Smooth Reference Modulation to Improve Dynamic Response in Electric Drive Systems

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Abstract

Response overshoot is an undesirable behavior that can be exhibited by a dynamical system. Reduction of overshoot, without compromising the speed of the system response, increases the permissible operational range by enabling the system to operate closer to its limits. Previous work related to set point modulation proposed an effective strategy to improve set point tracking by temporarily modifying the set point based on the trend of the response and its proximity to the set point. However, this strategy is designed for solid-state units with no inertia and is not directly applicable to applications such as electric drive systems, in which introducing additional step changes in the set point may cause mechanical stress. This paper addresses this issue and proposes an alternate strategy based on continuous, rather than step, changes in the set point. The proposed approach is implemented on an electric drive system. Simulation and experimental results confirm the desirable dynamic performance of the proposed approach.[1]

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[1] This report is based on

[1] M. Yazdanian, A. Mehrizi-Sani, R. Seebacher, K. Krischan, and A. Muetze, "Controller-agonostic reference modulation to improve dynamic response in drive systems," *IEEE Trans. Power Electron.*, submitted for review, Feb. 2016.

Contents

Chapter 1

Introduction

In control practice, selection of control parameters is a trade-off between the speed, overshoot, and settling time of the closed-loop system. Typically, a compromise is made by allowing a certain amount of overshoot in exchange for a faster response. However, this overshoot reduces the permissible operational range of the system. Furthermore, it may cause the system to violate its operational constraints and lead to instability. Therefore, mitigation of the overshoot with no or least possible adverse effect on the speed of the closed-loop system is of significant importance [1].

Prior work [2,3] proposed a strategy called set point automatic adjustment with correction enabled (SPAACE) to improve the set point tracking performance of power electronics–based distributed generation (DG) units in a microgrid. Fig. 1.1 shows the basics of this method. SPAACE augments the controllers that are already implemented in the field and monitors the controlled variable $x(t)$ and based on its variations and deviation from the set point $x_{sp}(t)$, temporarily modulates $x_{sp}(t)$ so that $x(t)$ closely tracks the set point. In a typical implementation of SPAACE, the variation in the set point is introduced as a step change from x_{sp} to $(1 - m)x_{sp}$, where m is a design parameter. The salient features of SPAACE are (i) robustness to changes in the system, (ii) not requiring the system model, and (iii) scalability and reliance merely on local signals. While showing great promise, SPAACE is not directly applicable to applications such as drive systems because the step changes introduced in the set point can cause torque pulsation and consequently mechanical fatigue and stress.

Electric drives are a significant consumer of electricity; they consume about 60% of

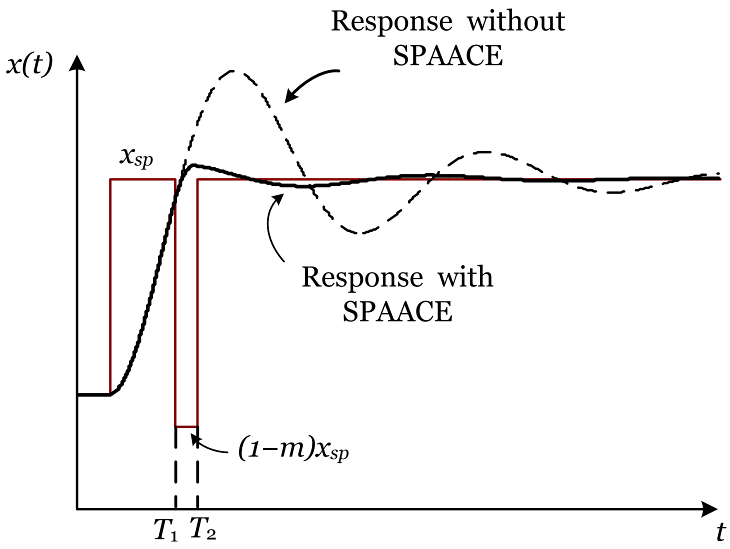

Figure 1.1: Example of application of SPAACE to improve reference set point tracking.

electricity in the United States and 45% in the world [4]. An electric drive is the combination of an electric motor and the power electronics–based circuitry required to control the motor, e.g., its speed or torque. Drive systems have numerous applications in many sectors such as transportation, manufacturing, and electricity generation. The research areas associated with the performance improvement of drive systems have exponentially grown in recent years. Reference [5] proposes a combined feedforward and feedback (FF/FB) controller to improve the robustness of an induction motor drive against parameter variations. Reference [6] proposes an input-output instantaneous power balancing approach to improve the dynamic response of the drive system and minimize the capacitance of the DC link. In [7], a torque control approach is developed based on introducing a torque estimator for a DC machine, which improves torque dynamic and attenuates the torque ripple. Reference [8] develops a combined predictive controller and observer to improve the robustness of a DC machine drive system against uncertainties of load inertia and time-varying load.

As mentioned above, accurate and fast control of drive systems is an important problem with a rich body of work accumulated in the past decades. The existing methods generally employ a detailed model of the motor to design the associated controllers. However, the performance of a controller can deteriorate as the operating point of the system on which the design is based changes over time. This change can be due to factors such as temperature variation, different modes of control, and load changes. Therefore, traditional control design methods such as model-based design (e.g., [9, 10]), model-based automatic tuning (e.g., Åström's work [11, 12]), and simulation-based optimization (e.g., Golé's work [13]), are not adequate: To redesign and reimplement new controllers, these methods require (i) updated models, (ii) a computational infrastructure, and (iii) access to the controller parameters. However, these facilities are not always available. Consequently, design methods that are relatively insensitive to system parameters and are nonintrusive can provide more desirable outcomes. As an example, in the context of electric drive systems, [14] proposes a feedforward control structure. This can be rearranged to a prefilter structure. The prefilter approach used in our case study reduces the overshoot subsequent to a step change in the closed-loop system by applying a low-pass filter between the set point and the input command of the system (outside the feedback loop). This low-pass filter should be designed such that the poles of the prefilter cancel the zeros of the closed-loop system. Appropriate design of the prefilter mitigates the overshoot of the system. However, this approach results in a slower system response.

This paper proposes and validates a smooth variant of SPAACE (SSPAACE) to autonomously improve the set point tracking capability and mitigate the overshoot without compromising the speed of the system response. SSPAACE modifies the set point more gracefully than SPAACE; that is, it introduces a smooth change as opposed to a step change. The performance of the proposed SSPAACE approach is evaluated and compared with SPAACE and prefilter approaches in a drive system under various scenarios.

The rest of this paper is organized as follows. Section 2 provides a background on existing control design methods. Section 3 discusses the basics of SPAACE. The proposed SSPAACE approach is discussed in Section 4. Modeling and controller design for a drive system are presented in Section 5. Section 6 presents the study system and case studies. Concluding remarks are provided in Section 7.

Chapter 2

Background on Controller Design

A prevalent problem in a small-scale system is that even small disturbances may lead to large transients. This problem becomes more pronounced when the parameters of the host system differ from those for which the controllers were initially designed. One way to address this problem is to redesign/retune the existing controllers. The literature on controller design is very rich. However, systematic design, e.g., model-based [9–12] or simulation-based [13, 15] design require performing new studies on the system, which in turn requires availability of the system data and models. On the other hand, a trial-and-error approach is time- and resource-intensive. Even if new controllers are designed, their implementation requires access to the internal structure of the controller, which is not always available and access to equipment becomes a hurdle. Other drawbacks of these approaches are (i) they rely on the availability of system models and (ii) once designed, the controller parameters are again appropriate only for a specific operating region; if the operating point of the host system changes significantly, e.g., due to a large load change, the devised controller parameters become irrelevant again, and the whole process needs to be reiterated. It is not feasible to frequently run studies to retune controllers in response to system changes. Therefore, a scalable approach to autonomously enhance the performance of existing controllers is desired and will have higher potential for industry adaptation. The rest of this section compares several existing methods as summarized in Table 2.1.

An approach that adaptively scales the proportional and integral gains of a PI controller based on comparison of the system response with a reference response is proposed in [16].

Table 2.1: Comparison of existing controller design methods

Approach	Model-Indept	Unintrusive	Parameter-Indept
PI Scaling	√	√	X
Ramp	√	√	√
MPC	X	√	X
PID	X	√	X
ES/IFL	√	X	X
Posicast	X	√	√
SPAACE	√	√	√

However, its performance is limited to (i) the chosen reference exponential curve, (ii) the initial choice of gains, and (iii) PI controllers. An operationally similar family of approaches is gain scheduling [17]. However, both these approaches require access to the internal parameters of the controller.

An alternate approach to reduce the over- and undershoot of controllers without requiring access to their parameters is to gradually ramp the set point. However, this has the following drawbacks: (i) the necessity of adjustment of set point is not known *a priori*, but in ramping, the set point is always modified regardless of how the existing controller may perform; (ii) selection of the ramp slope requires knowledge of system characteristics; and (iii) PI-based controllers, which dominate the power system, are inherently designed to track DC, and not ramp, commands.

A control approach that is increasingly gaining attention is model predictive control (MPC). MPC is a *de facto* standard for control of large and slow chemical plants [18,19] and offers (i) handling of multivariable problems, (ii) ease of tuning, and (iii) explicit treatment of constraints. MPC is a discrete-time, model-based strategy that determines the control sequence of the system by minimizing a cost function that reflects the system performance over a finite number of time steps. The cost function is a combination of terms to minimize the deviation of system states and terms to minimize the deviation of response from the set point. However, the performance of MPC depends on the accuracy of the available system model. Moreover, it requires an extensive computational infrastructure to solve the optimization problem at each time step.

A simple approach to include "prediction" in a controller is to use a derivative term, e.g., the D-term in a PID-based controller. This derivative term can be interpreted as linear prediction (extrapolation) [11], but it is prone to noise [20]. Moreover, it necessitates changing the existing controller, which as stated before, is not desirable in our intended applications.

A nonmodel-based approach for PID controller tuning is extremum seeking (ES) [21]. ES optimizes the step response of a closed-loop system (a PID controller and an unknown plant) by minimizing a cost function that measures the error between the reference and output. However, (i) ES is an intrusive method as it injects a sinusoidal test signal to the system input, and (ii) ES is an offline method as the cost function is evaluated only after the system response settles. A discrete variation of ES is iterative feedback tuning (IFT) [22]. While the performance of these approaches is comparable to model-based design methods, the disadvantages are that they (i) improve only the step response and (ii) require access to the controller parameters.

The only approach of which we are aware and has similarities to our proposed strategy is posicast [23–28]. In posicast, a certain step change in the set point, e.g., 0 to x_{sp}, is applied in two steps: first a fraction αx_{sp} is applied; α is calculated so that the resulting overshoot equals the reference x_{sp}. Then the remainder $(1-\alpha)x_{sp}$ is applied. Posicast was originally developed as an open-loop strategy for a second-order system. Again, the system parameters must be known.

In summary, while there is a large body of work on control, they have limited applicability:

- They have limited robustness to changes in parameters (even robust control methods).
- Mostly, a full-fledged dynamic and/or linearized model of the system is required.
- A communication channel is required to implement the redesigned controllers in the field.
- A computational infrastructure is required to conduct studies to redesign/update controllers.

Chapter 3

Review of SPAACE

SPAACE (set point automatic adjustment with correction enabled) improves the performance of an existing controller using an add-on feature we call *set point modulation.* The salient features of SPAACE are that it

- Improves the dynamic response of the system;
- Makes system more robust against disturbances, system parameters, and controller design;
- Does not require many pieces of information about the system; and
- Is structurally simple.

The term *set point* refers to the reference value of the variable, e.g., torque, speed, voltage, and current, that the controller acts upon; the term *modulation* refers to the proposed strategy that monitors the response and adjusts the set point based on its trend and sampled values. The objective of SPAACE is to achieve a response that is both fast (short settling time) and smooth (small overshoot). SPAACE predicts the future value of the output and compares it to a predetermined bound around the set point. As shown in Fig. 1.1, SPAACE switches the set point between the x_{sp} and x'_{sp} at some $t = T_1$, when it predicts a violation, to mitigate the overshoot. SPAACE brings back the set point to x_{sp} at some $t = T_2$, when it predicts that the output is within the limits. Previous studies have shown that SPAACE has the potential to result in significant improvements; representative case studies show 45% reduction in settling time and 30% reduction in overshoot [2,3].

Chapter 4

Proposed Smooth SPAACE

This section discusses the philosophy of operation of the proposed smooth variant of SPAACE (SSPAACE) [2, 3]. SSPAACE not only includes all salient features of SPAACE but also has superior performance as it modifies the set point more gracefully than SPAACE and can be used in a broader range of applications, including electric drives.

4.1 Relationship to the Drive System Controllers

The application of the proposed SSPAACE controller is not limited to a specific control practice. However, in this study, the speed control of a DC machine is considered to evaluate its performance. In this context, SSPAACE is located immediately before the standard speed controller of the DC machine as shown in Fig. 4.1. The set point provided by an outer control loop or an external command is fed into SSPAACE. SSPAACE observes the set point and output of the system and modifies the set point in order to achieve the desired trajectory. This modified set point is then fed into the speed controller.

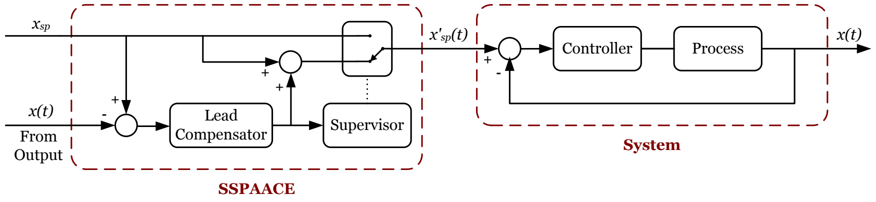

Figure 4.1: SSPAACE structure.

4.2 Description of SSPAACE

SSPAACE proposes a hybrid structure. It utilizes a supervisory switching scheme based on observing the set point and the predicted error between the set point and the response. SSPAACE changes the set point only when the predicted error is beyond the permissible range. The violation of this range can be caused by a rapid change in the set point or by a disturbance. SSPAACE can be described by the following supervisory switching rule:

$$x'_{sp}(t) = \begin{cases} x_{sp}, & e_{\text{min}} \leq e_{\text{pred}}(t) \leq e_{\text{max}} \\ x_{sp} + m(t), & \text{otherwise,} \end{cases} \tag{4.1}$$

where $m(t)$ is the adjustment signal applied to the set point and $e_{\text{pred}}(t)$ is the predicted error. The choice of e_{min} and e_{max} defines the permissible violation range and depends on the application. The prime difference between SPAACE and SSPAACE is that the adjustment signal in SPAACE is a factor of set point ($m(t) = m \times x_{sp}$), while the adjustment signal in SSPAACE is a factor of the predicted error ($m(t) = m \times e_{\text{pred}}(t)$). Generally, increasing m decreases the speed of the system and its overshoot. Using a constant value as the adjustment signal in SPAACE regardless of the error between set point and the response decreases the performance of the system and may result in oscillations in the steady state. This problem is not present in SSPAACE.

The error prediction can be achieved by applying the error signal to any prediction strategy. Utilization of linear and quadratic predictors in SPAACE is studied in [2, 3]. It should be noted that any type of compensator that encapsulates derivative action or provides phase lead can be viewed as a predictor [29]. In this paper, a lead compensator is employed as the predictor to reduce the complexity of the prediction algorithm. The predicted error can be calculated as follows:

$$e_{\text{pred}}(t) = \frac{sT + 1}{\alpha sT + 1} e(t), \qquad [\alpha < 1] \tag{4.2}$$

where $e(t)$ is obtained by comparing the set point and the response. T is a design parameter and should be selected such that the zero of the lead compensator matches the dominant

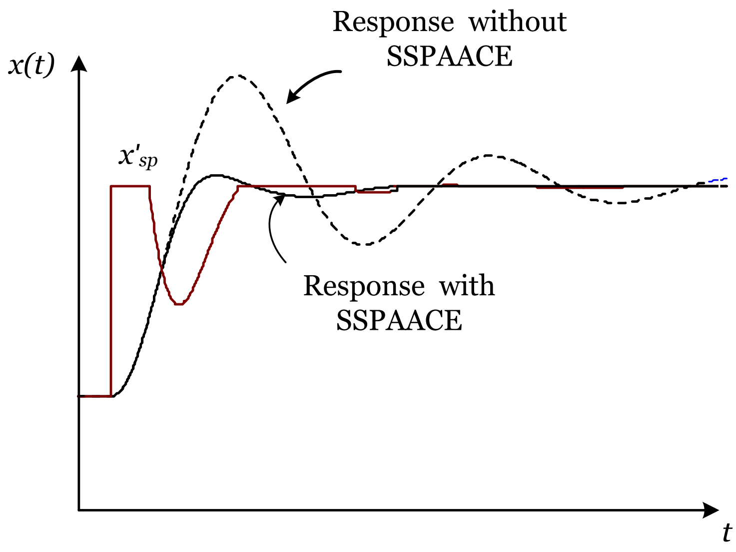

Figure 4.2: Example of application of SSPAACE to improve reference set point tracking.

pole of the system. α is also a design parameter and its tuning is a trade-off between the speed of the system and its robustness against noise. Generally, α is chosen between 0.05 and 0.3.

It should be noted that depending on the physical constraints of the system, $x'_{sp}(t)$ may be needed to be limited within an acceptable range. Fig. 4.2 shows the response of an example second-order system with and without applying SSPAACE.

Chapter 5

Study System: Electric Drive

Fig. 5.1 shows the system configuration and Fig. 5.2 shows a photograph of the experimental setup. The system parameters and ratings of the different components are shown in Table 5.1. The system consists of a DC motor mechanically coupled to an induction machine. The voltage, current, and shaft encoder measurements are applied to the dSPACE control system. dSPACE generates the gating signals of the converters. The DC machine operates under speed control mode based on the cascade control strategy, which consists of an inner current control loop and an outer speed control loop. The inner current control loop is designed based on the loop shaping method to achieve a rise time of 1 ms and an overshoot of 5%. The outer speed control loop is designed based on symmetrical optimum (SO) approach [30] to achieve an overshoot of 33%. The cut-off frequency of the speed filter is 20 Hz. The induction machine is torque-controlled using a rotor flux–oriented approach to emulate the

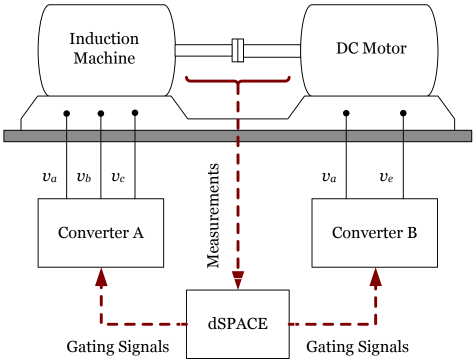

Figure 5.1: Schematic diagram of the study system.

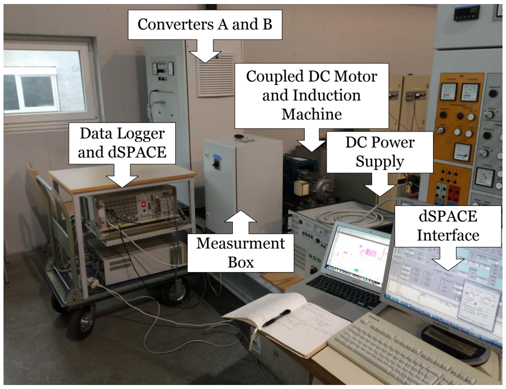

Figure 5.2: Experimental setup.

load torque.

Table 5.1: Parameters of the test system

Parameter	Value
GENERAL PARAMETERS	
Incremental encoder resolution, R	10 kPPR
Sampling frequency, f_s	5 kHz
Switching frequency, f_{sw}	5 kHz
DC MACHINE	
Rated power, P_{rated}	3.5 kW
Rated armature voltage, $V_{a,\text{rated}}$	120 V
Rated armature current, $I_{a,\text{rated}}$	35.5 A
Rated excitation voltage, $V_{e,\text{rated}}$	120 V
Rated excitation current, $I_{e,\text{rated}}$	0.79 A
Rated speed, ω_{rated}	3780 rpm
Armature resistance, R_a	389 mΩ
Armature inductance, L_a	1.389 mH
Excitation resistance, R_e	117.14 Ω
Moment of inertia, J_{dc}	0.013 26 kgm^2
INDUCTION MACHINE	
Rated power, P_{rated}	3 kW
Rated voltage, V_{rated}	72 V
Rated current, I_{rated}	37 A
Number of poles, P	4
Rated frequency, f_{rated}	150 Hz
Rated speed, ω_{rated}	4278 rpm
Stator resistance, R_s	170.62 mΩ
Stator leakage inductance, $L_{l,s}$	0.339 mH
Rotor resistance, R_r	116.29 mΩ
Rotor leakage inductance, $L_{l,r}$	0.339 mH
Magnetizing inductance, L_m	7.3 mH
Moment of inertia, J_{im}	0.003 74 kgm^2

Chapter 6

Performance Evaluation

A set of simulation and experimental case studies is reported in this section to evaluate the performance of SSPAACE in speed control of the study system. All simulation case studies are performed in MATLAB/Simulink. Table 6.1 provides the tuning parameters of SSPAACE, which are determined based on the guidelines provided in Subsection IV-B.

6.1 Small Step Change in the Speed Set Point

This case study evaluates the transient performance of the DC motor subsequent to positive and negative step changes in its speed set point. Initially, the DC motor operates in the steady state and $\omega_{\mathrm{ref}} = 500$ rpm. At $t = 0$ s, ω_{ref} is subjected to a positive step change from 500 rpm to 600 rpm. After 0.3 s, ω_{ref} is subjected to a negative step change back to 500 rpm.

Figs. 6.1 and 6.2 show the simulation and experimental results, respectively, for different approaches including the cascade PI-based control system with no modifications (base case),

Table 6.1: Tuning parameters of SSPAACE

Parameter	Value
m	2
T	$0.02\,\mathrm{s}^{-1}$
α	0.25
e_{min}	$-3\,\mathrm{rpm}$
e_{max}	$3\,\mathrm{rpm}$

Table 6.2: Transient performance of different control approaches

Approach	Overshoot (%)	Rise time (ms)	Settling time (ms)
Base case	42	32	140
Prefilter	10	57	110
SPAACE	30	32	140
SSPAACE	4	35	42

prefilter, SPAACE, and SSPAACE. Comparison of Figs. 6.1 and 6.2 confirms that the experimental results are highly consistent with the simulation results. Fig. 6.2(a) shows that the base case has an overshoot of 42%, a rise time of 32 ms, and a settling time of 140 ms. Fig. 6.2(b) shows that the prefilter approach improves the transient response and reduces the overshoot to 10% and settling time to 110 ms by changing the set point gradually; however, it deteriorates the speed of the system, and the rise time increases to 57 ms. SPAACE decreases the overshoot to 30% without compromising the speed of the system and settling time as shown in Fig. 6.2(c). Fig. 6.2(d) shows that SSPAACE leads to an overshoot of 4%, a rise time of 35 ms, and a settling time of 42 ms.

To facilitate the comparison, the actual speed of the DC motor for different control approaches is shown in a single plot in Fig. 6.3. Table 6.2 presents the transient performance of these different control approaches. Comparison of the dynamic response performance of the actual speed of the DC motor shows that SSPAACE has superior dynamic behavior in tracking of the changes in set point compared with the base case, prefilter, and SPAACE.

6.2 Large Step Change in the Speed Set Point

This case study evaluates the performance of the DC motor subsequent to a large step change in its speed set point. Initially, the DC motor operates in the steady state and $\omega_{\text{ref}} = 500$ rpm. At $t = 0$ s, ω_{ref} is subjected to a positive step change from 500 rpm to 1500 rpm. This large step change causes the armature reference current to saturate at its maximum value. Therefore, the DC motor speeds up linearly with a constant slope, which depends on the maximum armature current and maximum available torque.

Figs. 6.4 and 6.5 show the simulation results and the experimental results, respectively,

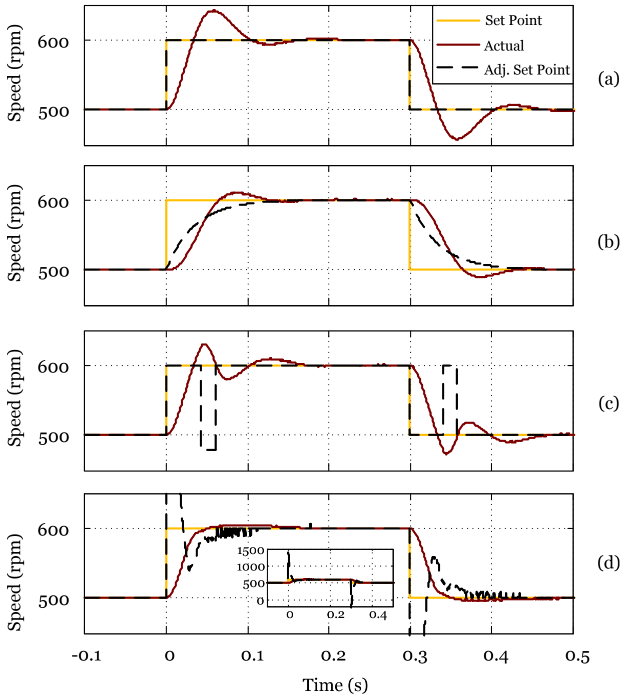

Figure 6.1: Simulation results of the transient response of the system speed subsequent to positive and negative step changes in ω_{ref}. a) base case, b) prefilter, c) SPAACE, and d) SSPAACE.

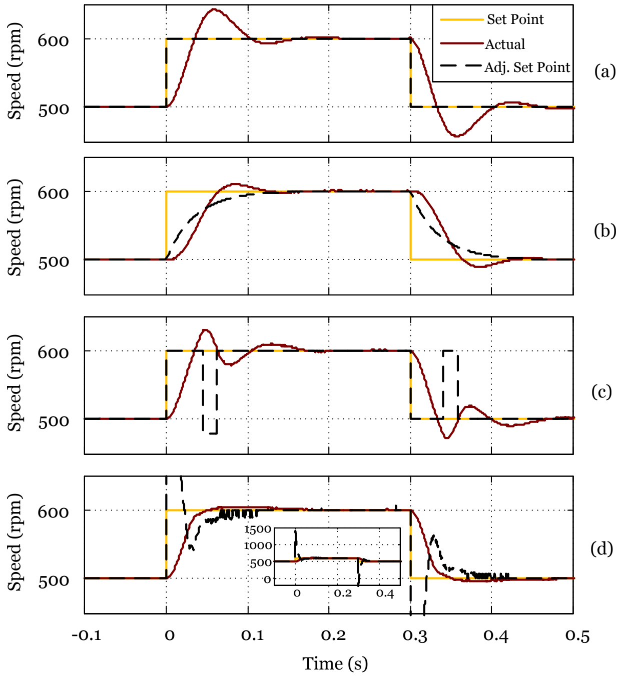

Figure 6.2: Experimental results of the transient response of the system speed subsequent to positive and negative step changes in ω_{ref}. a) base case, b) prefilter, c) SPAACE, and d) SSPAACE.

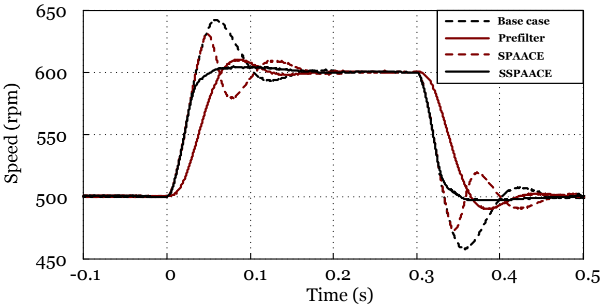

Figure 6.3: Experimental results of the transient response of the system speed subsequent to positive and negative step changes in ω_{ref} for different control approaches.

for different control approaches. This case study also confirms the consistency of the experimental with the simulation results. Fig. 6.5(a) shows that in response to this set point change, the speed increases linearly as expected, followed by an overshoot of 7%, a rise time of 225 ms, and a settling time of 310 ms. As shown in Fig. 6.5(b), the prefilter approach is ineffective in improving the transient response and reducing the overshoot. The reason is that the time constant of the prefilter is designed for linear operation of the system. In this case, the modified set point gets to the set point sooner than the actual speed; therefore, it can not affect the transient behavior of the system. Fig. 6.5(c) shows that SPAACE is also ineffective because the overshoot is very small. The response of the proposed approach is shown in Fig. 6.5(d). It can be seen that SSPAACE decreases the overshoot to 0% and settling time to 245 ms without compromising the speed of the system, which confirms the superior performance of SSPAACE compared with the base case, prefilter, and SPAACE.

6.3 External Disturbance

In this case study, the DC motor is subjected to a sudden load change to compare the robustness of the different control approaches against an external disturbance. Initially, the DC motor is under steady state condition with $\omega_{\text{ref}} = 500$ rpm and the induction machine provides a constant load proportional to the quadrature component of the stator current $i_{sq} = 0$ A. At $t = 0$ s, i_{sq} is subjected to a negative step change from 0 A to -20 A. After 0.5 s, i_{sq} is subjected to a positive step change back to 0 A. These step changes in i_{sq} cause step changes in the induction machine output torque and therefore in the DC machine load.

Figs. 6.6 and 6.7 show the simulation results and the experimental results, respectively,

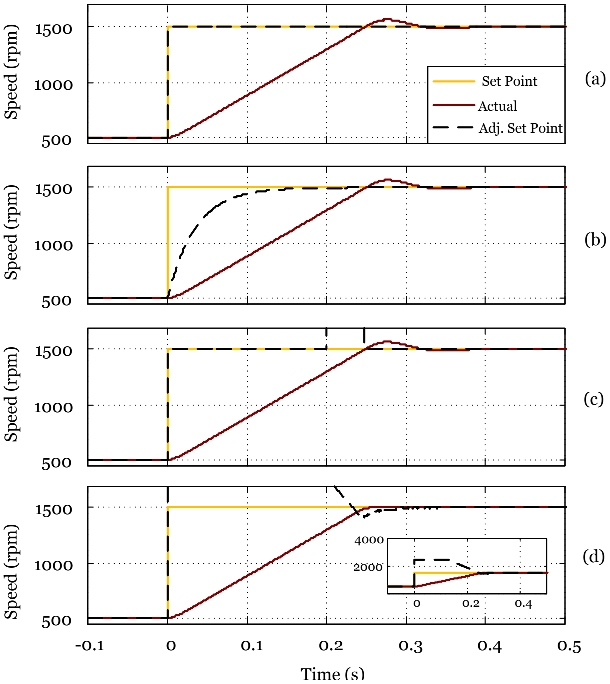

Figure 6.4: Simulation results of the transient response of the system speed subsequent to a large step change in ω_{ref}. a) base case, b) prefilter, c) SPAACE, and d) SSPAACE.

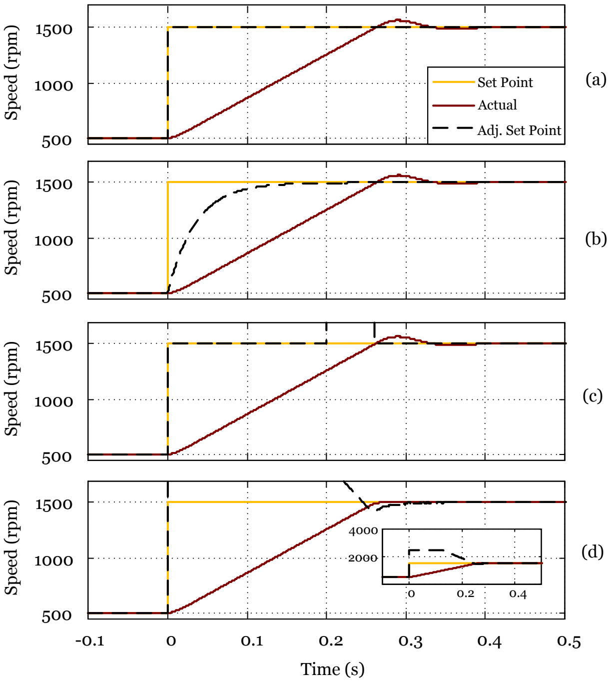

Figure 6.5: Experimental results of the transient response of the system speed subsequent to a large step change in ω_{ref}. a) base case, b) prefilter, c) SPAACE, and d) SSPAACE.

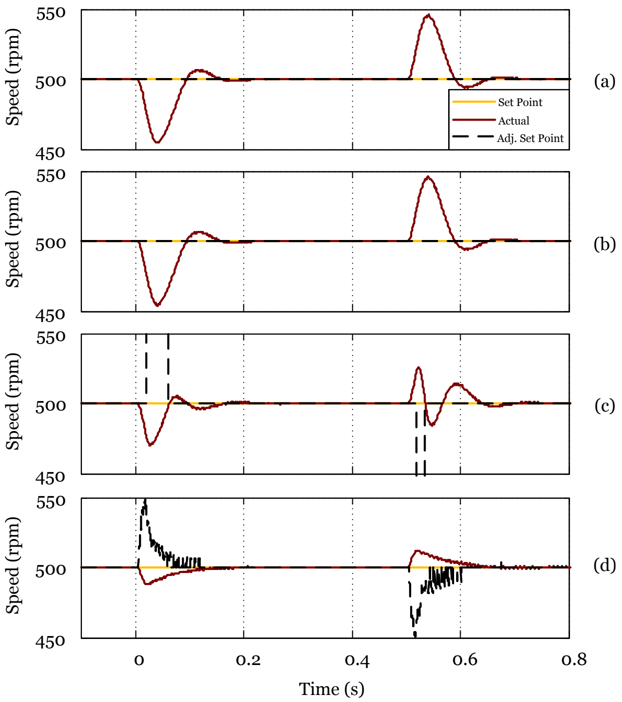

Figure 6.6: Simulation results of the transient response of the system speed subsequent to positive and negative step changes in i_{sq}. a) base case, b) prefilter, c) SPAACE, and d) SSPAACE.

for different control approaches. Fig. 6.7(a) shows that the sudden load changes causes the speed to deviate from its set point by 48 rpm. The settling time of this deviation is 90 ms. Fig. 6.7(b) shows that the prefilter approach does not improve the robustness of the system against an external disturbance because there are no changes in the set point; therefore, the modified set point remains unchanged. As shown in Fig. 6.7(c), SPAACE improves the robustness of the system against load changes by reducing the deviation to 42 rpm, while SSPAACE reduces the deviation even further to 12 rpm as shown in Fig. 6.7(d). The settling time of this deviation is 80 ms for SPAACE and 65 ms for SSPAACE. This case study confirms even further the superior robustness of the SSPAACE against the disturbances compared with the base case, prefilter, and SPAACE.

6.4 Sensitivity to System Parameters

To evaluate the robustness of SSPAACE to the system parameters, case study A is repeated with two simulation-based scenarios. In the first scenario, the total moment of inertia

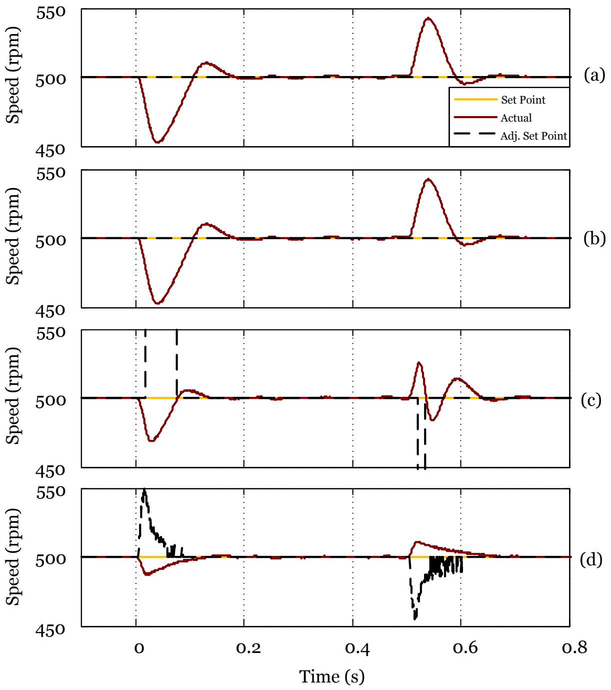

Figure 6.7: Experimental results of the transient response of the system speed subsequent to positive and negative step changes in i_{sq}. a) base case, b) prefilter, c) SPAACE, and d) SSPAACE.

of the coupled DC motor and induction machine is changed to one-third of its real value ($J_{\text{total}} = 0.0056\ \text{kgm}^2$), and in the second scenario, total moment of inertia of the coupled DC motor and induction machine is changed to thrice its real value ($J_{\text{total}} = 0.051\ \text{kgm}^2$). The parameters of the controllers are not changed. The transient response of the system speed subsequent to the aforementioned scenarios is shown in Figs. 6.8 and 6.9, respectively. Fig. 6.8 shows that SSPAACE reduces the overshoot from 50% to 0% and the settling time from 80 ms to 50 ms and increases the rise time from 15 ms to 28 ms; Fig. 6.9 shows that SSPAACE reduces the overshoot from 39% to 10% and the settling time from 0.4 s to 0.2 s without compromising the speed of the system. This case study confirms the robustness of the SSPAACE against changes in system parameters.

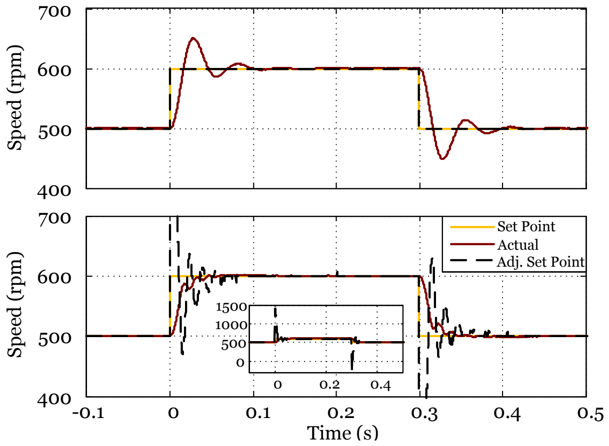

Figure 6.8: Transient response of the system speed with $J_{\text{total}} = 0.0056$ kgm^2. a) base case and b) SSPAACE.

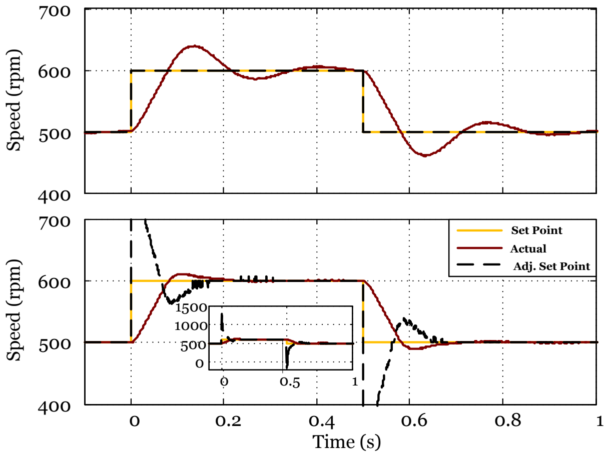

Figure 6.9: Transient response of the system speed with $J_{\text{total}} = 0.051$ kgm^2. a) base case and b) SSPAACE.

Chapter 7

Conclusions

The previous work developed a strategy called SPAACE to improve the set point tracking performance. While demonstrating great performance, SPAACE is not directly applicable to applications such as electric drive systems because the step changes introduced in the set point can cause torque pulsation and in turn mechanical fatigue and stress. In this paper, an approach based on a supervisory switching scheme is developed to improve the set point tracking capability of the system and reduce the overshoot without compromising the speed of the system. The design and implementation of SSPAACE is straightforward. Simulation and experimental results obtained from different case studies confirm that SSPAACE provides smaller overshoot and modifies the set point more gracefully than SPAACE. It also provides smaller overshoot and rise time compared with the prefilter approach. Furthermore, unlike the prefilter approach, it shows great performance in case of a large step change in the speed set point or external disturbance.

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