Accordingly, the *next focus* of this paper is to develop and present the relationships among these techniques. We will start with a general discussion on the basic features of DUEA in the comparison with robust control and adaptive control that are both proven to be effective in dealing with uncertainties, and then focus on two well established and closely related advanced control methods, namely IMC [33] and nonlinear output regulation (NOR) [34]. The *last focus* of the paper is on the application of the DUEA in several types of popular ac motor drives and a number of typical applications have been summarized. The concluding remarks and future directions are provided in the last part of the paper.

II. DISTURBANCES/UNCERTAINTIES IN AC MACHINE DRIVES

In most parts of the paper, we mainly focus on discussing PMSM system as a benchmark ac drive system. However, it is noticed that PMSM shares many similarities of the problem formulation, disturbance/uncertainty properties and control algorithms with a number of other advanced ac motor drives, such as IM, BLDCM, and switched reluctance motors [35]. For example, the differences and similarities among three most popular ac machine drives (PMSM, IM, and BLDCM) are listed in Table I. In this section as well as several subsequent sections, attention to other ac motors will be paid for the interest of readers in related areas.

A generic $d - q$ dynamic model of PMSM drives is given with respect to its rotor reference frame as

$$
\begin{aligned}
\frac{di_d}{dt} &= \frac{1}{L_d}\left(u_d - R_s i_d + n_p \omega L_q i_q\right), \\
\frac{di_q}{dt} &= \frac{1}{L_q}\left(u_q - R_s i_q - n_p \omega L_d i_d - n_p \omega \psi_f\right), \\
\frac{d\omega}{dt} &= \frac{1}{J}\left(T_e - d_T^{\text{fric}} - d_T^{\text{load}}\right), \\
T_e &= \frac{3}{2} n_p \left[\psi_f i_q + (L_d - L_q) i_d i_q\right], \, d_T^{\text{fric}} = B_v \omega
\end{aligned}
\tag{1}
$$

where ω is the rotor speed, i_d and i_q are stator currents in $d - q$ frame, u_d and u_q denote stator voltages in $d - q$ frame, d_T^{load} represents the load torque disturbance, d_T^{fric} is the friction torque disturbance, T_e is the electromagnetic torque, B_v is the frictional coefficient, L_d and L_q are stator inductances in $d - q$ frame, R_s is the stator resistance, ψ_f is the magnetic flux linkage, J is the moment of the total inertial (rotor and load), and n_p is the number of poles.

A basic field-oriented control framework consisting of a speed loop and two current loops is shown in Fig. 1. The dynamics of PMSMs are essentially nonlinear subject to a wide range of disturbances/uncertainties in many high-performance applications. In this section, the disturbances/uncertainties in PMSM systems, which are classified as unmodelled dynamics, parametric uncertainties, and external disturbances, are briefly reviewed first. The symbols, physical meanings and units of various disturbances/uncertainties are listed in Table II for the sake of clarity.

TABLE II
DISTURBANCES AND UNCERTAINTIES IN PMSM

Symbol	Meaning	Unit
d_T^{cog}	Cogging Torque	$N \cdot m$
d_T^{flux}	Flux Harmonic Torque	$N \cdot m$
$d_{dV}^{\text{dead}}, d_{qV}^{\text{dead}}$	Distortion Voltage	V
$d_{dC}^{\text{offset}}, d_{qC}^{\text{offset}}$	Current Offset Errors	A
d_T^{fric}	Friction Torque	$N \cdot m$
d_T^{load}	Load Torque	$N \cdot m$

A. Unmodeled Dynamics

1) Motor Body Structure Induced Torque: Due to utilization of different rotor materials in ac motors, the body structure may induce various pulsating torques.

1) *Cogging Torque:* As a kind of pulsating torque, cogging torque is basically generated by the interaction of the rotor magnetic flux and angular variations in the stator magnetic reluctance [36]. Note that cogging torque even exists when the system is disconnected from the power source. In general, this torque can be expressed as [5]

$$d_T^{\text{cog}}(N \cdot m) = \sum_{i=1}^{\infty} d_T^{\text{cogi}} \sin(iN_c\theta_e)$$

where N_c is the least common multiple between the number of slots and pole pairs, θ_e is the electrical angle denoted by $\theta_e(t) = \theta_e(t_0) + \int_{t_0}^{t} n_p\omega(\tau)d\tau$ and d_T^{cogi} is the amplitude of the ith-order harmonic cogging torque. There is no cogging torque in IMs. However, the skewed slot torque in IM has a similar structure and property as the cogging effects in PMSM [37].

2) *Flux Harmonics:* The most widely used material in the magnet of PMSM is Neodymium Iron Boron and its flux density is easily affected by the temperature variation. The resultant demagnetization phenomenon of permanent magnets due to temperature rise has a significant impact on the maximum torque capability and the efficiency of PMSM [38]. The flux linkage between the rotor and stator magnets can be expressed as [6]

$$\psi_f = \sum_{i=0}^{\infty} \psi_{fi} \cos(6i\theta_e)$$

where ψ_{fi} is the amplitude of the $6i$th-order harmonic flux. According to the definition of electromagnetic torque T_e, it is indicated by (1) that the effect of flux harmonics can be represented as follows:

$$d_T^{\text{flux}}(N \cdot m) = \frac{3}{2}n_p i_q \sum_{i=1}^{\infty} \psi_{fi} \cos(6i\theta_e).$$

3) *Others:* For BLDCM systems, in addition to cogging torque, there are mainly two other causes of pulsating torque: one is commutation torque which is caused by the different current slew rates between switching-in phase and switching-out phase [39], another is nonideal trapezoidal back electromotive force due to stator

winding action, the magnetization direction of rotor permanent magnets, and imperfections in machine manufacturing [40].

2) Dead-Time Effects: The dead-time causes a loss of a portion of the duty cycle and distortion of the voltage applied to the drives [7]. Note that such effects become extreme severe near the zero crossing of the current. The resultant current deterioration finally leads to the ripples in the electromagnetic torque. The dead-time effect can be represented on stator voltage channels in the $d - q$ frame as follows [7]:

$$d_{dV}^{\text{dead}}(V) = \sum_{i=0}^{\infty} d_{di} \sin(6i\theta_e), d_{qV}^{\text{dead}}(V) = \sum_{i=0}^{\infty} d_{qi} \cos(6i\theta_e)$$

where d_{di} and d_{qi} are the amplitudes of $6i$th-order harmonic signals of d_{dV}^{dead} and d_{qV}^{dead}, respectively.

3) Measurement Error Effects: In ac servomotors, the errors in measurements of either position or current inevitably cause torque ripples. As an example, the offset error in current measurements is taken to illustrate the adverse effects of measurement errors. The offset errors superimposing directly on the phase currents via the transform of Clarke and Park, cause ripples on stator currents in $d - q$ frames [6], [36], which can be modeled as [6] follows:

$$d_{dC}^{\text{offset}}(A) = d^{\text{offset}} \sin(\theta_e + \alpha), d_{qC}^{\text{offset}}(A) = d^{\text{offset}} \cos(\theta_e + \alpha)$$

where α is a constant angular displacement and d^{offset} is the amplitude of ripple.

B. Parametric Uncertainties

1) Mechanical Parameters: The inertia J of a PMSM system, including both rotor and load, is usually a constant during a short-term operation process. However, in some special applications, e.g., electric winding machine, the inertia of the whole system is time-varying, for example, increase as time goes by in [1] and [17]. If the inertia of the system increases to several times of the original inertia, the speed response will have a bigger overshoot and a longer settling time [1], [17].

2) Electrical Parameters: The thermal model of ac machines has a significant impact on the motor controller design [41]. The thermal model of ac machines is incorporated in the nominal models used for control design, and improves the performance of disturbance/uncertainty estimation. For example, the stator resistance R_s varies primarily with winding temperature while a small amount of skin and stray loss effects are neglected [2]. The resistance R_s at temperature T can be written as [38] follows:

$$R_s = R_0(235 + T)/(235 + T_0)$$

where R_0 is the resistance at temperature T_0. It can be observed from the PMSM model (1) that the stator resistance affects the plant bandwidth of the current loop directly. As such, the variation of stator resistance has a great impact on the current-loop regulation performance. Moreover, the resistance effect becomes much severe at low speeds or in high-load torque conditions [2].

Fig. 2.   Distribution of disturbance/uncertainty in PMSM systems.

In addition, the stator inductances L_d and L_q are hard to precisely obtain [42], and they are usually functions of current magnitude and current phase angle of the motor [2], [3]. For instance, the effects of cross saturation generally result in variations of stator inductances which affects both the plant gain and the open-loop electrical time constant of the motor, and hence, the performance of the drives at different operating conditions [43].

C. External Disturbances

1) Friction Torque: Friction is the tangential reaction force between two surfaces in contact [44]. It can be represented by static models (the Coulomb model, the Stribeck model, the Karnppp model, etc.) and dynamic models (the Dahl model, the Bristle model, the reset integrator model, and the LuGre model, etc.) [44]. The nonlinear effects of friction are unavoidable and widely exist in servo systems, which may cause steady-state errors, tracking lags and limit cycles in position regulation [44]. Taking the Stribeck model as an example, the friction torque d_T^{fric} is expressed as [44] follows:

$$d_T^{\text{fric}}(N \cdot m) = \left(T_c + (T_s - T_c) \, e^{-\left(\frac{\omega}{\omega_s}\right)^2} \right) \text{sign}\,(\omega) + B_v \omega$$

where T_s is the static friction torque, T_c is the Coulomb friction torque, ω_s is the Stribeck velocity, and sign $(\bullet)$ is the standard signum function.

2) Load Torque: Torque on the load side is generally deemed as one of the most severe disturbances affecting the dynamic performance. For example, since the transmission mechanism is not an ideal rigid body, mechanical resonance can be easily excited due to the load torque. Speed is inevitably changed when load torque is imposed on the motor.

3) Mechanical Factors: The effects raised by mechanical characteristics such as torsional vibrations, backlash, and uncertainties generated by misalignment of shaft, broken shaft and twisted shaft are another branch of causes restricting servo performance improvement of motor drives [45]. It is estimated that the misalignment of shaft causes over 70% of rotating machinery's vibration problems in industrial motor drives [46].

Distribution of Disturbance/Uncertainty in PMSM: The disturbance/uncertainty discussed above affects the PMSM system via different control loops. Malposed compensation of the disturbance/uncertainty definitely results in performance degradation of the servo system. As such, it is of great importance to know the distribution of disturbance/uncertainty in PMSMs. A diagram of the distribution of unmodeled dynamics and external disturbances in PMSM systems is shown in Fig. 2 (the

scenario of d frame current loop is ignored for simplicity). Clearly, the cogging torque, flux harmonics, friction torque, and load torque affect the PMSM system in the speed loop. The dead-time effect and offset error of Hall current sensors affect the PMSM system in the current loops. As mentioned above, disturbances/uncertainties are distributed in different control loops (speed and current loops) and appears in different forms (e.g., slowly-varying and periodic), which imposes challenges in disturbances/uncertainties attenuation for PMSM.

Generally speaking, disturbances/uncertainties attenuation for PMSMs can be divided into two groups [6], [36]: improving motor design and using advanced control strategies. This paper focuses on the later one.

III. An Overview on DUEA and Related Techniques in PMSM Drives

This part will give a brief overview on DUEA and related techniques in PMSM drives.

A. DUEA Methods in PMSM Drives

A number of DUEA techniques have been proposed since 1960s based on different disturbance/uncertainty estimators, including DOBC [47], extended state observer-based control (ESOBC, also called ADRC) [48], unknown input observer-based control (UIOBC) [49], generalized proportional integral observer-based control (GPIOBC) [50], equivalent input disturbance-based control (EIDBC) [51], uncertainty and disturbance estimator-based control (UDEBC) [52], sliding mode disturbance observer-based control (SMDOBC) [53], intelligent disturbance observer-based control (IDOBC) [54], and so on. Different from other control methods in handling disturbances and uncertainties, this group of algorithms is featured with a built-in estimation mechanism for the lumped disturbance and the influence of uncertainties [31]. In this survey paper, we aim to elaborate the similarities/differences among different DUEA and related methods rather than their detailed algorithms. The readers are referred to see the survey paper [31] for a comprehensive overview on these DUEA techniques. Among those DUEA techniques, DOBC and ADRC have received most extensive investigations and applications in ac machine drives.

1) DOBC: As a key component of DOBC, DOB was initiatively put forward by Ohnishi and his colleagues in 1980s to improve disturbance rejection and robustness in dc motors [47]. The early DOBC was designed on the basis of frequency-domain control theory. With the prevalence of state space design approaches for DOBC, nonlinear DOBC has attracted a great deal of attentions so as to further enhance the control performances of essential nonlinear dynamic systems. In what follows, we will try to illustrate the basic principles of typical frequency-domain DOBC and nonlinear DOBC via two benchmark design examples of the speed regulation of the PMSM system.

Frequency-Domain DOBC (FDDOBC): The nominal model utilized for FDDOBC design is generally linear one, while the nonlinearities of the motor plant are usually treated as a part of the lumped disturbances, which are estimated and attenuated in
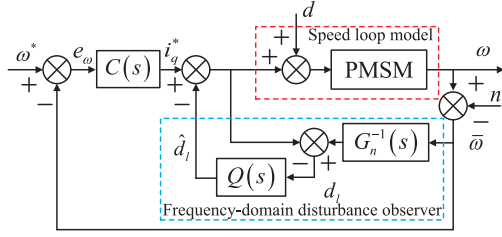
Fig. 3.   Structure diagram of FDDOBC for a PMSM.

the same manner as external disturbances. A design example of FDDOBC for PMSM speed regulation is presented as follows.

Example 1 (FDDOBC): Taking the speed regulation problem of the PMSM system (1) as a benchmark example, the dynamic model of the speed loop is given by

$$J\dot{\omega} = K_t i_q - B_v \omega + \frac{3}{2}n_p(L_d - L_q)i_d i_q - T_L + \varepsilon_\omega \quad (2)$$

where $K_t = 3n_p\psi_f/2$, and ε_ω denotes the unmodeled dynamics in speed channel. Denoting the current control signal in q frame as i_q^*, we have

$$J\dot{\omega} = K_t(i_q^* + d) - B_v\omega \quad (3)$$

with the disturbance term

$$d(t) = \frac{1}{K_t}\left[K_t(i_q - i_q^*) + \frac{3}{2}n_p(L_d - L_q)i_d i_q - T_L + \varepsilon_\omega\right]$$

where ε_ω denotes the unmodeled dynamics in the speed loop. Let $y = \omega$ and $u = i_q^*$. The transfer function model of (3) is written as follows:

$$y(s) = G(s)\left[u(s) + d(s)\right], G(s) = K_t/(Js + B_v).$$

The frequency-domain DOBC for the above speed regulation system is designed and shown in Fig. 3.

Besides the disturbance term $d(t)$, the parameters J, B_v, and K_t also have uncertainties in practice. Consequently, as shown in Fig. 3 the nominal model

$$G_n(s) = K_{to}/(J_o s + B_{vo})$$

with the nominal values of J_o, B_{vo}, and K_{to} is usually employed in DOB design.

As shown by Fig. 3, the frequency-domain DOB is employed to estimate the total disturbances/uncertainties including load toque disturbance, additional nonlinear dynamics, parametric uncertainties, and even couplings from the current loop of PMSM in the above example. It follows from Fig. 3 that

$$d_l(s) = \left[G_n^{-1}(s) - G^{-1}(s)\right]y(s) + d(s) - G_n^{-1}(s)n(s). \quad (4)$$

The first item relates to the mismatching between the physical system $G(s)$ and the nominal model $G_n(s)$, the second the external disturbance $d(s)$, and the last the measurement noise $n(s)$. Therefore, d_l captures all the disturbance and uncertainty influence. After letting it pass a filter $Q(s)$, the estimate of the lumped disturbance in DOB is given by

$$\hat{d}_l(s) = G_{u\hat{d}}(s)u(s) + G_{y\hat{d}}(s)\bar{y}(s) \quad (5)$$

where

$$G_{u\hat{d}}(s) = -Q(s), G_{y\hat{d}}(s) = G_n^{-1}(s)Q(s). \quad (6)$$

The design of the filter $Q(s)$ plays a central role in DOB. Various guidelines and methods for designing the filter $Q(s)$ can be found in [47], [55] to name but only a few. The utilization of frequency-domain DOBC to improve robustness and disturbance rejection performance of ac servo systems has been extensively investigated in literatures (see [18]–[22] for recent advances).

Nonlinear DOBC (NDOBC): The nonlinear part of an ac motor drive system can be deliberately ignored and deemed as a part of "lumped" disturbances, and then the above FDDOBC techniques can be applied to estimate the influence of the ignored nonlinearities so an appropriate action can be generated to compensate for that. However, for most of ac motor drive systems, the nonlinear dynamics may be known or at least partially known. The estimation and attenuation of real external unknown disturbance and uncertainty (or unmodeled dynamics) can be significantly improved if the (known) nonlinear dynamics could be exploited in design. This motivates the development of state-space DOBC, in particular NDOBC techniques for ac motor drives with nonlinear dynamics.

Example 2 (NDOBC): Here again, we consider the speed regulation problem of the PMSM system (1) as a benchmark example to illustrate the basic idea of NDOBC. The dynamic model of the motor drive (1) is rewritten as follows:

$$\frac{di_d}{dt} = \frac{1}{L_{do}}\left(u_d - R_{so}i_d + n_p\omega L_{qo}i_q + f_d\right)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qo}}\left(u_q - R_{so}i_q - n_p\omega L_{do}i_d - n_p\omega\psi_{fo} + f_q\right)$$

$$\frac{d\omega}{dt} = \frac{1}{J_o}\left[K_{to}i_q - B_{vo}\omega + \frac{3}{2}n_p(L_{do} - L_{qo})i_d i_q + f_\omega\right]$$

$$(7)$$

where $R_s = R_{so} + \Delta R$; $L_d = L_{do} + \Delta L_d$; $L_q = L_{qo} + \Delta L_q$; $\psi_f = \psi_{fo} + \Delta\psi$; $K_t = K_{to} + \Delta K$; $K_{to} = 3n_p\psi_{fo}/2$; and f_d, f_q, and f_ω denote lumped disturbances

$$f_d = \Delta L_{qo}n_p\omega i_q - \Delta R i_d - \Delta L_d\frac{di_d}{dt} + \varepsilon_d$$

$$f_q = -\Delta L_{do}n_p\omega i_d - \Delta R i_q - \Delta L_q\frac{di_q}{dt} - \Delta\psi n_p\omega + \varepsilon_q$$

$$f_\omega = \Delta K i_q + \frac{3}{2}n_p\left(\Delta L_d - \Delta L_q\right)i_d i_q - \Delta B_v\omega$$
$$\quad - T_L - \Delta J\frac{d\omega}{dt} + \varepsilon_\omega.$$

where ε_d and ε_q denote the unmodeled dynamics in d and q current channels, respectively. Let $x = [i_d, i_q, \omega]^\top$, $u = [u_d, u_q]^\top$ and $d = [f_d, f_q, f_\omega]^\top$. The dynamic models (7) can be represented in the following compact form

$$\dot{x} = f(x) + g_1(x)u + g_2(x)d. \quad (8)$$

The nonlinear disturbance observer (NDOB) is designed as [56]

$$\dot{z} = -l(x)\left[g_2(x)(p(x) + z) + f(x) + g_1(x)u\right]$$
$$\hat{d} = z + p(x) \quad (9)$$
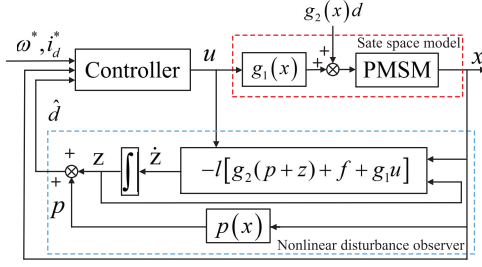
Fig. 4.   Structure diagram of NDOBC for a PMSM.

Fig. 5.   Structure diagram of ADRC for a PMSM.

where $p(x)$ is a nonlinear function to be designed. The observer gain $l(x)$ is determined by $l(x) = \partial p(x)/\partial x$. It has been shown in [57] that the NDOB asymptotically estimates the disturbance if the disturbance is constant and the observer gain $l(x)$ is chosen such that

$$\dot{e}_d = -l(x)g_2(x)e_d \qquad (10)$$

is asymptotically stable regardless of x where $e_d = d - \hat{d}$ is the disturbance estimation error.

There are many ways to choose the nonlinear gain $l(x)$ such that (10) is asymptotically stable. Since $g_2(x)$ is a constant matrix here, we can design a very simple linear gain l such that the matrix lg_2 is Hurwitz stable. The block diagram of NDOBC for the PMSM system is shown by Fig. 4. The utilization of NDOBC-like approaches to ac motor drives can be seen from [3], [4], [23]–[27].

2) ADRC: The concept of ADRC [48] was firstly proposed by Han in the 1990s, aiming to develop an alternative practical control method to classic PID. In the framework of ADRC, extended state observer (ESO) is generally regarded as a fundamental part, which was developed to estimate the lumped disturbances consisting of both nonlinearities and external disturbances. The basic design principle of ESO for motor drives can be seen from the following example.

Example 3 (ADRC): We consider a direct drive of PMSM system (1), that is, the voltage signal u_q is employed to regulate the rotor speed ω directly. The dynamic model is rearranged and given by

$$\ddot{y}(t) = f(y(t), \dot{y}(t), t) + bu(t) \qquad (11)$$

where $y(t) = \omega(t)$, $u(t) = u_q(t)$, $b = K_{to}/(J_o L_{qo})$ and

$$
\begin{aligned}
f = & \left(\frac{K_t}{JL_q} - \frac{K_{to}}{J_o L_{qo}} \right) u_q + \frac{1}{J} \left[-B_v \frac{d\omega}{dt} - \frac{dT_L}{dt} \right] \\
& + \frac{K_t}{L_q} \left(-R_s i_q - n_p \omega L_d i_d - n_p \omega \psi_f \right) \\
& + \frac{3}{2} n_p (L_d - L_q) \left(i_d \frac{di_q}{dt} + i_q \frac{di_d}{dt} \right) \bigg] + \varepsilon_f
\end{aligned}
$$

where ε_f denotes the lumped unmodeled dynamics. Note that besides the disturbances/uncertainties described in Section II, the nonlinear coupling dynamics from d-frame are also considered as a part of the lumped disturbance here. Letting $x = [y, \dot{y}]^\top$ and $d = f$, the dynamic model is rewritten as

$$\dot{x} = Ax + B_u u + B_d d, \ y = Cx \qquad (12)$$
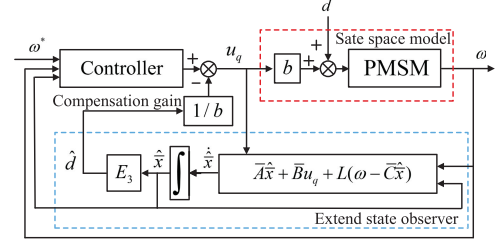
where

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \ B_u = \begin{bmatrix} 0 \\ b \end{bmatrix}, \ B_d = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \ C = \begin{bmatrix} 1 \\ 0 \end{bmatrix}^\top.$$

Choose the disturbance d as a new state and define $\bar{x} = [x^\top, d]^\top$. The augmented system is expressed as

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}u, \ y = \bar{C}\bar{x} \qquad (13)$$

where

$$\bar{A} = \begin{bmatrix} A & B_d \\ 0 & 0 \end{bmatrix}, \ \bar{B} = \begin{bmatrix} B_u \\ 0 \end{bmatrix}, \ \bar{C} = [C, 0]. \qquad (14)$$

ESO is designed to estimate all the states and lumped disturbance term f, given by [48]

$$\dot{\hat{\bar{x}}} = \bar{A}\hat{\bar{x}} + \bar{B}u + L(y - \hat{y}), \ \hat{y} = \bar{C}\hat{\bar{x}} \qquad (15)$$

where $\hat{\bar{x}}$ is the estimate of both the states and lumped disturbances, and L is the observer gain to be designed. It is easy to see the estimate of lumped disturbances is

$$\hat{d} = E_3 \hat{\bar{x}} \qquad (16)$$

where $E_3 = [0, 0, 1]$. The block diagram of ADRC for the PMSM system is shown by Fig. 5.

It is obvious that both the influences of model dynamics (including unmodelled dynamics and uncertainty) and external disturbances are estimated by the ESO. Only the relative degree of the system under consideration is required in the ESO design. So the significant feature of ESO is that it requires a minimum information about a dynamic system. Various extensions have been made to extend the basic ESO design to a wider range of dynamic systems. For more information about ESO and related ADRC, please refer to the recent survey paper [58]. Application of ADRC to ac motor drive systems can be referred to [9], [28]–[30].

B. Other Related Methods in AC Machine Drives

In addition to DUEA approaches, many other related methods, most notably robust and adaptive control, IMC, and output regulation, are extensively utilized to handle various disturbances/uncertainties in ac servo systems. Since those advanced control approaches for handling disturbances/uncertainties have been extensively discussed in various papers and books [35], [59], instead of paying too much attention on the details of
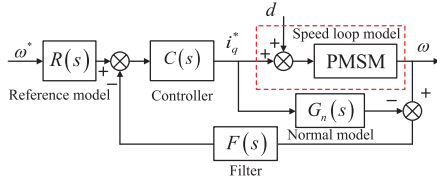
Fig. 6. Block Diagram of IMC for a PMSM.

each algorithms and their applications, this paper mainly focus on discussing the similarities/differences among them and DUEAs.

1) Robust Control and Adaptive Control: As both robust control and adaptive control have reached a relatively mature level, it is not surprising that both robust control and adaptive control approaches have been massively investigated in ac machine drives, for examples, see [8], [10]–[16], [60]. The basic idea of robust and adaptive control is quite intuitive; that is, robust control is employed to suppress disturbances and uncertainties, while adaptive control is applied for further improvement of precision by on-line identifying some key parameters such as inertial moment [61]. General discussions on relevances between DUEA and robust and adaptive control are presented in Section IV-A.

2) Internal Model Control (IMC): IMC is a quite popular and widely used method due to its simple concept and intuitive design philosophy. In the early 1980s, the idea of IMC was proposed by Garcia and Morari to attenuate the effects of external disturbances in control systems [33]. The block diagram of an IMC approach applied to PMSM is shown by Fig. 6.

By properly designing the filter $F(s)$ and controller $C(s)$, the IMC approach could achieve desired disturbance rejection and reference tracking performances. The application of IMC to ac servo systems can be found from [17] for an instance. The relationship between IMC and DOBC will be further discussed in Section IV-B.

3) Output Regulation and Internal Model Principle: The output regulation problem is also called the servomechanism problem, which aims to design a feedback controller to achieve asymptotic tracking and disturbance rejection for uncertain systems [62]. The internal models of references and external disturbances are usually incorporated into the controller design of output regulation approaches so as to achieve asymptotic tracking and disturbance compensation. The design philosophy of robust control is usually applied for output regulation to achieve robustness against various model uncertainties. The applications of output regulation and internal model principle to ac servo systems can be seen from [2] for example. A comparison study between NOR and nonlinear DOBC will be elaborated in Section IV-C.

IV. DUEA AND RELATED METHODS–RELEVANCES AND DISCUSSIONS

A. DUEA Versus Robust and Adaptive Control

1) Backgrounds: An attractive feature of DUEA methods is that the influence of uncertainty is considered to be a part of lumped disturbances so it is able to estimate the influence of uncertainty and improve robustness for uncertain systems including parameter uncertainties, unmodelled dynamics, and other variations. This section focuses on the robustness of DUEA in the presence of *only* uncertainty. Dealing with uncertainty has been a center of control engineering, and numerous methods/algorithms have been proposed. In a quite broad sense, these methods fall into two categories: robust control and adaptive control.

Robust control aims at designing a (fixed) controller that is not sensitive to uncertainty so stability and satisfactory performance is maintained under the uncertainty. In general, robust control is the *worst case* design; that is, the controller is designed to achieve best robust performance under all the possible variations (i.e., concerning the worst performance under all the described uncertainty). Although this design philosophy gives the best possible robustness performance, it may be overly conservative. The nominal performance may have to be sacrificed in order to achieve the best possible robustness (due to the design conflicts as discussed in [63]). Industrial systems may operate close to the nominal working conditions in most of their operation and only operate in the extreme conditions occasionally. Over concentrating on the worst case implies that the control systems may achieve degraded performance in most of the operational time.

In contrast, *adaptive control* aims to online adjust a control mechanism (e.g., tuning controller parameters) based on real-time input and output data of an uncertain system. Ideally, the control law can follow the changes of the controlled plant so a good performance (or even the optimal performance in some sense) can be achieved under all the possible variations. However, most of the existing adaptive control techniques focus on linear or nonlinear systems with linear unknown parameters (i.e., the uncertainty enters the system not only with a known structure but also being expressed as linear functions of uncertain parameters). Unfortunately, the uncertainty in real ac motor applications could be quite complicated and does not necessarily satisfy these conditions; for example, the dynamic system may have unmodelled dynamics (or high order dynamics are ignored for the ease of control strategy development). An adaptive control system may become unstable in applications in the presence of unstructured uncertainty or disturbances.

2) Relevances and Discussions: DUEA is a *methodology between robust control and adaptive control*. This explains the fact that although, in most cases, it is regarded as a robust control method due to its promising robustness, it is also regarded as an adaptive control method by some researchers (for example, [64]). As an alternative methodology to robust control and adaptive control, DUEA can alleviate some shortcomings in robust control and adaptive control described above. This can be explained by using the basic diagram of DOBC as in Fig. 3 by ignoring both sensor noise and external disturbance. The inner disturbance observer loop acts as an adaption mechanism in the presence of uncertainty. Rather than directly estimating the uncertain parameters as in many adaptive control algorithms, as shown in (4), it estimates the total difference between the nominal model $G_n(s)$ and the physical system
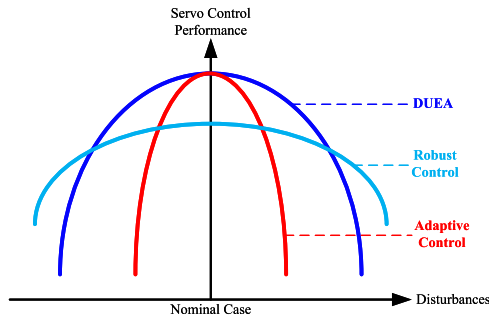
Fig. 7.   Diagram of control performance of DUEA, robust control, and adaptive control in PMSM drives.

$G(s)$, which may include both structured or unstructured uncertainty. So it is a "crude" adaptive control mechanism. Although it might not achieve the same control performance as other adaptive control algorithms when the uncertainty is structured (e.g., represented by linear functions of unknown parameters), it is more *robust* than most of adaptive control algorithms. On the other side, as the inner loop is not activated when there is no difference between the nominal model and the physical system, the nominal tracking and regulation performance is maintained. In the presence of uncertainties, the inner disturbance observer loop is activated to estimate and attenuate the influence of the uncertainty. Therefore, compared with robust control methods that are based on the worst case design, the robustness of DUEA may be not as good as these methods since they are designed to achieve best possible robust performance in the presence of the worst uncertainty. So in the sense, DUEA can be regarded as a "refined" robust control method. However, it provides a promising approach for trading off between the nominal performance and robustness. In a summary, DUEA provides an alternative approach to widely used robust control and adaptive control methods for dealing with uncertain (linear or nonlinear) systems.

Based on the above analysis, the servo control performance of DUEA, robust control and adaptive control for PMSM drives are shown by Fig. 7.

B. DOBC Versus IMC

As the internal model of a dynamic system is also embedded in the IMC design as in DOBC, it is interesting to discuss their similarities and differences. A complete IMC structure shown in Fig. 6, rather than a classic simple IMC structure, is adopted from [33] to facilitate the discussion. At the first glance, comparing Figs. 1 and 6 shows that these two control structures are quite similar. It shall be noted that adding a reference model to DOBC is straightforward as shown in a number of papers (e.g., [65]) if required for improving tracking performance. More notably, both these two schemes have an explicit internal model of the physical plant in the loop, a filter and a feedback controller. The reason for developing both these two schemes is also similar, i.e., improving disturbance rejection and robustness without sacrificing tracking performance.

However, carefully examining these two schemes reveals subtle but important difference. The feedback signal for the closed-loop controller $C(s)$ is different. The difference between the output of the real plant and its model is fed back in IMC while, as in most of feedback systems, the output of the physical system is fed back in DOBC. This has significant implication in control system design and implementation. In IMC, if there is no mismatching between the physical system and its model, and the system is not subject to disturbance, the feedback loop is not activated. The system operates in an open-loop fashion so the alternation of the controlled dynamics mainly relies on the reference model [and the controller $C(s)$], which may cause problems in achieving satisfactory performance for some systems such as systems with unstable dynamics. In contrast, in the absence of disturbance and mismatching between the plant and its model, DOBC now reduces to a typical single degree of freedom feedback control system. Therefore, all the existing control methods could be applied to design a closed-loop system to achieve stability and satisfactory performance. Furthermore, in IMC, the disturbance is equivalent to the output whereas all the disturbance and uncertainty is equivalent to the control input in all the classic DOBC schemes. In other words, the IMC structure is better in dealing with output disturbance while the DOBC structure is more suitable for handling input disturbance.

C. DOBC Versus NOR

The NOR theory provides an elegant and rigorous framework in handling the tracking and disturbance compensation problem of nonlinear systems subject to disturbances generated by exogenous systems [34]. The objective of both DOBC and NOR are similar, that is, to achieve zero tracking errors in the presence of disturbances (and uncertainties). The basic principle in NOR is that, similar to the internal model principle for linear systems [66], a feedforward input term is generated to cancel the influence of disturbance by embedding the disturbance model in the loop. The *central manifold* plays a core role in NOR, and asymptotic disturbance rejection depends on the existence of an invariant manifold. Due to this specific reason, there are a number of differences between nonlinear DOBC and NOR.

1) *Complexity of Design*: In the context of NOR, the solutions of coupled partial differential equations (PDEs) are involved in the controller/compensator synthesis. Solvability of such a set of PDEs have been rigorously investigated, however, despite all the efforts, solving these PDEs is still not easy for general nonlinear systems. There is a simple PDE involved in calculating the observer gain in DOBC for nonlinear systems, which is much easy to solve; a systematic method for solving it has been proposed (for example, [56]).

2) *Uncertainty Attenuation*: The approaches on uncertainty attenuation in DOBC and NOR are different. In the context of NOR, only the external disturbances are compensated while the model uncertainties have to be suppressed by feedback control action. As for DOBC, both the external disturbances and model uncertainties are *lumped together* for estimation and final compensation. The tasks of

Methods	Advantages	Disadvantages	Applications
Robust Control	Strong robustness (in particular in the worst case); conceptual intuitive and straightforward for implementation	Robustness is achieved at a price of sacrificing nominal control performance	[11]–[13]
Adaptive Control	Strong adaptiveness against severe parameter uncertainty, for example, inertial variation in ac motor	Sensitive to structural uncertainties such as unmodelled dynamics and complex disturbances	[14]–[18]
Output Regulation	Fully exploiting disturbance model for control design; expected higher disturbance rejection performance	Structure not flexible; complex for implementation	[2], [21]
IMC	Simple control structure; 2-degree of freedom design for tracking and disturbance rejection	Limited control performance in the presence of complex disturbances	[20]
DUEA	Conceptual intuitive; good balance among performances; different disturbance types	Extra efforts required to explore the features of disturbances for appropriate choices of DUEA methods	[27]–[32]

feedback control and compensation control in DOBC are quite transparent, where the feedback control is used for tracking and stabilization while the compensation control acts like an added-on "patch" to enhance robustness against disturbances/uncertainties.

3) *Flexibility of Structure*: In NOR, the controller and the disturbance compensation are designed by solving two PDE equations simultaneously. Similar to other DUEA, the DOBC structure allows one to design a controller and a disturbance observer independently and then integrate them together. This provides the flexibility of combining different controller (e.g., PID, linear quadratic regulator, model predictive control, and sliding mode control) and different disturbance observer (e.g., DOB, ESO, unknown input observer) design methods together. This property is very attractive since it enables the development of a more suitable composite controller tailored for a specific application. It also allows to adding the disturbance/uncertainty compensation loop directly on an existing control system to improve its disturbance rejection and/or robustness.

A brief comparison on advantages and disadvantages of DUEA and related methods is summarized as shown in Table III.

V. APPLICATIONS OF DUEA IN AC MACHINE DRIVES

In this section, we will further discuss the practical applications and industrialization issues of DUEA in ac machine drives.

A. Typical Utilizations of Disturbance Observations

The aforementioned disturbance observation techniques have been intensively applied to estimate disturbances and uncertainties including load torque, torque ripple, variation of inertia, frictions, etc., in ac servo systems such as PMSM, IM, and BLDCM. The typical utilizations are summarized as follows:

1) Load Torque Observer: The recovery performance after turbulence of a sudden load variation is one of the most important performance specification in ac servo system. One of the early motivations on developing DOB was to design an on-line load toque observer in motor drives. Recently, disturbance observation techniques have been extensively investigated as load toque observation, for example, see DOB [19], [20], [67],

[68], ESO [9], [28], [30], generalized proportional integral observer (GPIO) [69], sliding mode disturbance observer (SMDO) [70] and intelligent disturbance observer (IDO) [54], [71] for PMSM ([9], [19], [20], [28], [30], [70]), IM ([67], [69], [71]) and BLDCM ([68]), respectively.

2) Inertia Identification: In some applications, e.g., welding robots, or transfer robots with heavy loads, the inertia increases to more than several times of the original inertia, and the large mismatch between the plant and model will result in severe degradations of closed-loop control performance. Disturbance observation techniques provide an adequate way for inertia identification and adaptive control of PMSM systems, see [15], [17], [61].

3) Friction Compensator: The effect of friction is a dominant consideration in ac servo systems. The presence of various frictions always cause undesirable influences on control precision improvement. Based on the fundamental friction models, friction estimators and compensation are generally utilized for high precision servo control of ac motors such as PMSM [14], [15], [22], [29], and IM [69].

4) Torque Ripple Estimator: The torque ripple is a crucial disturbance caused by the distortion of the cogging effect, stator flux linkage distribution, and current measurement errors, which results in great performance degradation of ac servo systems. By incorporating the internal model of disturbance ripples in the observer design, various torque ripple estimators have been proposed for PMSM systems [2], [3], [25], [26]. In [39], disturbance observation technique is used to estimate the torque ripple caused by back-EMF of BLDCM.

5) Lumped Disturbance/Uncertainty Estimator: Since uncertainties in ac servo system could be treated as disturbances in the framework of DUEA, lumped disturbance/uncertainty estimator is also a very popular utilization due to its intuitive concept, straightforward design and implementation. For this kind of applications, see DOB [4], [21], [24], [27], SMDO [72], ESO [73], [74], GPIO [69] and IDO [71] applied to PMSM ([4], [21], [24], [72]), IM ([69], [71]), BLDCM ([73]) and switching reluctance motor ([74]) to name but just a few.

In practical engineering, the servo system is usually subject to multiple disturbances rather than single one. Combination of load toque observer, inertial identification, friction compensator and torque ripple estimator should be conducted for the controller to handle multiple sources of disturbances and uncertainties [15], [27].

TABLE IV
COMPARISONS OF DIFFERENT DUEA METHODS IN AC MACHINE DRIVES

DUEA Methods	Complexity		Capability					
	Output Feedback	Computation Burden	Load Torque Observer	Inertial Identification	Friction Compensation	Torque Ripple Estimator	Lumped Estimator	Used in product
ADRC	$\checkmark$	Low	$\checkmark$	$\times$	$\times$	$\times$	$\checkmark$	$\checkmark$
EIDBC	Possible	Medium	$\checkmark$	$\times$	Possible	$\times$	$\checkmark$	$\times$
FDDOBC	$\checkmark$	Low	$\checkmark$	Possible	Possible	$\times$	$\checkmark$	$\checkmark$
GPIOBC	$\checkmark$	Medium	$\checkmark$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
IDOBC	Possible	High	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\times$
NDOBC	$\times$	High	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\times$
SMDOBC	Possible	High	$\checkmark$	Possible	$\checkmark$	$\checkmark$	$\checkmark$	$\times$
UDEBC	$\times$	Medium	$\checkmark$	$\times$	Possible	$\times$	$\checkmark$	$\times$
UIOBC	Possible	Medium	$\checkmark$	Possible	Possible	$\checkmark$	$\checkmark$	$\times$

B. Manners of Combination With Advanced Feedback Control

From the point view of control design, the disturbance observation techniques can be flexibly incorporated with various feedback control approaches including PID control [15], [22], [28], [29], adaptive and robust control [14], nonlinear control [19], [21], [72], model predictive control [4], [9], sliding mode control [20], [24], [30], [70] and fuzzy logic controller [54] for difference purposes. For instance, disturbance estimators are combined with adaptive and robust control to further enhance adaptiveness and robustness of servo systems [14]. In [20], [30], [70], the disturbance observation techniques are employed to reduce the control chattering problem existing in traditional sliding mode control approaches.

C. Commercialization and Industrialization

In addition to numerous academic achievements on DUEA approaches, compared with other advanced control methods, one significant feature of DUEA is its large-scale commercialization and industrialization in ac servo systems. It has been embedded in a number of servo and drive products in the market. For instance, DOBC techniques have been embedded in the products of Panasonic MINAS A5-series ac servo motors and drives for a variety of purposes including torque observation and compensation [31]. ADRC approach has been utilized in the products of Estun EDC-08 APE and EDB-10 AMA series ac servo drives for inertia moment identification and disturbance/uncertainty attenuation [31].

The differences among different DUEA methods in ac machine drives are comparatively summarized and explicitly shown in Table IV.

VI. CONCLUSION AND PROSPECTS

A. Concluding Remarks

This paper has provided a systematic overview of disturbances/uncertainties in PMSM drives, and also DUEA and other relevant methods in handling disturbances and uncertainties for PMSM systems. More importantly, it has been argued in this paper that DUEA method has provided an alternative to robust control and adaptive control, and complementary to them in the field of PMSM drives. The similarities and differences between DOBC (particularly NDOBC) and two other well known methods widely applied in dealing with disturbances in ac motor drives, namely IMC and NOR, have been provided. As there is a wealth of theoretic tools and methods in these well established control methods, understanding these relationships makes it possible to improve theoretic studies in DUEA and other relevant advanced control methods for improving disturbance attenuation and robustness of ac servo systems.

B. Open Issues

In spite of significant progress has been made for DUEA techniques in ac machine drives, there are still many open issues to be addressed in the future:

1) *Disturbance/Uncertainty Modeling*: The models of disturbance/uncertainty are generally employed in DUEA approaches, albeit they actually do not rely on precise models. More information of the disturbance/uncertainty utilized in the controller will be definitely helpful for performance improvements. Consequently, a promising future direction is to develop new tools for more accurate disturbance/uncertainty modeling in ac machine drives.

2) *Multiple Disturbance Attenuation*: The ac machine drives are generally subject to multiple disturbances and uncertainties rather than a single one. Combination of different DUEA approaches together provides a promising manner to handle this problem. However, rigorous performance analysis is difficult, and furthermore how to integrate different DUEAs together is not easy. As such, design and synthesis of DUEA techniques for ac machine drives under multiple disturbance/uncertainty is also an open issue to be addressed.

3) *Constraint Handling*: Quite often, there are various constraints on the physical variables/parameters in ac machine drives. Most DUEA approaches have not considered those issues, however, violating the constraints would degrade performance even compromise safety of ac servo control systems. New tools and techniques [75] on constraint handling are interesting and imperative for application of DUEA in ac machine drives.

4) *Condition Monitoring*: Machine vibration analysis and motor current spectral analysis (MCSA) have been widely used for abnormal condition monitoring [76]. Development of condition monitoring techniques is sometimes helpful for disturbance modeling. For example, making full use of the information obtained by MCSA is beneficial for disturbance modeling and estimation design. As such, combination condition monitoring with DUEA will further improve the servo control performance of machine drives in the practical application.

5) *New Methods and Applications*: With the fast development of machine drives and control theory, it expected that new DUEAs should be explored to meet the new requirement of new generation of ac machine drives. For instance, a control strategy called finite control set model predictive control has been proposed recently for motor drives and power electronics without resorting to the pulse-width modulating technique [77]. New DUEA approaches shall be investigated to integrate with this and other novel control strategies.

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Jun Yang (M'11) received the B.Sc. degree from the Department of Automatic Control, Northeastern University, Shenyang, China, in 2006, and the Ph.D. degree in control theory and control engineering from the School of Automation, Southeast University, Nanjing, China, in 2011.

He is currently an Associate Professor with Southeast University. His research interests include disturbance estimation and compensation, advanced control theory and its application to flight control systems, and motion control systems.

Wen-Hua Chen (SM'06) received the M.Sc. and Ph.D. degrees from Northeast University, Shenyang, China, in 1989 and 1991, respectively.

He is currently a Professor with the Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, U.K. His research interests include the development of advanced control strategies and their applications in aerospace, and automotive engineering. Currently, much of his work has also involved the development of Unmanned Autonomous Intelligent Systems.

Lei Guo was born in Qufu, China, in 1966. He received the B.S. and M.S. degrees from Qufu Normal University, Shandong, China, in 1988 and 1991, respectively, and the Ph.D. degree in control engineering from Southeast University, Dhaka, Bangladesh, in 1997.

He is currently a Professor with the School of Automation and Electronic Engineering, Beihang University, Beijing, China. His research interests include robust control, stochastic systems, fault detection, filter design, and nonlinear control with their applications to aerospace systems.

Yunda Yan (S'15) was born in Yixing, China, in 1990. He received the B.Sc degree from the School of Automation, Southeast University, Nanjing, China, in 2013, where he is currently working toward the Ph.D. degree in control theory and control engineering.

His research interests include the development of advanced control strategies and their applications in ac servo systems.

Shihua Li (SM'10) received the Bachelor's, Master's, and Ph.D. degrees in automatic control from Southeast University, Nanjing, China, in 1995, 1998, and 2001, respectively.

Since 2001, he has been with the School of Automation, Southeast University, where he is currently a Professor and the Director of the Mechatronic Systems Control Laboratory. His main research interests include modeling, analysis, and nonlinear control theory with applications to mechatronic systems, including manipulators, robots, ac motors, power electronic systems, and others.