Robust Control of a Buck-Converter-DC-Motor Topology Under the Action of a Time-Varying Current Load

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Abstract— **Active Disturbance Rejection Control (ADRC) and Flatness Based Control (FBC) are used to regulate the response of a DC motor affected by the action of unknown exogenous time-varying load current (torque) demands and driven by a DC-to-DC Buck power converter. A Generalized Proportional Integral (GPI) observer is used to estimate and cancel the time-varying disturbance signals. In this proposed control an important parameter is the \emph{control input gain}, which could even be unknown and still providing proper regulation. Simulation results are shown to demonstrate the robustness of the method.**

Keywords: Active Disturbance Rejection Control, Buck converter, time-varying load current, GPI observer, control input gain.

I. INTRODUCTION

Conventional linear regulators are inadequate in modern electronic applications due to factors as high dissipation, considerable size and large storage capacitors requirements even for nominal power operation values, apart from the fact that they cannot provide the extended hold-up time required for the controlled shutdown in digital storage systems (see [1]). The voltage step-down DC-buck power converter is a convenient alternative for DC-to-DC bus voltage regulation due to its high power conversion efficiency. However, a limitation of this topology is the need of a reliable control strategy to properly drive the switching action of the involved commutation semiconductor to enhance the required output voltage regulation. Therefore, if a convenient control scheme can be provided to the Buck-Converter-DC-Motor topology, an efficient energy managing system with robustness against exogenous or endogenous current load disturbances can be obtained. This work is aimed to deal with such matter. Different research works have addressed the problem of disturbance rejection in DC-to-DC electronic converters: In [2] a PID controller plus a linear-to-nonlinear translator is proposed to enhance the performance of a boost converter. In [3] load disturbance rejection is achieved in a positive buck-boost converter by decoupling the capacitor voltage from the inductor current with the disadvantage of an increase in the switching loss. The work presented in [4] uses current-mode control in a quadratic buck converter to obtain a certain degree of robustness in the transient response due to step changes in the load. The transient response for step changes in the load resistance of a boost converter is analyzed in [5] under the action of a cascade control of a PI and a sliding-mode-control schemes. A hybrid digital adaptive control is used in [6] to achieve near-time-optimal responses for a wide range of step-load transients in a buck converter. Active Disturbance Rejection Control (ADRC) is based on the estimation of the system disturbance for its further cancelation. ADRC has been addressed, including observers, by professor Han and his coworkers (see [7], [8], [9], [10], [11]). Practical applications of this type of control can be found in [12], [13], [14]. On the other hand, Professor Fliess took the concept of state dependent perturbation inputs and proposed the Intelligent PID Control (IPIDC), see [15] and [16]. The theoretical basis of this can be found in [17}].

Recalling that Flatness is a system property that extends the notion of Controllability from linear systems to nonlinear dynamical systems, a system with the flatness property, has a (fictitious) flat output which can be used to explicitly express all states and inputs in terms of the flat output and a finite number of its derivatives. In this way the time-varying state dependent control gains are considered as piece-wise constant gains that can be on line identified. Linear Generalized Proportional Integral (GPI) observers are used to locally estimate the joint effects of exogenous and endogenous additive disturbances, while the control input gain is assumed to be known and, at most, output dependent. GPI observers are capable of accurate on-line estimations of: a) the output related phase variables, b) the, state dependent, additive perturbation input signal itself and c) the estimation of a certain number of the perturbation input time derivatives. This last feature facilitates the task of perturbation input prediction as GPI observers are most naturally applicable to the control of perturbed differentially flat nonlinear systems with measurable flat outputs (see [18] and [19]).

This article is organized as follows: Section 2 presents the problem formulation, the main statements under which the proposed control methodology is established and the generalities about the GPI observers. In section 3 the single buck-converter DC-motor topology is considered as a case study for the proposed robust control under the action of load variations. Section 4 presents the obtained simulation results. Conclusions of this study are presented in section 5.

2. MAIN STATEMENT AND SUPPORTING REMARKS

2.1. Problem Formulation

Given a system composed by a buck converter and a DC motor, it is desired to efficiently track the reference angular velocity under the action of a variable load torque.

2.2. Main Statement

An important difference between nonlinear differential equations and the corresponding linear differential equations with injected exogenous time-varying signals is established.

Consider the following nonlinear, time-varying, vector differential equation with a linear term

$$\dot{y}(t) = Ay + \phi(t,y),\ y(0) = y_0,\ y \in \Re^n \quad (1)$$

where A is a Hurwitz, $n \times n$, matrix of constant coefficients and $\phi(t, y)$ is a vector of nonlinearities including time-varying signals. The solution of the above nonlinear system of differential equations is denoted by $y(t, y_0)$.

Let z be an n-dimensional vector and consider the following linear system with a time-varying exogenous disturbance injection:

$$\dot{z}(t) = Az + \phi(t, y(t, y_0)),\ z(0) = y_0 + b \quad (2)$$

where b is a constant.

The following two remarks take place:

Remark. *The time-varying vector, $y(t, y_0)$, trivially satisfies the identity*

$$\dot{y}(t, y_0) = Ay(t, y_0) + \phi(t, y(t, y_0)),\ y(0, y_0) = y_0 \quad (3)$$

Remark. *The linear differential equation for z includes a copy of the nonlinear term $\phi(t, y)$ particularized for the solution $y = y(t, y_0)$ of the nonlinear differential equation. As such, for every fixed initial condition, y_0, the term: $\phi(t, y(t,y_0))$, is a function of time and is denoted by $\xi(t) = \phi(t, y(t, y_0))$.*

By defining the error vector as $e = y - z$, then, e satisfies the following linear differential equation

$$\dot{e} = Ae,\ e(0) = -b$$

Since A is a Hurwitz matrix then $\lim_{t\to\infty} e(t) = 0$ for all $b \in R^n$. Moreover, if b is set to zero, and the initial conditions for y and z coincide, then $y \equiv z$ for all $t \geq 0$. The natural consequence of this simple fact is that the nonlinear system

$$\dot{y}(t) = Ay + \phi(t,y),\ y(0) = y_0,\ y \in \Re^n$$

and the linear system with exogenous injection

$$\dot{z}(t) = Az + \phi(t, y(t, y_0)),\ z(0) = y_0$$

may be regarded as equivalent. The distinction between z and y becomes irrelevant.

The practical implication of this is that any problem (such as an observer design problem) defined on the nonlinear system, may be now posed on the equivalent linear dynamics, viewed without any ambiguity as:

$$\dot{y} = Ay + \xi(t),\ y(0) = y_0 \quad (4)$$

Customarily, in practice, the nonlinear function, $\phi(t, y)$, is unknown due to unknown parameter values or due to complex nonlinearities, or simply due to the presence of unknown exogenous time signals affecting $\phi(t, y)$. Let $\hat{\xi}$ be an estimate of the unknown time function, $\xi(t)$, such that the difference $\xi(t) - \hat{\xi}(t)$ is guaranteed to be uniformly absolutely bounded, in norm, by a small positive constant, ε, i.e.,

$$sup_t \left\| \xi(t) - \hat{\xi}(t) \right\| \leq \varepsilon, \quad (5)$$

then it can be shown that the error vector e is ultimately uniformly absolutely bounded in norm by a small positive constant, $\delta(\varepsilon)$, which depends on the largest eigenvalue, λ, of A, i.e., that which is closest to the imaginary axis in the complex plane. Since A is Hurwitz, for any given symmetric positive definite matrix $Q = Q^T > 0$, there exists a positive definite matrix P, such that $A^T P + P A = - Q$. Consider the Lyapunov function candidate $V(e) = \frac{1}{2} e^T Pe$, $P = P^T > 0$.

Then, along the solutions of the perturbed error system

$$\dot{e} = Ae + \left(\xi(t) - \hat{\xi}(t)\right), \quad (6)$$

the time derivative of $V(e)$ satisfies:

$$\begin{aligned} \dot{V} &= \frac{1}{2} e^T \left(A^T P + PA\right) e + e^T P \left(\xi(t) - \hat{\xi}(t)\right) \\ &= -\frac{1}{2} e^T Qe + \|e\| \|P\| \varepsilon \\ &\leq -\frac{1}{2} \|e\|^2 \sqrt{\lambda_{\min}(QQ^T)} + \|P\| \, \|e\| \, \varepsilon \\ &\leq -\left\{\sqrt{\lambda_{\min} AA^T}\right\} \|P\| \, \|e\|^2 + \|P\| \, \|e\| \, \varepsilon \end{aligned} \quad (7)$$

$\dot{V}(e)$ is negative outside the ball, B, defined by

$$\mathscr{B} = \left\{ e \in \Re^n \mid \|e\| \leq \delta(\varepsilon) = \frac{\varepsilon}{\sqrt{\lambda_{\min}(AA^T)}} \right\} \quad (8)$$

and, hence, all solution trajectories, $e(t)$, approach the ball, B, from the outside. Otherwise, they evolve uniformly bounded inside B. Clearly, the more negative the eigenvalues of A, the smaller the radius of the ball, B. The implications of the above result on the observation, or control, of the nonlinear scalar system

$$y^{(n)} = \varphi(t,y)u + \phi(t, y, \dot{y}, \ldots, y^{(n-1)}) \quad (9)$$

where the control input gain, $\varphi(t, y)$, is assumed to be known and, $\phi(t, y, \dot{y}, \ldots, y^{(n-1)})$, being unknown, are immediate. Indeed, an active disturbance rejection control designed on the basis of the equivalent system, $y^{(n)} = v + \xi(t)$, which is of the form:

$$\varphi(t,y)u = v = [y^*(t)]^{(n)} - \hat{\xi}(t) - \sum_{i=0}^{n-1} \kappa_{n-i} e_y^{(i)} \quad (10)$$

for suitably selected κ, with a reference signal, y^*, and a passive output error, e_y, yields a tracking error system governed by the perturbed vector equation

$$\dot{\chi} = F\chi + g(\xi - \hat{\xi}(t)) \quad (11)$$

with $\chi = (e_y, \dot{e}_y, \ldots, e_y^{(n-1)})^T$ and F in companion form, with, g, being a column vector of zeros with a 1 in the last entry.

2.3. GPI Observers

The function, $\xi(t) = \varphi(t, y(t, y_0))$, considered as a perturbation input, needs to be online estimated for a subsequent cancelation at the controller stage. This function, viewed from the observer design perspective, represents an exogenous time-varying quantity which is easily shown to be observable in the sense of Diop and Fliess [20]. The linear observer design strategy consists of estimating this time-varying quantity, $\xi(t)$, using an, instantaneous, internal time polynomial model, realized in the form of a chain of integrators of length, $p - 1$, at the observer stage for a fixed, sufficiently large integer p. When forcing the dominantly linear, perturbed, output estimation error dynamics to exhibit an asymptotically convergent behavior, the internal model for $\xi(t)$ is automatically and continuously self-updated. It is now assumed that $\xi(t)$ and a finite number of its time derivatives, $\xi^{(k)}(t)$, are uniformly absolutely bounded, for $k = 1, 2, \ldots, p$, for some sufficiently large integer p. The following general result takes place:

Theorem. *The GPI observer-based dynamical feedback controller:*

$$u = \frac{\left[[y^*(t)]^{(n)} - \Sigma_{j=0}^{n-1} \left(\kappa_j [y_j - (y^*(t))^{(j)}] \right) - \hat{\xi}(t) \right]}{\phi(t, y, \dot{y}, \cdots, y^{(n-1)}, \zeta(t))}$$

$$\hat{\xi}(t) = z_1$$

$$\begin{aligned} \dot{y}_1 &= y_2 + \lambda_{p+n-1}(y - y_1) \\ \dot{y}_2 &= y_3 + \lambda_{p+n-2}(y - y_1) \\ &\vdots \\ \dot{y}_n &= \phi(t, y)u + z_1 + \lambda_p(y - y_1) \\ \dot{z}_1 &= z_2 + \lambda_{p-1}(y - y_1) \\ &\vdots \\ \dot{z}_{p-1} &= z_p + \lambda_1(y - y_1) \\ \dot{z}_p &= \lambda_0(y - y_1) \end{aligned}$$

asymptotically exponentially drives the tracking error phase variables, $e_y^{(k)} = y^k - [y^*(t)]^k$, $k = 0, 1, .., n-1$ to an arbitrary small neighborhood of the origin, of the tracking error phase space, which can be made as small as desired from the appropriate choice of the controller gain parameters, $\{\kappa_0, \ldots, \kappa_{n-1}\}$. Moreover, the estimation errors: $\tilde{e}^{(i)} = y^{(i)} - y_{i+1}, i = 0, \ldots, n-1$ and the perturbation estimation errors: $z_j - \xi^{(j-1)}(t)$, $j = 1, \ldots, p$, asymptotically exponentially converge towards a small as desired neighborhood of the origin of the reconstruction error space, with the appropriate choice of the~ observer gain parameters, $\{\lambda_0, \ldots, \lambda_{p+n-1}\}$.

See [21] for a consistent proof of this theorem.

3. BUCK-CONVERTER DC-MOTOR COMBINATION

Consider the following model for the composite system consisting of a “Buck” DC-to-DC power converter in cascade with a DC motor, as figure 1 shows:

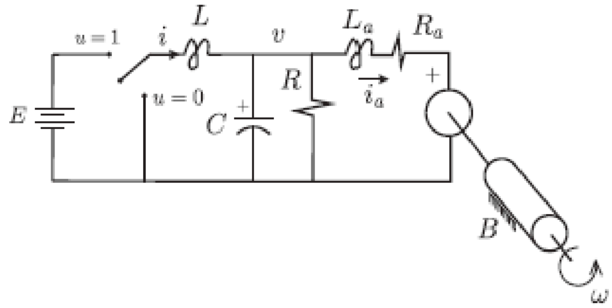

Figure 1. Control of Buck-converter DC-motor combination.

$$\begin{aligned} L\frac{di}{dt} &= -v + uE, \; C\frac{dv}{dt} = i - \frac{v}{R} - i_a \\ L_a\frac{di_a}{dt} &= -R_a i_a - K_m\omega + v, \; J\frac{d\omega}{dt} = -B\omega + K_m i_a - \tau_L \end{aligned} \quad (12)$$

where the first line of (12) corresponds to the controlled “buck” power converter and the second line corresponds to the armature controlled dc motor. The two equations in the first line are taken in an average sense with a continuous input $u \in [0, 1]$.

By defining the following state and time coordinates transformation; $x_1 = (i/E)\sqrt{L/C}$, $x_2 = v/E$, $x_3 = (i_a/E)\sqrt{L/C}$, $x_4 = \omega\sqrt{LC}$, $\tau = t/\sqrt{LC}$, the following normalized average system model (13) is obtained:

$$\begin{aligned} \frac{dx_1}{d\tau} &= -x_2 + u, \; \frac{dx_2}{d\tau} = x_1 - \frac{x_2}{Q} - x_3 \\ \alpha\frac{dx_3}{d\tau} &= -Q_a x_3 - \kappa x_4 + x_2, \; \beta\frac{dx_4}{d\tau} = -Q_B x_4 + \kappa x_3 - T_L \end{aligned} \quad (13)$$

where

$$\begin{aligned} Q &= R\sqrt{C/L}, \; Q_a = R_a\sqrt{C/L}, \; Q_B = \frac{B}{E^2C\sqrt{C/L}}, \\ \alpha &= \frac{L_a}{L}, \; \beta = \frac{J}{LC^2E^2}, \; \kappa = \frac{K_m}{E\sqrt{LC}}, \; T_L = \frac{\tau_L}{E^2C} \end{aligned}$$

The normalized average system is flat, with flat output given by x_4, and therefore, all system variables can be written as differential functions of x_4, which is now renamed as F, yielding:

$$x_4 = F$$
$$x_3 = \frac{1}{\kappa}\left[\beta \dot{F} + Q_B F + T_L\right]$$

$$x_2 = \frac{\alpha\beta}{\kappa}\ddot{F} + \left(\frac{\alpha Q_B + Q_a\beta}{\kappa}\right)\dot{F} + \left(\frac{Q_a Q_B}{\kappa} + \kappa\right)F + \frac{Q_a}{\kappa}T_L + \frac{\alpha}{\kappa}\dot{T}_L$$

$$x_1 = \frac{\alpha\beta}{\kappa}F^{(3)} + \left(\frac{\alpha Q Q_B + Q Q_a\beta + \alpha\beta}{\kappa Q}\right)\ddot{F} + \left(\frac{Q Q_a Q_B + \kappa^2 Q + \alpha Q_B + \beta Q_a}{\kappa Q} + \frac{\beta}{\kappa}\right)\dot{F}$$
$$+ \left(\frac{Q_a Q_B + \kappa^2 + Q Q_B}{\kappa Q}\right)F + \left(\frac{Q_a + Q}{\kappa Q}\right)T_L + \left(\frac{Q Q_a + \alpha}{\kappa Q}\right)\dot{T}_L + \left(\frac{\alpha}{\kappa}\right)\ddot{T}_L$$

$$u = \frac{\alpha\beta}{\kappa}F^{(4)} + \left[\frac{\alpha Q Q_B + Q Q_a\beta + \alpha\beta}{\kappa Q}\right]F^{(3)} + \left[\frac{\alpha\beta}{\kappa} + \frac{\beta}{\kappa} + \frac{Q Q_a Q_B + \kappa^2 Q + \alpha Q_B + Q_a\beta}{\kappa Q}\right]\ddot{F}$$
$$+ \left[\frac{Q_a Q_B + \kappa^2 + Q_B Q}{\kappa Q} + \frac{\alpha Q_B + Q_a\beta}{\kappa}\right]\dot{F} + \left[\frac{Q_a Q_B}{\kappa} + \kappa\right]F + \left[\frac{\alpha}{\kappa}\right]T_L^{(3)} + \left[\frac{Q_a Q + \alpha}{\kappa Q}\right]\ddot{T}_L$$
$$+ \left[\frac{Q_a + Q}{\kappa Q} + \frac{\alpha}{\kappa}\right]\dot{T}_L + \left[\frac{Q_a}{\kappa}\right]T_L \quad (14)$$

Observer design:

For observer construction purposes, the complete system can be seen as the following linear perturbed system

$$F^{(4)} = \left(\frac{\kappa}{\alpha\beta}\right)u + \xi(\tau)$$

where

$$\xi(\tau) = -\varphi\left(F^{(3)}, \ddot{F}, \dot{F}, F, T_L, \dot{T}_L, \ddot{T}_L, T_L^{(3)}\right)\left(\frac{\kappa}{\alpha\beta}\right).$$

By denoting F_j, $j = 0, 1, 2, 3$ as the estimates of $F^{(j)}$, the following observer is proposed:

$$\dot{F}_0 = F_1 + \lambda_{m+3}(F - F_0)$$
$$\dot{F}_1 = F_2 + \lambda_{m+2}(F - F_0)$$
$$\dot{F}_2 = F_3 + \lambda_{m+1}(F - F_0)$$
$$\dot{F}_3 = \frac{\kappa}{\alpha\beta}u + z_1 + \lambda_m(F - F_0)$$
$$\dot{z}_1 = z_2 + \lambda_{m-1}(F - F_0)$$
$$\vdots$$
$$\dot{z}_{m-1} = z_m + \lambda_1(F - F_0)$$
$$\dot{z}_m = \lambda_0(F - F_0)$$

The estimation error defined as, $e = F - F_0$ satisfies the following linear perturbed differential equation

$$e^{(m+4)} + \lambda_{m+3}e^{(m+3)} + \cdots + \lambda_1\dot{e} + \lambda_0 e = \xi^{(m)}(\tau)$$

If $\xi^{(m)}(\tau)$ is uniformly absolutely bounded, then a suitable choice of the set of coefficients, $\{\lambda_0, \ldots, \lambda_{m+3}\}$., yields ultimately the uniformly absolutely bounded estimation error phase variables: $e^{(j)}$, $j = 0, \ldots, m+3$, which evolve inside a small as desired neighborhood of the origin of the estimation error phase space, characterized by the vector: $\chi = (e_y, \dot{e}_y, \ldots, e_y^{(m+3)})^T$.

If $\xi^{(m)}(\tau)$ is not uniformly absolutely bounded, then solutions of the plant equations

$$F^{(4)} = \frac{\kappa}{\alpha\beta}u - \frac{\kappa}{\alpha\beta}\varphi\left(F^{(3)}, \ddot{F}, \dot{F}, F, T_L, \dot{T}_L, \ddot{T}_L, T_L^{(3)}\right)$$

do not even *exist* for any finite u.

On the other hand, convergence of e, and its time derivatives, to a vicinity of the origin of the χ-space, along with the equation

$$e^{(4)} = \varphi(\tau) - z_1 - \lambda_m e$$

demonstrate that z_1 constitutes an arbitrarily close estimate of the unknown function $\xi(\tau)$.

An active disturbance rejection feedback controller, (ADRC), with, $\hat{\xi} = z_1$, and F_0 substituted by F, and a reference output, F^*, is proposed as,

$$u = \frac{\alpha\beta}{\kappa}\left[[F^*(\tau)]^{(4)} - \sum_{i=0}^{3}\kappa_i\left(F_i - [F^*(\tau)]^{(i)}\right) - \hat{\xi}\right]$$

Given that,

$$F^{(i)} = F_i + e^{(i)},\ i = 1, 2, 3$$

the closed loop tracking error system, with $e_F = F - F^*(\tau)$, $e_F^{(i)} = F^{(i)} - [F^*(\tau)]^{(i)}$, $i = 1, 2, 3$, satisfies:

$$e_F^{(4)} + \kappa_3 e_F^{(3)} + \cdots + \kappa_0 e_F = \xi(\tau) - \hat{\xi} + \sum_{i=1}^{3}\kappa_i e^{(i)}$$

Since the $e^{(i)}$'s converge to a small as desired vicinity of zero and the difference, $\xi(t) - \hat{\xi}(t)$, is as small as desired, the right hand side of the previous linear tracking error equation is arbitrarily small.

It follows that e_F and its time derivatives converge to a small vicinity of the origin of the tracking error phase space, $\theta = (e_F, \dot{e}_F, \ldots, e_F^{(3)})^T$, provided the set of gains, $\{\kappa_0, \ldots, \kappa_3\}$, are chosen moderately but sufficiently high so as to have the poles of the corresponding dominating characteristic polynomial: $p(s) = s^4 + \kappa_3 s^3 + \ldots + \kappa_0$, far into the left half of the complex plane.

4. SIMULATION RESULTS

The Buck-converter DC-DC-Motor System of figure 1 has been simulated for tracking a reference angular velocity, $\omega^*(t)$, under the influence of a variable load torque, $\tau_L(t)$ (emulated by an array of various periodic signals). The obtained results are presented in figure 2. As it can be seen, the estimated disturbance, $\hat{\xi}(t)$, allows a proper cancelation of the torque variations so that the system angular velocity, $\omega(t)$, conveniently tracks the reference velocity $\omega^*(t)$.

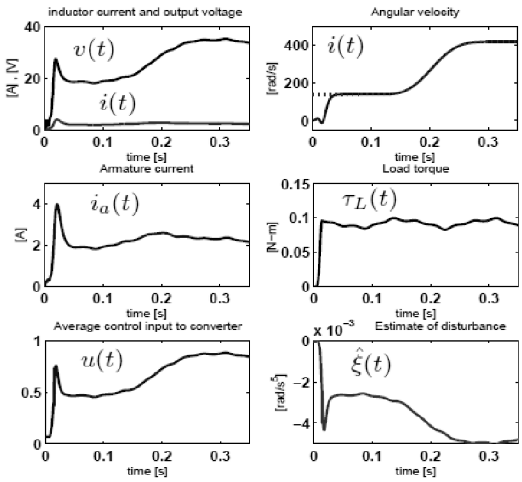

Figure 2. Simulation results of the Buck-converter DC-Motor combination.

4.1. Simulation of robustness with respect to the control input gain. Buck-converter DC-Motor

In the previous simulation, the control input gain, $\mu = \frac{\kappa}{\alpha\beta}$, of the linear system was assumed to be known. If the control input gain, μ, is not precisely known, but instead an estimate, $\hat{\mu}$, is available, then for simulation purposes, the following estimated gain, $\hat{\mu} = \left(\frac{\kappa}{\alpha\beta}\right) f$, can be used in both, the GPI observer and the linear Active Disturbance Rejection controller. The constant factor, *f,* is a real number modeling the percentage of error committed in the gain estimation with respect to its actual value. Naturally, $f = 1$, represents exact knowledge of the control input gain. When the simulations were carried out, it was found that for a factor, *f,* approximately ranging in the set:

$$f \in [0.7, 11],$$

the closed loop system exhibits an accurate trajectory tracking of the desired angular velocity profile, $\omega^*(t)$. This can be verified in figures 3 and 4 for $f > 1$ and $f < 1$, respectively.

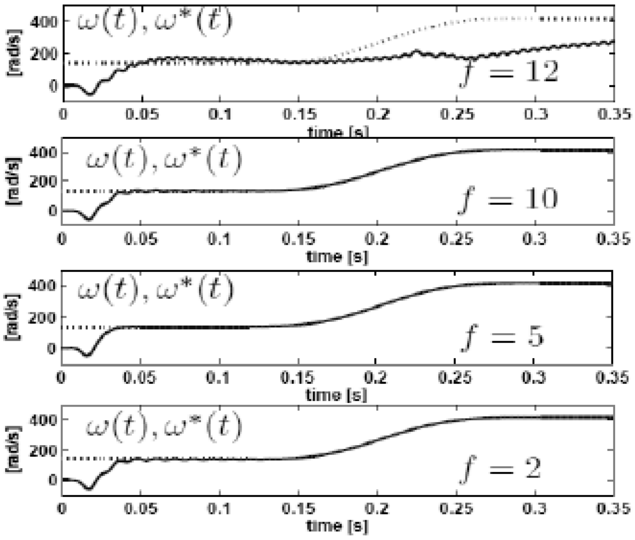

Figure 3. Robustness with respect to the control input gain, $f > 1$.

5. CONCLUSIONS

A robust control technique based on Active Disturbance Rejection Control and Flatness Control has been presented in this article. The presence of unmodelled exogenous disturbances is estimated by the Generalized Proportional Integral observers followed by a proper cancellation in the control strategy. The ***control input gain***, which is normally unknown, is accounted for by the proposed technique. The Buck-converter DC-Motor under the action of variable load torques (disturbances) has been studied applying the proposed technique showing that the proposed control provides robustness in the output variable and the regulation/trajectory tracking issues are fulfilled.

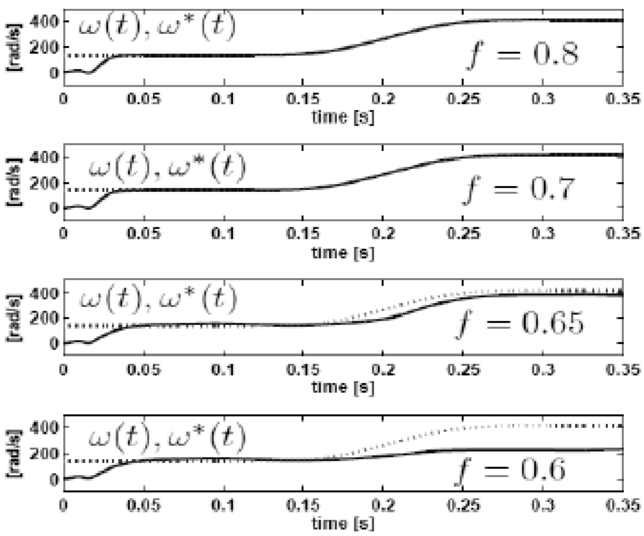

Figure 4. Robustness with respect to the control input gain, $f < 1$.

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