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Active Disturbance Rejection Control of a DC Motor

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***Abstract*—Preceding conventional model-based control techniques applied to the DC motor has not been effective in achieving reference tracking, canceling parametric uncertainties and rejecting external disturbances. Hence, this paper presents a two-degree-of-freedom (2DOF) active disturbance rejection control (ADRC) structure for the speed control of the separately-excited DC motor, where good set-point tracking and disturbance rejection are both achieved. Its aim is fundamentally built on the prospect of online estimating the unknown disturbance inputs affecting the DC motor by means of suitable observers and proceeding to canceling them via an appropriate feedback control law, using the gathered disturbance estimate. An extended state observer (ESO) in real-time estimates the general disturbance, consisting of the external disturbance and internal uncertainties, and feeds it back in the control loop thus canceling them out. While the state controller provides usual feedback control. The proposed controller features a revolutionary departure from the model-based feedback control paradigm, as it does not require a precise but coarse model of the motor to design a suitable controller. Computer simulations are presented to validate the effectiveness of the proposed control scheme.**

***Index Terms*—Active disturbance rejection control, Extended State Observer, Speed control, Disturbance rejection, DC Motor Control.**

I. INTRODUCTION

Due to their high reliability, flexibility, and relatively low cost, DC motors are a common choice for various industrial applications, robot manipulators, and home appliances where speed and position control of motors are required [1, 2]. As a result, a recurrent control objective is to precisely regulate its speed in the presence of uncertainties, parametric variations, and external disturbances. Separately-excited direct-current motors (SEDCM) refer to a class of direct-current (DC) motors whose armature and field circuits are supplied from independent voltage sources [1,2]. Theoretically, the speed of an SEDCM can be controlled via different methods. However, with this work, consideration is given solely to the armature voltage option where the armature voltage is varied, causing a corresponding variation in the developed torque; and thus, the speed of the motor.

It has long been established among control theorists and practitioners alike that industrially, the application of the proportional-integral-derivative (PID) controller is rife [3]. However, PID controller, though ubiquitous, has certain limitations [4]. In this paper, the active disturbance rejection control (ADRC) paradigm initially developed by J. Han [4, 5] and further simplified in [6], will be utilized to regulate the speed of the SEDCM. In light of previous research carried out on speed regulation of SEDC motors using the feedback-feedforward compensation technique [1], together with its attendant limitations, an exhaustive comparative analysis of the results obtained with this new proposed approach ADRC compared with [1] IMC-feedforward (IMC-FF) , and the classical PID schemes will be presented.

Hence this paper proposes a two-degree-of-freedom (2DOF) ADRC control structure for the motion control of the DC motor, where good set-point tracking and disturbance rejection are both achieved. It has the following objectives:

- To use the ADRC law which features a revolutionary departure from the traditional model-based feedback control paradigm, which does not require a precise but rather coarse model, of the process to design a suitable controller.
- An extended state observer (ESO) in real-time is used to estimate the generalized disturbance – consisting of the external disturbance and internal uncertainties – which is fed back to the control loop, hence achieving good disturbance rejection performance.
- While a state-feedback controller is designed to provide nominal feedback control for the DC motor achieving good reference tracking performance.

Hence, the proposed control approach delivers both better reference tracking and disturbance rejection performance for the DC motor.

The proposed scheme uses experimental science to actively estimate and compensate the disturbances and unknown dynamics in the motor. This control scheme not only gives desired performance characteristics but also cancels model uncertainties in real-time, while retaining the tuning simplicity and error-driven framework characteristic of PID control [4, 6]. With this control scheme; a complex, non-linear, and time-varying process is reduced to a much simpler form – an ideal physical form – by actively estimating and rejecting the generalized disturbance using an Extended State Observer (ESO). To idealize a physical process – like the DC motor – the ADRC control scheme gets rid of all its imperfections. This generalized disturbance represents the combined effects of the unmodeled plant dynamics and the external disturbances [6]. As outlined in [4], the ADRC paradigm fundamentally involves utilizing an augmented state-space model of the plant which contains the generalized disturbance as an additional state, this extra state approximates the disturbance. Initially, the ESO uses nonlinear observer gains, however, to further simplify the tuning and implementation process, linear gains are used instead and are parameterized as in [6], making the observer bandwidth the only tuning parameter. With a well-behaved observer, further simplification of the controller tuning is achieved by making its parameters, functions of the closed-loop bandwidth. This final expression is termed parameterized linear Active Disturbance Rejection Control (LADRC) [7].

With the transition from analogue to novel digital processors, there is a need for a corresponding shift in the control design paradigms required to fully exploit the possibilities these powerful processors afford us [4]. The ARDC approach heralds this very crucial transition and is gradually replacing the classical PID control and even the more recent model-based solutions among practitioners [8]. One key reason why this is the case is the fact that it can

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adapt to variable process parameters in different control scenarios, as various simulative studies have shown [8-10]. As a result, it has gained considerable traction in recent years, finding application in areas such as motion control [9, 11], power electronics[9, 12, 13], fuel-cell systems[10], water supply systems[14], pH regulation in photobioreactor systems[15], and in bearingless permanent magnet synchronous motors[16]. Other applications of the ADRC technology are discussed in [17-25].

The rest of this paper is organized as follows. The dynamic model of the SEDCM as well as the proposed observer-based control technique is introduced in Section II. Section III features simulative experiments and interpretations. Finally, concluding notes and recommendations for further research are given in Section IV.

II. MODELLING AND CONTROL

The dynamic model of the SEDCM is well documented in literature [1, 3, 26, 27, 28, 29, 30]. The DC motor is a linear time-invariant second-order plant:

$$\ddot{y} = -a_1\dot{y} - a_0 y + bu \tag{1}$$

With a_0 and a_1 unknown, $f = -a_1\dot{y} - a_0 y$ in this case. The DC motor, which in this case, is a second-order system is depicted thus

$$\ddot{y} = f(y, u, d) + bu \tag{2}$$

Where b is the high-frequency gain of the plant, y is the output, u is the input, and f is the generalised disturbance. Constructing an augmented state variable such that the generalized disturbance for the DC motor is captured; let $z_1 = y$, $z_2 = \dot{y}$, $z_3 = f$ and assuming f is differentiable (2) takes the form:

$$\dot{x} = Ax + Bu + E\dot{f} \tag{3}$$

$$y = Cx \tag{4}$$

Where:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ b \\ 0 \end{bmatrix}, \quad E = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$c = [1 \quad 0 \quad 0]$ and $z = [z_1 \quad z_2 \quad z_3]^T$.

With the ADRC approach, a well behaved Linear Extended State Observer (LESO) for the augmented model is designed, given by

$$\dot{z} = Az + Bu + L(y - \hat{y}) \tag{5}$$

$$\hat{y} = Cz \tag{6}$$

The observer gain vector L is chosen such that all the poles of the ESO are located at $-\omega_O$. That is

$$L = [3\omega_O \quad 3\omega_O^2 \quad \omega_O^3]^T$$

With a well-behaved observer, z_1, z_2 and z_3 closely track y, $\dot{y}$, and f respectively. The observer is designed such that the Observer Tracking Error $e = x - z$ asymptotically converges to zero as time goes to infinity and its derivative, $\dot{e} = (A - LC)e$ is Hurwitz. The ADRC control law, given by

$$u = \frac{(-z_3 + u_0)}{b} \tag{7}$$

reduces the DC motor to a nominal double integral plant

$$\ddot{y} = u_0 \tag{8}$$

which easily be controlled by a Proportional-Derivative (PD) controller

$$u_0 = k_p(r - z_1) - k_d z_2 \tag{9}$$

where r is the reference signal. The state-feedback controller gain K is chosen such that all the closed-loop poles are located at $-\omega_C$, that is:

$$k_p = \omega_c^2, \; k_d = 2\omega_c \tag{10}$$

Various pole placement techniques that will achieve the desired stable closed-loop characteristic polynomial is used, such as Ackermann's Formula which states

$$L = d(A)P_O^{-1}[0 \;\; 0 \;\; \ldots \;\; 1]^T \tag{11}$$

where $d(A) = A^n + \alpha_1 A^{n-1} + \cdots + \alpha_n I$ is the desired closed-loop characteristic polynomial and $P_O = [C^T \; A^T C^T \; (A^2)^T C^T \ldots (A^{n-1})^T C^T]^T$ is the observability matrix. This means that there are only two parameters to tune for the ADRC controller: L, the observer gain for the ESO, and the controller gain K, that is, the major tuning parameters for this controller are ω_c controller bandwidth and ω_o observer bandwidth. Higher values of ω_c and ω_o will result in an improved disturbance-rejection performance but a more aggressive control action [31]. Hence, with this two-degree-of-freedom (2DOF) Linear ADRC control structure, good set-point tracking and disturbance rejection are both achieved. The block diagram of the 2DOF ADRC control approach is given in Figure 1.

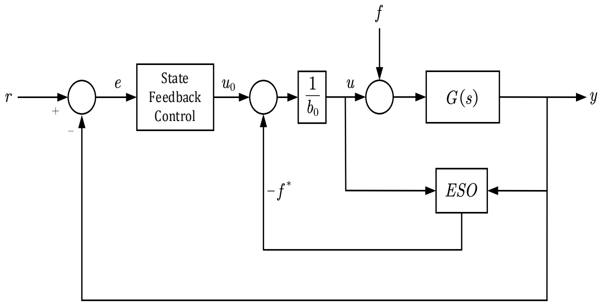

Fig. 1.. 2DOF Output-based ADRC Design .

III. SIMULATION RESULTS AND DISCUSSION

MATLAB/Simulink is used for the software simulation. Consider a particular motion control example, given by the second-order DC motor

$$\ddot{y} = -7.6\dot{y} - 97.39y + 142.94u - T_d \tag{12}$$

Where $b = 142.94$, T_d is the load torque which constitutes a disturbance to the DC motor, and a particular ADRC designed with $\omega_O = \omega_c = 40\,rad/sec$. The reference speed levels for the SEDCM was chosen as $\omega_{reference} = 1200\,rpm$. DC motors are typically run at speeds below their rated, which for this case study is $\omega_{rated} = 1750\,rpm$. The response of the ADRC controller was compared with that of the conventional PID and IMC-Feedforward controllers in [1].

The servo-control performance of the ADRC controller is shown in Figure 2. From the resultant response, it can be seen that the ADRC controller produces faster reference tracking with a smaller settling time compared to the other control schemes. Its response is also non-oscillatory and damped.

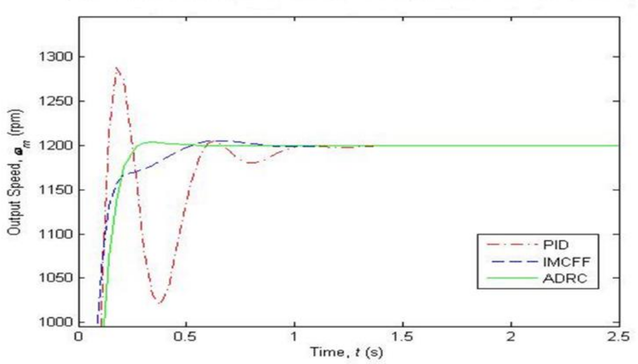

Fig. 2. Servo-control Performance of the ADRC controller.

A disturbance of 40 Nm representing the load torque T_d is applied to the DC motor after 5 $seconds$, at constant reference speed. The regulatory control (disturbance rejection) performance of the ADRC controller is shown in Figure 3.

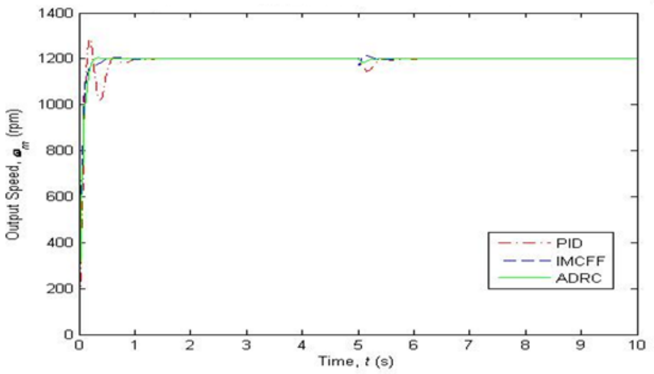

Fig. 3. Regulatory Control Performance of the ADRC controller

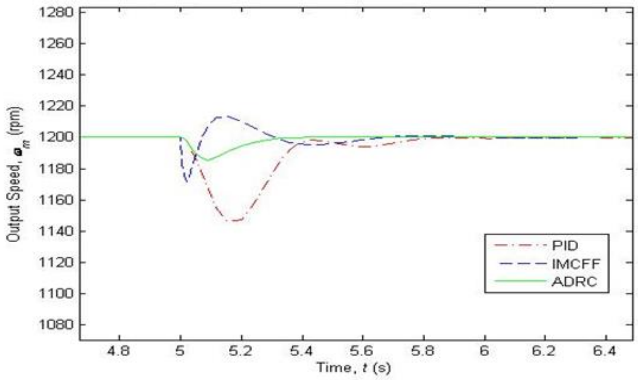

Fig. 4. Disturbance Rejection of the ADRC controller (magnified)

From the derived response, it can be seen that the ADRC controller is more robust and possesses better disturbance rejection properties compared to the other featured controllers.

IV. CONCLUSION

The ADRC approach provides a two-degree-of-freedom (2DOF) control structure for the motion control of the DC motor where good set-point tracking and disturbance rejection are both achieved. The extended state observer (ESO) in real-time estimates the general disturbance – consisting of the external disturbance and internal uncertainties – and feeds it back in the control loop thus achieving good disturbance rejection performance. While the state-feedback controller provides typical feedback control for the DC motor achieving good reference tracking performance. Hence the proposed scheme delivers both better reference tracking and disturbance rejection performance for the DC motor.

There are only two key parameters to tune for the ADRC controller: the observer bandwidth and the controller bandwidth, where higher values of both will result in an improved disturbance-rejection performance but more rigorous control action.

Finally, the ADRC control approach idealizes the physical process – the DC motor – by getting rid of all its imperfections. Future research can be extended from this work towards the implementation of the ADRC approach on the DC motor using discrete-based controllers – like the PLC – to make it turnkey and to bridge the control theory-practice gap.

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