A review on ADRC based PMSM control designs

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***Abstract*—Permanent magnet synchronous motor (PMSM) is extensively used in industries. Recently, active disturbance rejection controller (ADRC) based control designs stand out due to advantages for a complex uncertain PMSM servo system. A general design procedure for the ADRC based PMSM control is discussed at the beginning. Then, the ADRC based control designs applied to PMSM servo systems are fully reviewed, in which several aspects are involved: position control, speed control, current control, cascaded ADRC control, and position identification. Moreover, to verify the effectiveness of the ADRC based control, simulations for the PMSM speed control are conducted in the Matlab/Simulink. Conclusions and the future research directions are indicated in the end.**

***Keywords*—ADRC; PMSM; Extended State Observer (ESO); design philosophy; disturbance definition; compensation; feedback**

I. Introduction

On account of the high efficiency, light weight, and high power density, PMSMs are extensively used in industries, what is more, the direct drive PMSM with double back-to-back PWM converters structure has been widely employed in the renewable energy variable speed systems [1-6]. A classical control for a PMSM is designed to be a double-loop structure with PI regulators applied to both the inner current loop and the outer speed loop [4-6]. PI controllers have been widely used for its simplified structure, high steady state accuracy, and high stability, particularly, in a linear time-invariant system [4]. Nevertheless, a PMSM is a typical nonlinear multi-variable coupled system [4-6], [17-42], which is often disturbed by various uncertainties such as the external uncertain loads disturbances, the internal non-constant friction, and the non-linear magnetic field effects.

Recently, large efforts have been devoted towards the high-precision control of PMSMs [4-6]. Among various novel algorithms, ADRC stands out due to its advantages for the complex uncertain PMSM servo system [17-42].

ADRC is proposed in 1998 [7]. A first systematical introduction to the ADRC in English is published in 2001[8]. Then, to provide a full account of this new paradigm, another paper in English is published [9]. Massive basic research on ADRC has been conducted for almost two decades [7-16].

Originating from [11] published in 1980, a fact is pointed out that many dynamic systems, linear or nonlinear, under some conditions, can be transformed into a canonical form of cascade integrators via the feedback. Then, in [12], the unmeasured state of the system, or the so-called 'total disturbances' is regarded as an extended state. To observe the total disturbances exactly, a special state observer is required; meanwhile, considering the weakness of a classical PID, the more efficient feedback control is needed [12].

After that, the efforts are devoted towards two directions: To solve the limitations of a linear PID controller, several nonlinear modules are formulated in [13], [14]. 1) A transient profile (TP) is applied to address the overshoot and improve the robustness; 2) A noise-tolerant tracking differentiator (TD) is employed to mitigate the noise sensitivity; 3) A nonlinear control (NLC) of 'large error, small gain; small error, large gain' is used to make the controller more efficient. Later, an extended state observer (ESO) is proposed in [15], which can estimate the total unknown disturbances and compensate the influences in the closed-loop dynamics in real time.

So far, the theory prerequisite for the ADRC has been mature. On the base of inheriting advantages of the modern control theory, the ADRC is formed (see Fig. 1) [7-16].

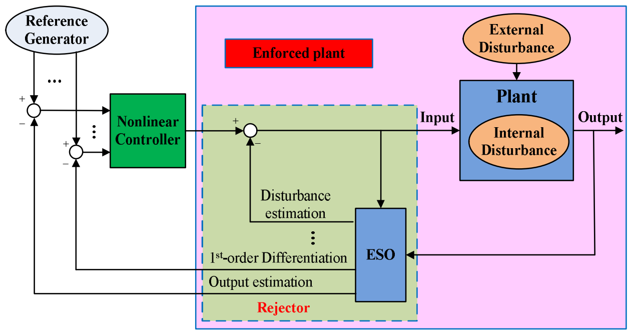

Fig. 1. ADRC structural schematic

Because of the abilities in dealing with the uncertainties, robustness, and advantages of less dependent on the plant model, ADRC has become attractive for industry applications such as the motion control, power electronics, and robotic systems [16]. The ADRC was early introduced into induction motors in [17] [18], and then, it is widely applied to PMSM systems, which mainly involves the following aspects: position control [19-25], speed control [26-31], current control [32-37], cascaded ADRC control [38], position identification [32] [35] [39], and other applications [40-43].

The precise position control for PMSMs is still a challenge due to various uncertain disturbances. To achieve the high-precision motion control, a robust position controller based on a first-order ADRC is developed [19]. Then, the second-order ADRC based position control model is put forward in [20-22]. Moreover, [22] applies a fuzzy logic to choose the ADRC nonlinear feedback parameters in real time. Recently, a third-order ADRC model has been proposed in [23-25].

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Similarly, ADRC has been widely applied in PMSM speed regulation system. Papers [26-29] replace the PI controller with a first-order ADRC in the PMSM speed control loop, but the control performance depends largely on the ESO estimation precision. To decrease the estimation burden and increase its accuracy, partial disturbances are identified in [27-29]. Moreover, a first-order ADRC based speed controller neglects the dynamics of the current loop; to avoid this simplification, a second-order ADRC based speed control design is proposed in [30]. Furthermore, Smith Predictor is introduced to overcome the time delay of the speed loop in a direct drive PMSG wind power system [31].

A high-performance current controller is needed to fulfill conditions of fast transient response and small steady state errors. In [32], [33], ADRC based regulators current control are elaborated, which realizes fast dynamics and the high steady state accuracy. A linear ADRC is applied in the current loop in [34] [35]. Furthermore, the digital time delay caused by PWM is considered in an improved ADRC based current regulator in [36] [37]. Then, [38] combines a first-order speed control and current control together, a cascaded ADRC based control strategy is proposed.

Speed and position identification are required in a position sensor-less PMSM servo system, a speed observer based on the ADRC q axis current control is designed in [35] [39], which can obtain the rotor speed and position. Similarly, an identification strategy based on the d axis current control is proposed in [32].

Besides, the ADRC based control is applied to many other applications such as direct torque control [40] [41] and series multi-PMSM or double-PMSM synchronous control [42] [43].

Large implementations prove the advantages of ADRC for a PMSM servo system. However, as a relatively novel control method, there is still not a systematical review on the previous work, which results in large repetitive efforts on the issues resolved. Moreover, a general philosophy is needed to instruct its practical design. To deal with these issues, the following work has been conducted. In section II, the mathematical model of PMSM is presented. How to formulate a practical problem into standard form properly is the key of a successful application of ADRC, so a general design procedure for ADRC based PMSM control is provided in section III. Section IV reviews the ADRC based control designs applied to PMSM servo systems. Simulations on the PMSM speed control are conducted to verify the effectiveness of the ADRC based control in section V. In the last section, conclusions and future research directions are indicated.

II. MATHEMATICAL MODEL OF PMSM

In the synchronous dq frame [3], the PMSM is modeled as

$$\begin{cases} v_d = L_d \dfrac{di_d}{dt} + R_s i_d - \omega_e L_q i_q \\ v_q = L_q \dfrac{di_q}{dt} + R_s i_q + \omega_e (L_d i_d + \psi_f) \end{cases} \tag{1}$$

where v_d and v_q the stator voltage vector of q axis and d axis; i_d and i_q the stator current vector of q axis and d axis; R_s the stator winding resistance; L_d and L_q the inductance of stator winding of q axis and d axis; Ψ_f the permanent magnet flux vector, ω_e the rotor electrical rotation speed.

The electromagnetic torque T_e under dq frame is given as

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

where P_n is the number of pole pairs.

If $L_d = L_q$ or $i_d = 0$, then (2) can be modified as

$$T_e = \frac{3}{2} p_n \psi_f i_q \tag{3}$$

A dynamic formula between the mechanical rotation speed ω, the mechanical torque T_{mec}, and T_e is built as

$$J \frac{d\omega}{dt} = T_e - T_{mec} - B\omega \tag{4}$$

where J the total inertia; B the friction factor.

III. PRACTICAL PROBLEM FORMULATION

In [11], it is pointed out that many complex systems under some conditions can be transformed into the canonical form of cascade integrators via a feedback, which is represented by

$$\begin{cases} \dot{x}_1 = x_2 \\ \vdots \\ \dot{x}_{n-1} = x_n \\ \dot{x}_n = f_1(x_1, x_2, \cdots, x_n, w(t), t) + f_0(x_1, x_2, \cdots, x_n) + bu \end{cases} \tag{5}$$
$$y = x_1$$

Where $x_1, x_2 \cdots x_n$ are the state variables, y is the output; u is the input, $w(t)$ is the uncertain external disturbance; $f(x_1, x_2 \cdots x_n, w(t), t)$ represents the unknown disturbances; $f_0(x_1, x_2 \cdots x_n)$ represents the known disturbances.

The key in a successful application of the ADRC is how to reformulate the practical control problem to a standard model as (5) [7-10]. A general design procedure (see Fig. 2) can be followed for the ADRC based control.

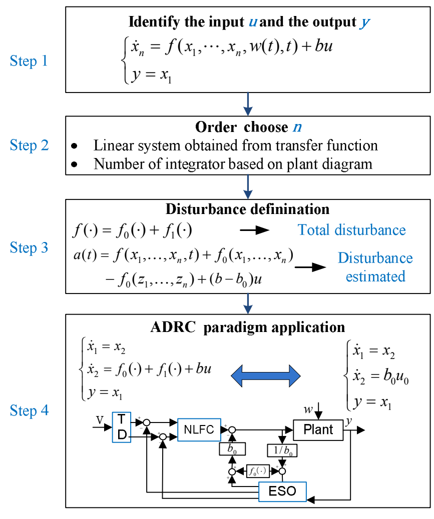

Fig. 2. General design philosophy of ADRC based applications

Firstly, it should be clear which is the output y to be controlled and which is the input u to be manipulated, meanwhile, the estimation value b_0 of input coefficient b is needed; then, the order of ADRC can be chosen based on the PMSM mathematical model or the integrators number of the direct path; moreover, a key step is how to reformulate the problem by lumping various the known, unknown components into the total disturbances [9]. Finally, with all issues above well identified, a standard model as (5) is achieved and the ADRC paradigm can be applied.

IV. Reviews of ADRC based PMSM control designs

A PMSM global control diagram is shown in Fig. 3, which includes three control levels, namely the position control, the speed control, and the current control. A review of ADRC applications to these aspects is provided in this section.

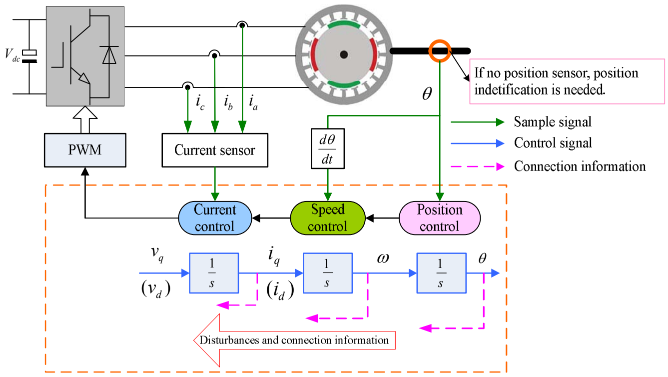

Fig. 3. PMSM global control diagram

A. Position control design

A large amount of uncertainties including the load torque change, the uncertain friction factor, parameters variations in PMSM are unavoidable, which bring challenges for the position control. ADRC strategies are proposed to improve the accuracy and dynamics in [19-25].

1) 1st-order ADRC based position control

A differentiation model exists between the speed ω and the position θ as

$$\frac{d\theta}{dt} = \omega + f(w(t),\ldots) \tag{6}$$

where $f(\cdot)$ represents the total disturbances of the plant.

Following the design procedure in section III, the first-order position control problem is simple to reformulate. Firstly, as the control objective is to realize precise position control, position θ is the output y, ω is the input u; secondly, the ADRC order is 1; let $y = x_1 = \theta, u = \omega$, $f_1(\cdot)$ represents the total disturbances, a first-order standard model is given as

$$\begin{cases} \dot{x}_1 = f_1(\cdot) + \omega \\ y = x_1 \end{cases} \tag{7}$$

2) 2nd-order ADRC based position control

Substitute (2) into (6), then the mechanical dynamic equation between the output θ and the input i_q is obtained as

$$\frac{d^2\theta}{dt} = \frac{d\omega}{dt} = \frac{1.5P_n\psi_f}{J} i_q - \frac{T_{mec}}{J} - \frac{B}{J}\omega \tag{8}$$

Following the same procedure above, firstly, θ is the output y, i_q^* is the input u, and $b_0 \approx \frac{1.5P_n\psi_f}{J}$; Secondly, the ADRC order is 2 as shown in Fig. 3; Compared with a first-order system, the disturbance definition of a second-order ADRC model is complicated, the tracking accuracy depends much on the quantities of total disturbances estimated by the ESO, so the disturbance definition is crucial for the design.

Paper [26] takes $-\frac{T_{mec}}{J} - \frac{B}{J}\hat{\omega}$ as the total disturbances as case 1 shown in table I, which is easier to be implemented, however, due to the speed changes or sudden torque fluctuations, the ESO estimation efficiency will be affected. In [27], to mitigate the effect of a sudden speed change, $-\frac{B}{J}\hat{\omega}$ is identified as case 2, where $\hat{\omega}$ is estimated by the ESO. In case 3, the load torque and inertia J are identified in [28] [29], if $b = b_0 = \frac{1.5P_n\psi_f}{J}$, the disturbances estimated by the ESO will be quite small, the estimation accuracy improves.

TABLE I. Different disturbance definition strategies

Disturbance defination	Total disturbance estimated
$f_{case1}(\cdot) = f_1(\omega, T_{mec}) = -\frac{T_{mec}}{J} - \frac{B}{J}\omega$	$a_{case1}(t) = -\frac{T_{mec}}{J} - \frac{B\omega}{J} + (b-b_0)i_q$
$f_{case2}(\cdot) = f_0(\hat{\omega}) + f_1(T_{mec}) = -\frac{B}{J}\hat{\omega} + (-\frac{T_{mec}}{J})$	$a_{case2}(t) = -\frac{T_{mec}}{J} - (\frac{B\omega}{J} - \frac{B\hat{\omega}}{J}) + (b-b_0)i_q$
$f_{case3}(\cdot) = f_0(\hat{\omega}, \hat{T}_{mec}, \hat{J}) = -\frac{B}{\hat{J}}\hat{\omega} - \frac{\hat{T}_{mec}}{\hat{J}}$	$a_{case3}(t) = -\frac{T_{mec}}{J} - \frac{B\omega}{J} - (-\frac{B}{\hat{J}}\hat{\omega} - \frac{\hat{T}_{mec}}{\hat{J}}) + (b-b_0)i_q$

Now, let $y = x_1 = \theta$, $x_2 = \omega, u = i_q^*$, $f_1(\cdot)$ represents the unknown disturbances, $f_0(\cdot)$ is the known model. Based on table I, the position control problems are reformulated to the standard ADRC models as given in the table II.

TABLE II. Standard models of position control

Case 1	Case 2	Case 3
$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_1(\omega, T_{mec}, t) + b_0 i_q^* \\ y = x_1 \end{cases}$	$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_0(\hat{\omega}) + f_1(T_{mec}, t) + b_0 i_q^* \\ y = x_1 \end{cases}$	$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_0(\hat{\omega}, \hat{T}_{mec}, \hat{J}) + b_0 i_q^* \\ y = x_1 \end{cases}$

3) 3rd-order ADRC based position control

A third-order ADRC model is developed in [23-25]. A third-order model can be derived from (1) and (8) as

$$\begin{cases} \dddot{\theta} = f(v_q, i_q, i_d, \psi_f, \dot{T}_{mec}, \dot{\omega}) + \frac{1.5P_n\psi_f}{J \cdot L_q} v_q \\ f(\cdot) = \frac{1.5P_n\psi_f}{J \cdot L_q}(-R_s i_q - \omega_e(L_d i_d + \psi_f)) - \frac{\dot{T}_{mec}}{J} - \frac{B}{J}\dot{\omega} \end{cases} \tag{9}$$

Similarly, the rotor position θ is output y, v_q^* is input u, $b_0 \approx \frac{1.5P_n\psi_f}{JL_q}$; the ADRC order is 3; the disturbance is formulated under the dq coordinate with (9); let $x_1 = \theta$, $x_2 = \omega, u = v_q^*$, $y = \theta, b =$, $f_1(\cdot)$and $f_0(\cdot)$ are the unknown model and the known model respectively. Finally, a third-order ADRC standard model of position control is formulated as (10). Now, a third-order ADRC paradigm can be implemented.

$$
\begin{cases}
\dot{x}_1 = x_2 \\
\dot{x}_2 = x_3 \\
\dot{x}_3 = f_0(\cdot) + f_1(\cdot) + b_0 v_q^* \\
y = x_1
\end{cases}
\tag{10}
$$

B. Speed control design

To improve the speed dynamics, ADRC has been widely applied in PMSM speed regulation in [26-31]. A first-order formula between ω and i_q is given as

$$
\dot{\omega} = \frac{1.5 P_n \psi_f}{J} i_q - \frac{T_{mec}}{J} - \frac{B}{J}\omega
\tag{11}
$$

Then, ω is the output y, i_q is the input u; the ADRC order is 1, and $b_0 = \frac{1.5 P_n \psi_f}{J}$; the disturbance definition strategies can follow the same principles as table I; let $x_1 = \omega, u = i_q^*,\ y = \omega$, $f_1(\cdot)$ and $f_0(\cdot)$ represent the unknown and known disturbances respectively. In the Table III, a series of first-order standard models are formulated. Finally, a first-order ADRC based speed control can be applied.

TABLE III. STANDARD MODELS FOR SPEED CONTROL

Case 1	Case 2	Case 3
$\begin{cases}\dot{x}_1 = f_1(\omega, T_{mec}, t) + b_0 i_q^* \\ y = x_1\end{cases}$	$\begin{cases}\dot{x}_1 = f_0(\hat{\omega}) + f_1(T_{mec}, t) + b_0 i_q^* \\ y = x_1\end{cases}$	$\begin{cases}\dot{x}_1 = f_0(\hat{\omega}, \hat{T}_{mec}, \hat{J}) + b_0 i_q^* \\ y = x_1\end{cases}$

C. Current control design

Considerable ADRC based current control approaches are proposed in [32-37]. Based on (1), the first-order formulas between the current and the voltage are given as

$$
\begin{cases}
\dfrac{di_q}{dt} = f_q(i_q, i_d, \psi_f, \omega_e) + \dfrac{1}{L_q} v_q \\
\dfrac{di_d}{dt} = f_d(i_q, i_d, \omega_e) + \dfrac{1}{L_d} v_d
\end{cases}
\tag{12}
$$

with $f_q(\cdot) = -\frac{\omega_e}{L_q}(\psi_f + L_d i_d) - \frac{R_S}{L_q} i_q$, $f_d(\cdot) = -\frac{R_S}{L_d} i_d + \frac{\omega_e L_q}{L_d} i_q$. Similarly, let $b_q = \frac{1}{L_q}, b_d = \frac{1}{L_d}$, the standard models of the current control are shown in Table IV.

TABLE IV. STANDARD MODELS OF CURRENT CONTROL

Standard model	q axis model	d axis model
$\begin{cases}\dot{x}_1 = f(x_1, w, t) + bu \\ y = x_1\end{cases}$	$\begin{cases}\dfrac{di_q}{dt} = f_q(i_q, i_d, \psi_f, \omega_e) + b_q v_q^* \\ y = i_q\end{cases}$	$\begin{cases}\dfrac{di_d}{dt} = f_d(i_q, i_d, \omega_e) + b_d v_d^* \\ y = i_d\end{cases}$

D. Cascaded control design

Based on (11) and (12), a cascaded ADRC based control design is proposed in [38] as shown in Fig. 4.

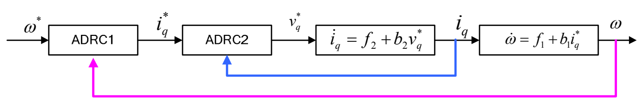

Fig. 4. The control structure of cascade ADRC design

It is noted the inner current loop should be designed to be faster than the outer speed loop, namely, the timescale of the inner loop is smaller than that of the outer loop.

The ADRC based control standard models for the different control loops reviewed above are summarized in Fig. 5. From the discussions above, it can see the ADRC based PMSM control design is extensive in practice. Firstly, the ADRC order can be chosen differently, the position control can be designed to be a first-order [19], a second-order [20-22], or a third-order ADRC [23-25]. Besides, the cascaded control makes ADRC applications more flexible [38], two-level, or three-level cascaded control strategies can be implemented.

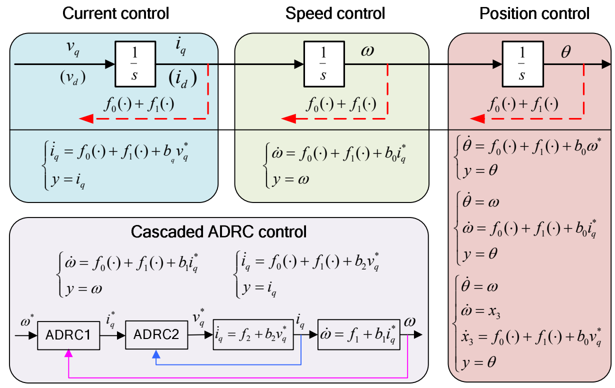

Fig. 5. ADRC based standard models for PMSM

E. Position identification

In position sensor-less PMSM servo system, the speed and position identification are required. The ADRC based position and speed identification diagram of both d axis and q axis proposed in [32] [35] [39] are indicated respectively in Fig. 6.

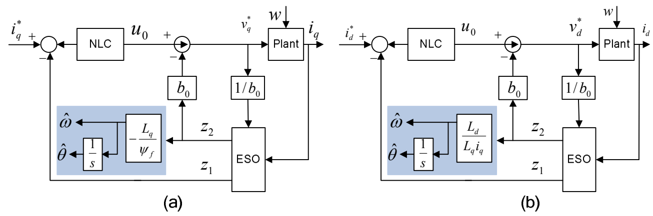

Fig. 6. Speed and position identification diagram based on ADRC

A position estimation approach based on the q axis current control is formulated below. The total disturbance estimated by ESO can be defined as

$$
a(t) = -\frac{\omega_e}{L_q}(\psi_f + L_d i_d)
\tag{13}
$$

Normally, the d axis command is set to be zero, so the disturbance can be simplified with $a(t) = -\frac{\omega_e}{L_q}\psi_f$, and then the speed can be identified as

$$
\hat{\omega}_e = -\frac{L_q}{\psi_f} Z_2
\tag{14}
$$

The rotor position can be identified by integrating (28)

$$
\hat{\theta}_e = \int \hat{\omega}_e dt
\tag{15}
$$

Paper [32] identifies the rotation speed based on the d axis current control, the disturbance estimated by ESO is

$$
a(t) = -\frac{R_s}{L_d} i_d + \frac{\omega_e L_q}{L_d} i_q
\tag{16}
$$

Similarly, in a well-controlled system $i_d = 0$, $\hat{\omega}_e$ is obtained as

$$\hat{\omega}_e = \frac{L_d}{L_q i_q} z_2 \tag{17}$$

However, the drawbacks of these methods are obvious, as the disturbances estimated by ESO are the total disturbances including both external disturbances and internal dynamics, so the disturbances estimated in practice does not consist with the disturbances defined as (13) and (16) ; also, the identification approaches depends on the accuracy of PMSM parameters. It only works efficiently when having an accurate knowledge of plant parameters and no external uncertain disturbances.

V. SIMULATION STUDY

In order to verify the effectiveness of the ADRC based control strategy, a first-order ADRC based speed control has been conducted in the Matlab/Simulink.

A. ADRC paradigm

The diagram of an ADRC based speed control is shown in Fig. 7. The transient profile is neglected in this design.

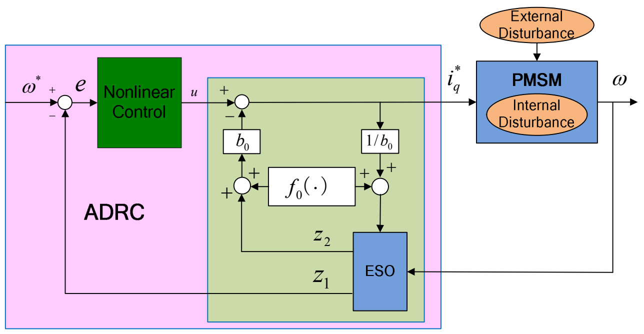

Fig. 7. Diagram of ADRC based speed control

1) Nonlinear control law

A nonlinear law of (18) is applied to make the feedback control and the ESO estimation more efficient, which has been proved in large implementations [8-10].

$$fal(\varepsilon,\alpha,\delta) = \begin{cases} |\varepsilon|^{\alpha}\,\mathrm{sgn}(\varepsilon), & |\varepsilon| > \delta \\ \varepsilon / \delta^{1-\alpha}, & |\varepsilon| \le \delta \end{cases} \tag{18}$$

The nonlinear law depends on the parameters α and δ [9]. If $0 < \alpha < 1$, (18) has a characteristic of 'large error, small gain; small error, large gain' which makes the control more efficiently as shown in Fig. 8(a). The control law also varies with different δ values as shown in Fig. 8(b).

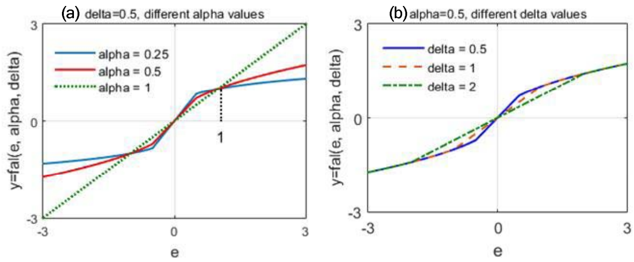

Fig. 8. Nonlinear law of 'large error, small gain; small error, large gain'

2) Extended State Observer

An ESO can estimate both the states and the disturbances simultaneously. Its mathematical model is described as

$$\begin{cases} \varepsilon_1 = z_1 - \omega \\ \dot{z}_1 = z_2 - \beta_1 fal(\varepsilon_1,\alpha_1,\delta_1) + b_0 i_q^* \\ \dot{z}_2 = -\beta_2 fal(\varepsilon_1,\alpha_2,\delta_1) \end{cases} \tag{19}$$

where z_1, z_2 is the estimation of the speed ω and the total disturbances, respectively, β_1, β_2 are the observer gains.

3) Nonlinear feedback control

Finally, the nonlinear weighted sum can be represented as (20). The nonlinear control law is applied to make the feedback control more efficient.

$$\begin{cases} e_1 = \omega^* - z_1 \\ i_{q0} = \beta_0 fal(e_1,\alpha_0,\delta_0) \\ i_q = i_{q0} - z_2 / b_0 \end{cases} \tag{20}$$

where β_0 is the proportional gain. Tuning principles of the control parameters have been fully discussed in [8-10].

To highlight, if the partial disturbance has a certain known model, then (19) and (20) can be rewritten as

$$\begin{cases} \dot{z}_1 = z_2 + f_0(\cdot) - \beta_1 fal(\varepsilon_1,\alpha_1,\delta_1) + b_0 i_q^* \\ i_q = i_{q0} - \dfrac{(z_2 + f_0(\cdot))}{b_0} \end{cases} \tag{21}$$

Finally, with the disturbances compensated in real time, a nonlinear system is reduced to a cascade integral form as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = b_0 u_0 \\ y = x_1 \end{cases} \tag{22}$$

B. Simulation results

The global PMSM control diagram with ADRC based speed regulation is shown in Fig. 9. The parameters of the PMSM are shown in table V.

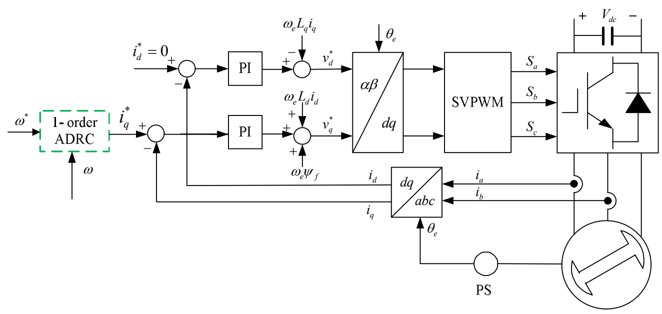

Fig. 9. ADRC based control diagram of PMSM servo system

TABLE V. PMSG PARAMETERS

Parameters	Value	Parameters	Value
Armature resistance	0.17 Ω	Pole pairs number	4
d-axis inductance	0.0017 H	Total inertia	$0.0048 Kg \cdot m^2$
q-axis inductance	0.0019 H	Friction coefficient	$0.01\ N \cdot m \cdot s$
Magnet flux vector	0.11 Wb	Switch frequency	10 KHz

1) *Different disturbance definitions*

Three different disturbance definition strategies in table I are considered in the simulation. A constant reference speed is applied and a load torque disturbance happens at t=0.1s. In case 3, the total disturbance estimated by ESO is nearly zero as shown in Fig. 10(a), which performs best in three cases as shown in Fig. 10(b). Simulation results have proved the effectiveness of the proper disturbance compensation. In the following simulation, only case 3 is considered.

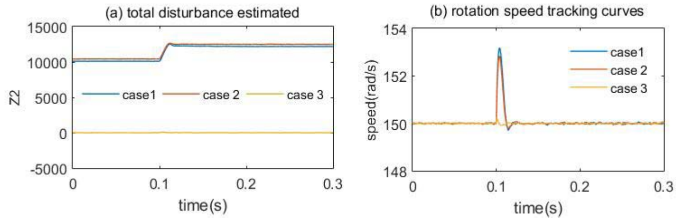

Fig. 10. Distubance estimated and speed dynamic response

2) *Comparison between PI and ADRC*

Firstly, an ADRC based speed control strategy for PMSM is simulated with $\omega^* = 180\mathrm{rad/s}$. A load torque of -50N.m is initially applied, and then decreased to -60N.m at 0.1s. Compared with the PI controller, the speed tracking process of the ADRC is more efficient and stable in face of a torque disturbance as shown in Fig 11(a). Fig 11(b) shows that i_q has a smaller overshoot and faster dynamic response.

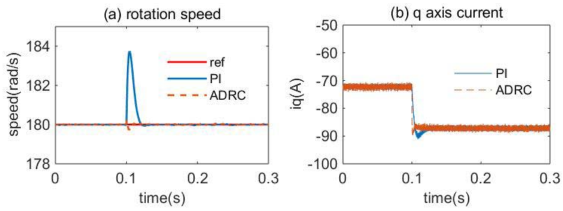

Fig. 11. Dynamic response of ADRC based speed control

Secondly, a constant $T_{mec} = -50N.m$ is conducted, and reference ω^*changes from 150rad/s to 180rad/s at 0.1s. The speed tracking process of both controllers are almost the same as shown in Fig. 12(a), but the overshoot of i_q is reduced with ADRC control as shown in Fig. 12(b).

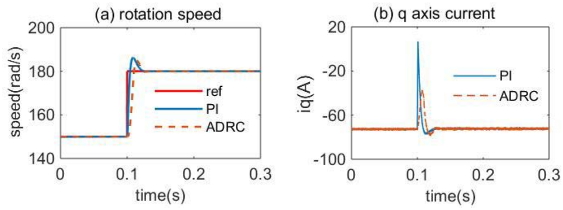

Fig. 12. Dynamic response of ADRC based speed control

Owing to space constraints, other simulation results will not be covered in this paper.

VI. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The ADRC theory has been proposed for more than two decades, which stands out among various algorithms due to its advantages for a complex uncertain physical system. The key point to successful applications of the ADRC is not the ADRC paradigm itself but how to formulate a physical system full of perturbations, uncertainties and nonlinear elements to be a standard cascaded integrators model. Firstly, a general design philosophy for the ADRC based control is proposed, then a detailed survey of the ADRC applications in PMSM system is conducted in this paper. Furthermore, simulation results have proved the effectiveness of the ADRC based speed control. Moreover, several significant research directions are indicated.

- ADRC based synchronous control has been applied in the series multi-PMSM or double-PMSM [42] [43]. What is more, the stability and robustness of PI control caused by the parallel power electronics, such as the parallel UPS or distributed renewable energy systems, are a tough issue. How to improve the robustness and stability by taking full use of ADRC will be a key point.
- To comply fully with the modern control theory, Linear Active Disturbance Rejection Control (LADRC) has been presented in [44], which makes ADRC applications more practical [34], [35]. Particularly, it can profit the mature frequency domain analysis methods such as the bandwidth and stability margins [45]. Hence, LADRC application is a hot research point.
- Additionally, paper [25] extends ADRC design to the αβ frame with a generalized proportion integral observer (GPIO), which simplifies the procedure of dq coordinate transformation. This brings a new design perspective for a three-phase system.

REFERENCES

[1] M. Hauck, I. Munteanu, A. I. Bratcu, S. Bacha, and D. Roye, "Operation of Grid-Connected Cross-Flow Water Turbines in the Stall Region by Direct Power Control," IEEE Trans. Ind. Electron., vol. 58, no. 4, pp. 1132–1140, 2011.

[2] L. Belhadji, S. Bacha, I. Munteanu, A. Rumeau, and D. Roye, "Adaptive MPPT Applied to Variable-Speed Microhydropower Plant," IEEE Trans. Energy Convers., vol. 28, no. 1, pp. 34–43, 2013.

[3] L. Belhadji, S. Bacha, and D. Roye, "Modeling and control of variable-speed micro-hydropower plant based on axial-flow turbine and permanent magnet synchronous generator (MHPP-PMSG)," in IECON 2011-37th Annual Conference on IEEE Industrial Electronics Society, 2011, pp. 896–901.

[4] J. Jung, V. Q. Leu, T. D. Do, E. Kim, and H. H. Choi, "Adaptive PID Speed Control Design for Permanent Magnet Synchronous Motor Drives," IEEE Trans. Power Electron., vol. 30, no. 2, pp. 900–908, 2015.

[5] K. Paponpen and M. Konghirun, "An Improved Sliding Mode Observer for Speed Sensorless Vector Control Drive of PMSM," in 2006 CES/IEEE 5th International Power Electronics and Motion Control Conference, Shanghai, 2006, no. 2, pp. 1–5.

[6] S. Barkat and A. Tlemc, "Noninteracting Adaptive Control of PMSM Using Interval Type-2 Fuzzy Logic Systems," IEEE Trans. Fuzzy Syst., vol. 19, no. 5, pp. 925–936, 2011.

[7] J. Han, "Active disturbance rejection controller and its applications, " Control Decis, 13(1):19–23, 1998, (in Chinese).

[8] Z. Gao, Y. Huang, and J. Han, "An alternative paradigm for control system design," in Proceedings of the 40th IEEE Conference on Decision and Control (Cat. No.01CH37228), Orlando, FL, 2001, pp. 4578-4585 vol.5.

[9] J. Han, "From PID to Active Disturbance Rejection Control," IEEE Trans. Ind. Electron., vol. 56, no. 3, pp. 900–906, 2009.

[10] J. Han, "From PID to auto disturbances rejection control," Control Eng., vol. 9, no. 3, pp. 13–18, 2002, (in Chinese).

[11] J. Han, "The structure of linear system and computation of feedback system," in Proc. of National Conference on Control Theory and Its Application, Academic Press. p. 121-133, 1980, (in Chinese).

[12] J. Han, “Control theory: Model approach or control approach,” Syst. Sci. Math., vol. 9, no. 4, pp. 328–335, 1989, (in Chinese).

[13] J. Han and W. Wang, “Nonlinear tracking-differentiator,” Syst. Sci. Math., vol. 14, no. 2, pp. 177–183, 1994, (in Chinese).

[14] J. Han, “Nonlinear PID controller,” J. Autom., vol. 20, no. 4, pp. 487–490, 1994, (in Chinese).

[15] J. Han, “Extended state observer for a class of uncertain plants,” Control Decis., vol. 10, no. 1, pp. 85–88, 1995, (in Chinese).

[16] Y. Huang and W. Xue, “Active disturbance rejection control: Methodology and theoretical analysis,” ISA Trans., vol. 53, no. 4, pp. 963–976, 2014.

[17] G. Feng, L. Huang, and D. Zhu, “A Nonlinear Auto-Disturbance Rejection Controller for Induction Motor,” in Industrial Electronics Society, 1998. IECON ’98. Proceedings of the 24th Annual Conference of the IEEE, ,Aachen, 1998, pp. 1509–1514.

[18] G. Feng, L. Huang, and D. Zhu, “A robust controller for improving disturbance rejection in speed control of induction motors,” in 1999. PEDS ’99. Proceedings of the IEEE 1999 International Conference on Power Electronics and Drive Systems, 1999, vol. 1, pp. 432–437.

[19] Y. X. Su, C. H. Zheng, and B. Y. Duan, “Automatic Disturbances Rejection Controller for Precise Motion Control of Permanent-Magnet Synchronous Motors,” IEEE Trans. Ind. Electron., vol. 52, no. 3, pp. 814–823, 2005.

[20] K. Sun and Y. Zhao, “A New Robust Algorithm to Improve the Dynamic Performance on the Position Control of Magnet Synchronous Motor Drive,” in 2010 2nd International Conference on Future Computer and Communication (ICFCC), 2010, pp. 268–272.

[21] Z. Yuefei, L. Chuang, F. Hui, Z. Tao, and H. Ye, "A decoupled active disturbance rejection controller for PMSM speed-regulation system with position feedback," in 2015 18th International Conference on Electrical Machines and Systems (ICEMS), Pattaya, 2015, pp. 1769-1774.

[22] J. Gai, S. Huang, Q. Huang, M. Li, H. Wang, D. Luo, X. Wu, and W. Liao, “A New Fuzzy Active-disturbance Rejection Controller Applied in PMSM Position Servo System,” in International Conference on Electrical Machines and Systems (ICEMS), 2014, pp. 2055–2059.

[23] J. Gao, J. Kuang, S. Huang, Q. Huang, Z. Xu and Y. Chen, "A novel position controller for PMSM servo system based on variable structure active disturbance rejection controller," in 2011 International Conference on Electrical Machines and Systems, Beijing, 2011, pp. 1-5.

[24] H. Sira-ramírez, J. Linares-flores, C. García-rodríguez, and M. A. Contreras-ordaz, “On the Control of the Permanent Magnet Synchronous Motor: An Active Disturbance Rejection Control Approach,” IEEE Trans. Control Syst. Technol., vol. 22, no. 5, pp. 2056–2063, 2014.

[25] E. W. Zurita-Bustamante, H. Sira-Ramirez and J. Linares-Flores, "On the sensorless rotor position control of the permanent magnet synchronous motor: An active disturbance rejection approach," in 2016 13th International Conference on Power Electronics (CIEP), Guanajuato, 2016, pp. 12-17.

[26] P. Yu, C. Chen, and S. Li. "Active Disturbance Rejection Control of PMSM Speed-adjusting System," Electric Drive, 2005, vol. 9, p. 002,(in Chinese).

[27] L. Wang, H. Zhang and X. Liu, "Robust sensorless of ADRC controlled PMSM based on MRAS with stator resistance identification," in Proceedings of the 30th Chinese Control Conference, Yantai, 2011, pp. 3575-3579.

[28] S. Li and Z. Liu, “Adaptive Speed Control for Permanent-Magnet Synchronous Motor System With Variations,” IEEE Trans. Ind. Electron., vol. 56, no. 8, pp. 3050–3059, 2009.

[29] T. Zhou, H. Guo, J. Xu, X. Kuang, and H. Qian, "Research on PMSM active disturbance rejection controller based on model compensation," in 2015 18th International Conference on Electrical Machines and Systems (ICEMS), Pattaya, 2015, pp. 1593-1596.

[30] Z. Liu and S. Li, “A Two-order Active Disturbance Rejection Control Algorithm for Permanent Magnetic Synchronus Motor,” in 2007 Chinese Control Conference, Wunan, 2007, pp. 68–71.

[31] S. Li and J. Li, "Output Predictor based Active Disturbance Rejection Control for a Wind Energy Conversion System with PMSG," in IEEE Access , vol.PP, no.99, pp.1-1

[32] Y. Han and H. Li, "Research on PMSM sensor-less system based on ADRC strategy," in 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), Hefei, 2016, pp. 1829-1834.

[33] Sravya K, B. V. R. S. B. Seshu, and S. Malladi, "Speed control of electric drives using Active Disturbance Rejection Control," in 2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE), Bangalore, 2016, pp. 1-6.

[34] L. Du, K. Zhang, and G. Jin, "Linear auto disturbance rejection controller for vector-controlled PMSM drive system," in Proceedings 2011 International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE), Changchun, 2011, pp. 879-882.

[35] J. Zhang and L. Kang, "A sensorless vector control system of permanent magnet synchronous motor based on line active disturbance rejection controller," in 2014 17th International Conference on Electrical Machines and Systems (ICEMS), Hangzhou, 2014, pp. 1140-1144.

[36] L. Qiong, X. Qiang, and R. Wu, "An improved predictive current method for permanent magnet synchronous motors," in 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), Beijing, 2014, pp. 1-6.

[37] X. Gan, C. Liu, K. Wang, Y. Hu, and Y. Zuo, "Active Disturbance Rejection Controller for PMSM Current Loop Based on Improvement of Time Delay," in 2016 IEEE Vehicle Power and Propulsion Conference (VPPC), Hangzhou, 2016, pp. 1-5.

[38] S. Li, C. Xia, and X. Zhou, “Mechatronics Disturbance rejection control method for permanent magnet synchronous motor speed-regulation system,” Mechatronics, vol. 22, no. 6, pp. 706–714, 2012.

[39] K. Sun, Y. Zhao, and Q. Shu, "A position sensorless vector control system of permanent magnet synchronous motor based on active-disturbance rejection controller," in 2009 International Conference on Mechatronics and Automation, Changchun, 2009, pp. 3833-3837.

[40] S. Wei, B. Wu, M. Qiu, and C. Liu, "Autodisturbance rejection controller in direct torque control of permanent magnet synchronous motor drives," In 4th International Power Electronics and Motion Control Conference, 2004. IPEMC 2004, Xi'an, 2004, pp. 1268-1272.

[41] Q. F. Teng, G. F. Li, J. G. Zhu, Y. G. Guo and S. Y. Li, "ADRC-based model predictive torque control for PMSMs fed by three-phase four-switch inverters," in 2016 35th Chinese Control Conference (CCC), Chengdu, 2016, pp. 4550-4555.

[42] Z. Xiao, J. Wang, H. Liu, H. Han, and L. Liu, "Active disturbance rejection control strategy for symmetrical six-phase and three-phase PMSM two-motor series-connected system," in 2015 12th IEEE International Conference on Electronic Measurement & Instruments (ICEMI), Qingdao, 2015, pp. 1354-1358.

[43] Q. Chen, F. Dong, L. Tao, and Y. Nan, "Multiple motors synchronization based on active disturbance rejection control with improved adjacent coupling," in 2016 35th Chinese Control Conference (CCC), Chengdu, 2016, pp. 4510-4516.

[44] Z. Gao, “Scaling and Bandwidth-Parameterization Based Controller Tuning,” in Proceedings of the American control conference, 2006, pp. 4989–4996.

[45] G. Tian and Z. Gao, “Frequency Response Analysis of Active Disturbance Rejection Based Control System,” in CCA 2007 IEEE International Conference on Control Applications, 2007, pp. 1–3.