Smooth Reference Modulation to Improve Dynamic Response in Electric Drive Systems

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***Abstract*—Response overshoot is an undesired behavior that can be experienced by a dynamic 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 frequent 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 for an electric drive system. Simulation and experimental results confirm the desirable performance of the proposed approach.**

***Index Terms*—Control, dc motor, disturbance mitigation, drive, electric machine, induction machine, transient response.**

I. INTRODUCTION

In CONTROL practice, the selection of control parameters for a band-limited physical system is a tradeoff between the speed, overshoot, and settling time of the closed-loop system [1], [2]. 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 the least possible adverse effect on the speed of the closed-loop system is of significant importance.

Prior work [3]–[5] 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 units in a microgrid. Fig. 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 $x_{\mathrm{sp}}(t)$, temporarily modulates $x_{\mathrm{sp}}(t)$ so that $x(t)$ closely tracks it. In a typical implementation of SPAACE, the variation in the set point is introduced as a step change from x_{sp} to $(1-m)x_{\mathrm{sp}}$, where m is a design parameter. The salient features of SPAACE are robustness to changes in the system, not requiring the system model, and 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.

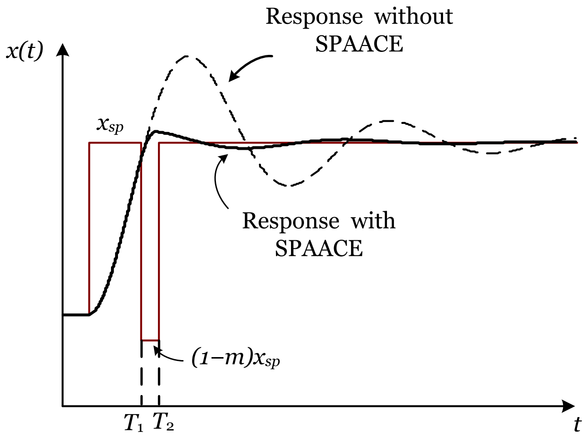

Fig. 1. Example of application of SPAACE to improve reference set point tracking.

Electric drives are a significant consumer of electricity; they consume about 60% of electricity in the United States and 45% in the world [6]. 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 grown significantly in recent years. In [7], a combined feedforward and feedback controller is proposed to improve the robustness of an induction motor drive against parameter variations. In [8], an input–output instantaneous power

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balancing approach is proposed to improve the dynamic response of the drive system and minimize the capacitance of the dc link. In [9], 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. In [10], a combined predictive controller and observer is developed 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., [11] and [12]), model-based automatic tuning (e.g., Åström's work [13], [14]), and simulation-based optimization (e.g., Golé's work [15]), are not adequate. To redesign and reimplement new controllers, these methods require updated models, a computational infrastructure, and 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.

This paper proposes and validates a smooth variant of SPAACE (SSPAACE). 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 salient features of SSPAACE compared with SPAACE are as follows.

1) SSPAACE provides superior transient performance.
2) SSPAACE is more robust against external disturbances.
3) SSPAACE is more robust against the system parameters.
4) SSPAACE reduces the torque transients more effectively.

The rest of this paper is organized as follows. Section II provides a background on existing control design methods. Section III discusses the basics of SPAACE. The proposed SSPAACE approach is discussed in Section IV. Modeling and controller design for a drive system are presented in Section V. Section VI presents the study system and case studies. Concluding remarks are provided in Section VII.

II. 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 [11]–[14] or simulation-based [15], [16] 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 that they rely on the availability of system models, and 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 I.

TABLE I
COMPARISON OF EXISTING CONTROLLER DESIGN METHODS

Approach	Robust to model	Unintrusive	Robust to parameter
PI scaling	✓	✓	X
Ramp	✓	✓	✓
MPC	X	✓	X
PID	X	✓	X
ES/IFL	✓	X	X
Posicast	X	✓	✓
SPAACE	✓	✓	✓

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 [17]. However, its performance is limited to the chosen reference exponential curve, the initial choice of gains, and proportional-integral (PI) controllers. An operationally similar family of approaches is gain scheduling [18]. 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:

1) 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;
2) selection of the ramp slope requires knowledge of system characteristics;
3) 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 [19], [20] and offers handling of multivariable problems, ease of tuning, and 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) [13], but it is prone to noise [21]. 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) [22]. 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, ES is an intrusive method as it injects a sinusoidal test signal to the system input; it is also an offline method as the cost function is evaluated only after the system response settles. A discrete variation of ES is iterative feedback tuning [23]. While the performance of these approaches is comparable to model-based design methods, the disadvantages are that they improve only the step response and require access to the controller parameters.

In [24], a feedforward control structure, which can be rearranged to a prefilter structure, is proposed. This prefilter approach reduces the overshoot subsequent to a step change 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. An appropriate design of the prefilter mitigates the overshoot of the system. However, this approach results in a slower system response. The only approach of which we are aware and has similarities to our proposed strategy is posicast [25]–[30]. 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 $(1-\alpha)x_{\mathrm{sp}}$ 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:

1) they have limited robustness to changes in parameters (even robust control methods);
2) mostly a full-fledged dynamic and/or linearized model of the system is required;
3) a communication channel is required to implement the redesigned controllers in the field;
4) a computational infrastructure is required to conduct studies to redesign/update controllers.

III. Review of SPAACE

SPAACE improves the performance of an existing controller using an add-on feature we call *set point modulation*. The salient features of SPAACE are as follows:

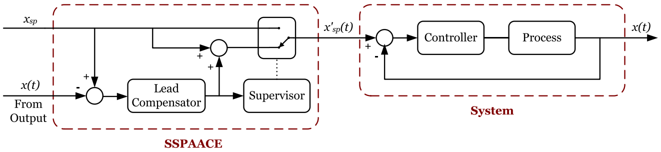

Fig. 2. SSPAACE structure.

1) it improves the dynamic response of the system;
2) it makes system more robust against disturbances, system parameters, and controller design;
3) it does not require many pieces of information about the system;
4) it 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, 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 [3], [4].

IV. Proposed Smooth SPAACE

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

A. 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 and induction motor is considered to evaluate its performance. In this context, SSPAACE is located immediately before the standard speed controller of the dc machine and induction machine as shown in Fig. 2. 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.

B. Description of SSPAACE

SSPAACE proposes a hybrid structure. It utilizes a supervisory scheme based on observing the predicted value of the error between the reference set point and the response. SSPAACE changes the set point only when the predicted error is beyond the permissible range; that is, when undershoot or the overshoot of the response is not acceptable. Such violations can be caused by, for example, a rapid change in the set point or a disturbance. SSPAACE can be described by the following supervisory switching rule:

$$x'_{\mathrm{sp}}(\mathrm{t}) = \begin{cases} x_{\mathrm{sp}}, & \mathrm{e}_{\mathrm{min}} \le \mathrm{e}_{\mathrm{pred}}(\mathrm{t}) \le \mathrm{e}_{\mathrm{max}} \\ x_{\mathrm{sp}} + \mathrm{m}(\mathrm{t}), & \text{otherwise} \end{cases} \tag{1}$$

where $m(t)$ is the adjustment applied to the set point and $e_{\mathrm{pred}}(t)$ is the predicted error. The choice of e_{min} and e_{max} defines the permissible violation range and depends on the application and system specifications. The adjustment signal is defined as

$$m(t) = m \times e_{\mathrm{pred}}(t). \tag{2}$$

Generally, increasing m decreases the speed of the system, but it also decreases its overshoot. In many systems, a modest value of $m = 0.2$ can result in significant improvements in the system response; in practice, reasonable values of m can be found based on offline studies—however, note that due to the self-corrective nature of the proposed strategy, its performance is not sensitive to the exact value of m. The prime difference between SPAACE and SSPAACE is that the adjustment signal in SPAACE is proportional to the set point $(m(t) = m \times x_{\mathrm{sp}})$, whereas the adjustment signal in SSPAACE is proportional to the predicted error. Using a constant value as the adjustment signal $(m(t) = m)$ in SPAACE regardless of the tracking error decreases the performance of the system and may result in oscillations in the steady state. This problem is not present in SSPAACE.

The predicted error $e_{\mathrm{pred}}(t)$ can be calculated by applying the error signal to any prediction strategy. The error signal is defined as

$$e(t) = x_{\mathrm{sp}} - \mathrm{x}(\mathrm{t}). \tag{3}$$

Utilization of linear and quadratic predictors in SPAACE is studied in [3] and [4]. Any type of compensator that encapsulates derivative action or provides phase lead can be viewed as a predictor [31]. In this paper, a lead compensator is used as the predictor to reduce the complexity of the prediction algorithm. The predicted error can be calculated as

$$e_{\mathrm{pred}}(s) = \frac{sT+1}{\alpha sT+1} e(s), \qquad \alpha < 1 \tag{4}$$

where $e(s)$ is the Laplace transform of $e(t)$. The lead compensator provides a phase lead to the system in the frequency range of $[\frac{1}{T}, \frac{1}{\alpha T}]$ and the maximum phase lead occurs at medium frequency ω_m, which is equal to

$$\omega_m = \frac{1}{T}\sqrt{\frac{1}{\alpha}}. \tag{5}$$

In (4), T and α are design parameters and should be selected such that the medium frequency is equal to the frequency of the transients. Typically, T is selected such that the zero of the compensator matches the dominant pole of the system. Selection of α is a tradeoff between the response speed and robustness to noise. A smaller α increases the phase lead but decreases the sensitivity of the system to noise and deteriorates the steady-state performance of the system. An α between 0.05 and 0.3 is a recommended choice for most cases.

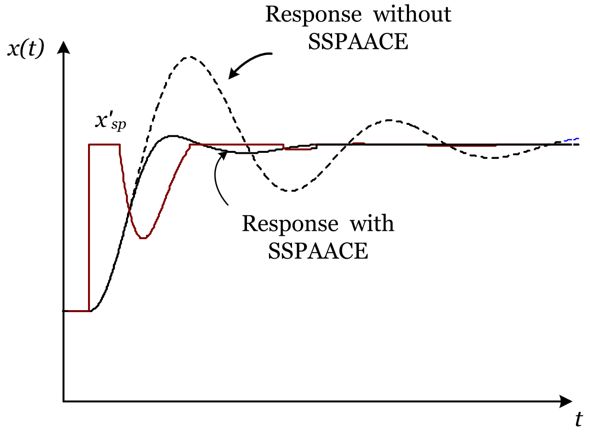

Fig. 3. Example of application of SSPAACE to improve reference set point tracking.

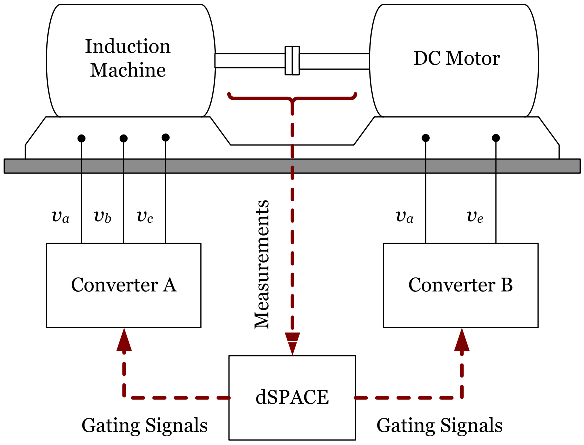

Fig. 4. Schematic diagram of the study system.

Depending on the physical constraints of the system, $x'_{\mathrm{sp}}(\mathrm{t})$ may be needed to be limited within an acceptable range. Fig. 3 shows the response of an example second-order system with and without applying SSPAACE. It should be noted that SSPAACE is a generic control approach applicable to a wide range of applications without any limitation on the order of the system. However, this paper investigates its performance for an electric drive system.

V. STUDY SYSTEM: ELECTRIC DRIVE

Fig. 4 shows the system configuration and Fig. 5 shows a photograph of the experimental setup. The system parameters and ratings of the different components are shown in Table II. 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, which then 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

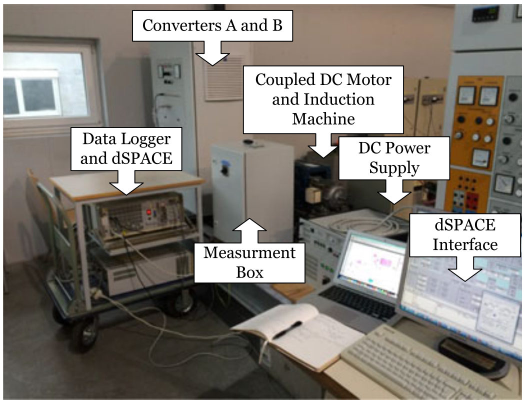

Fig. 5. Experimental setup.

TABLE II
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 r/min
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}	0.01326 kg·m^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 r/min
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}	0.00374 kg·m^2

outer speed control loop. The inner current control loop is designed based on the loop shaping method [24] to achieve a rise time of 1 ms and an overshoot of 5%. The outer speed control loop is designed based on symmetrical optimum approach [32] 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. SSPAACE is located before the standard speed controller of both machines and feeds the modified set point into the speed controllers. Both machines are used as example case studies for the proposed control approach. Note that the two different controller designs of these two machines illustrate well that the proposed SSPAACE approach is a generic approach, which can be applied to different types of machines and controllers.

TABLE III
TUNING PARAMETERS OF SSPAACE

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

VI. 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 III provides the tuning parameters of SSPAACE, which are determined based on the guidelines provided in Section IV-B. In the case studies that follow, the simulation and experimental results show the system responses obtained with four methods: the cascade PI-based control with no modifications (base case), prefilter, SPAACE, and SSPAACE. For a meaningful comparison, all these methods are add-on controllers. Approaches that design a completely new controller, e.g., sliding mode control, do not address the motivation of this paper, which aims to improve the response of a system with controllers that are already installed and cannot be changed.

A. *Small Step Change in the Speed Set Point of the DC Motor*

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 $\omega_{\text{ref}} = 500$ r/min. At $t = 0$ s, ω_{ref} is subjected to a positive step change from 500 to 600 r/min. After 0.3 s, ω_{ref} is subjected to a negative step change back to 500 r/min.

Figs. 6 and 7 show the simulation and experimental results, respectively, for four different approaches. Comparison of Figs. 6 and 7 confirms that the experimental results are highly consistent with the simulation results. Fig. 7(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. 7(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. 7(c). Fig. 7(d) shows that SSPAACE leads to an overshoot of 4%, a rise time of 35 ms, and a settling time of 42 ms. Whereas SSPAACE increases the set point at the beginning of the transient; the slope of the response is similar to the base case with no increased set point. The reason is that this step change saturates the armature reference current, and higher values of the set point will not increase the slope of the speed transient because the armature reference current is already saturated at its maximum value. However, all controllers are

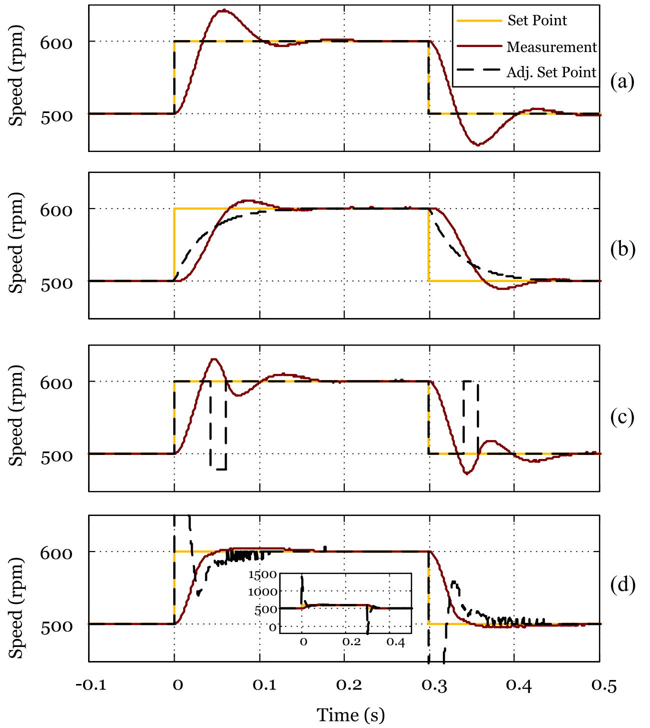

Fig. 6. Simulation results of the transient response of the speed of the dc motor subsequent to positive and negative step changes in ω_{ref}. (a) Base case, (b) Prefilter, (c) SPAACE, and (d) SSPAACE.

antiwindup controllers; therefore, the overshoot is mainly due to the dynamic of the system. Note that a limiter on the output of SSPAACE cannot necessarily improve the system response. This is because such a limiter needs to have a threshold greater than the unmodified set point in the base case, but our study system is already saturated even in the base case.

To facilitate the comparison, the measured speed of the dc motor for different control approaches is shown in a single plot in Fig. 8. Table IV 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.

To demonstrate the effectiveness of SSPAACE in reducing the mechanical stress, Fig. 9 shows the shaft torque of the system subsequent to the aforementioned scenario. It can be seen that SSPAACE reduces the torque transients more effectively than the base case and SPAACE; however, the prefilter method performs slightly better than SSPAACE at the expense of reducing the speed of the system. The dc motor and induction machine are coupled via a torque transducer. The chatter in the measured shaft torque in Fig. 9 shows that the applied torque excites the first eigenfrequency of torsional vibration of the mechanical system.

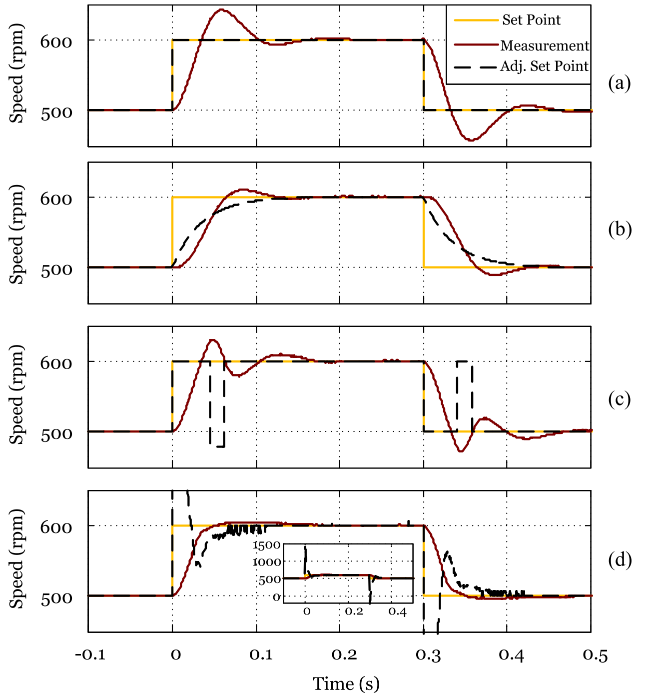

Fig. 7. Experimental results of the transient response of the speed of the dc motor subsequent to positive and negative step changes in ω_{ref}. (a) base case, (b) prefilter, (c) SPAACE, and (d) SSPAACE.

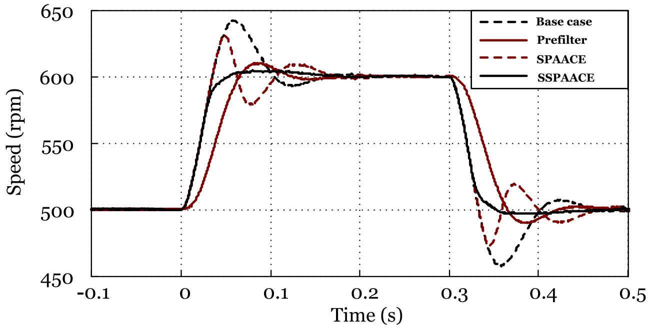

Fig. 8. Experimental results of the transient response of the speed of the dc motor subsequent to positive and negative step changes in ω_{ref} for different control approaches.

TABLE IV
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

B. Large Step Change in the Speed Set Point of the DC Motor

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 $\omega_{\mathrm{ref}} = 500$ r/min. At $t = 0$ s, ω_{ref} is subjected to a positive step change from 500 to 1500 r/min. 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. 10 and 11 show the simulation results and the experimental results, respectively, for different control approaches.

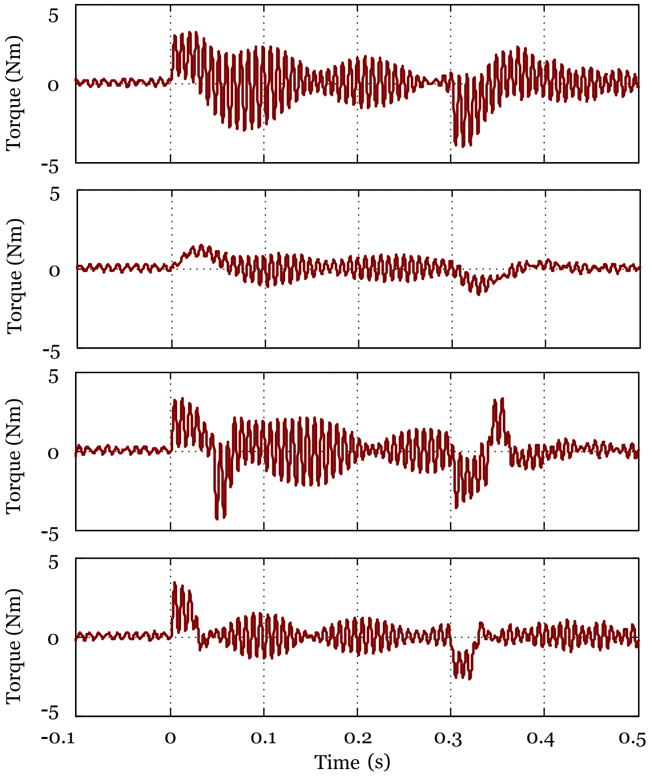

Fig. 9. Experimental results of the transient response of the shaft torque of the dc motor subsequent to positive and negative step changes in ω_{ref}. (a) base case, (b) prefilter, (c) SPAACE, and (d) SSPAACE.

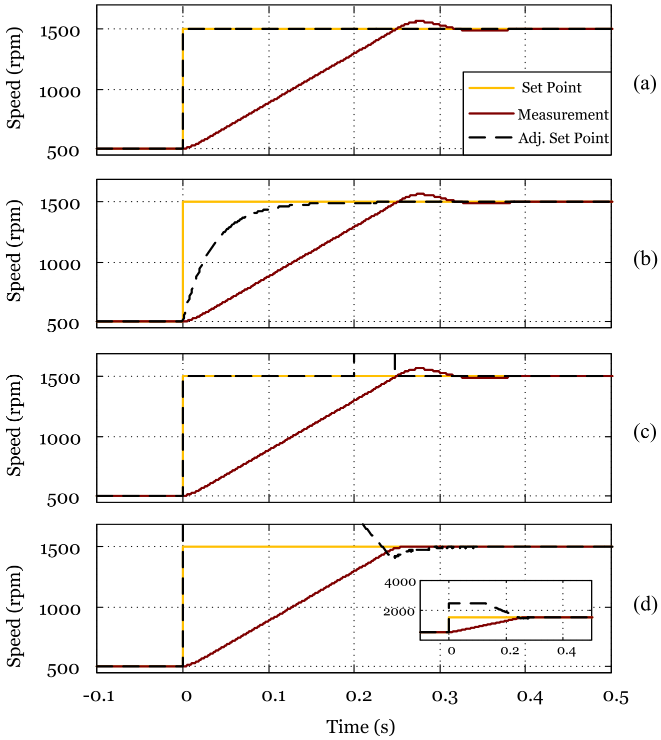

Fig. 10. Simulation results of the transient response of the speed of the dc motor subsequent to a large step change in ω_{ref}. (a) base case, (b) prefilter, (c) SPAACE, and (d) SSPAACE.

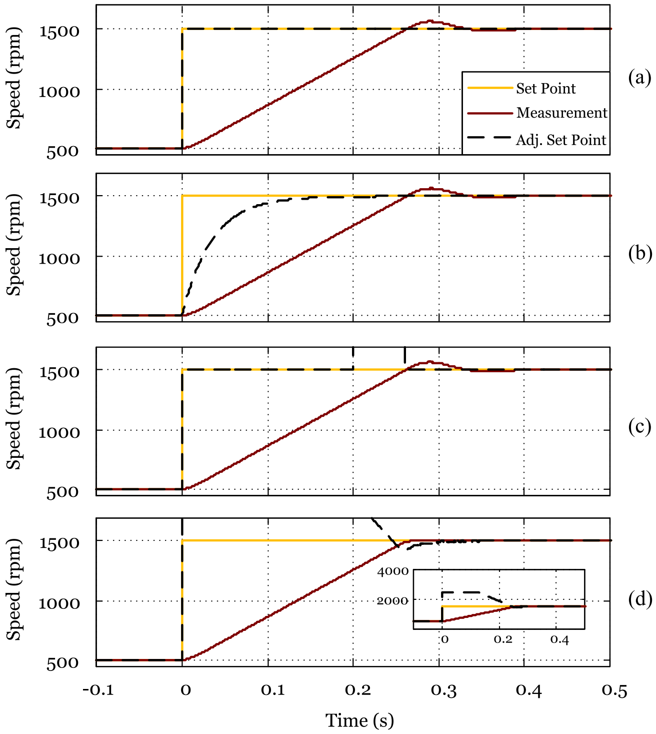

Fig. 11. Experimental results of the transient response of the speed of the dc motor subsequent to a large step change in ω_{ref}. (a) base case, (b) prefilter, (c) SPAACE, and (d) SSPAACE.

This case study also confirms the consistency of the experimental with the simulation results. Fig. 11(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. 11(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 settling time of the modified set point is shorter than the rise time of the system; therefore, it cannot affect the transient behavior of the system. Fig. 11(c) shows that SPAACE is also ineffective because the overshoot is very small. The response of the proposed approach is shown in Fig. 11(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.

C. External Disturbance

In this case study, the robustness of different control approaches against an external disturbance is investigated. The case studies are performed for the dc machine. Initially, it operates in the steady state with $\omega_{\text{ref}} = 500$ r/min and the induction machine provides a constant load proportional to the quadrature component of the stator current $i_{\text{sq}} = 0$ A. At $t = 0$ s, i_{sq} is subjected to a negative step change from 0 to -20 A. After 0.5 s, i_{sq} is subjected to a positive step change back to 0 A. These

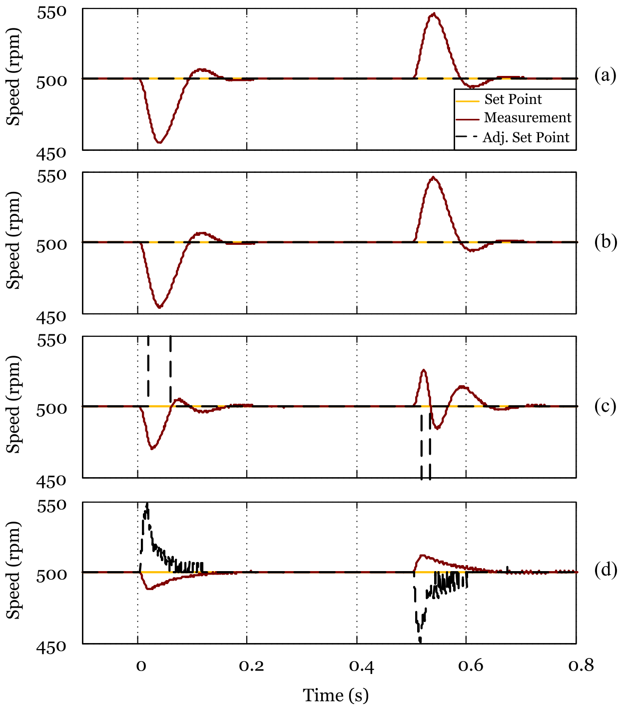

Fig. 12. Simulation results of the transient response of the speed of the dc motor subsequent to positive and negative step changes in i_{sq}. (a) base case, (b) prefilter, (c) SPAACE, and (d) SSPAACE.

step changes in i_{sq} cause step changes in the induction machine output torque and therefore in the dc machine load.

Figs. 12 and 13 show the simulation and experimental results, respectively, for different control approaches. Fig. 13(a) shows that the sudden load changes cause the speed to deviate from its set point by 48 r/min. The settling time of the response is 90 ms. Fig. 13(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. 13(c), SPAACE improves the robustness of the system against load changes by reducing the deviation to 42 r/min, whereas SSPAACE reduces the deviation even further to 12 r/min as shown in Fig. 13(d). The settling time of the response is 80 ms for SPAACE and 65 ms for SSPAACE. This case study reconfirms the superior robustness of the SSPAACE against the disturbances compared with the base case, prefilter, and SPAACE approaches.

As illustrated in these case studies, compared with the prefilter approach, SSPAACE has the following salient features.

(i) SSPACE has a smaller overshoot and rise time.

(ii) SSPAACE smoothes out the response of the system subsequent to external disturbances but prefilter does not react to external disturbances.

(iii) The performance of SSPAACE does not depend on the saturation of the controller output, but the prefilter approach cannot be adjusted to address a system with saturated controller output.

D. Sensitivity to System Parameters

To evaluate the robustness of SSPAACE to the system parameters, the case study described in Section VI-A is repeated with two simulation-based scenarios. In the first scenario, the total moment of inertia of the coupled dc motor and induction machine is changed to one-third of its real value ($J_{\mathrm{total}} = 0.0056\ \mathrm{kg{\cdot}m^2}$), and in the second scenario, the total moment of inertia of the coupled dc motor and induction machine is changed to three times its real value ($J_{\mathrm{total}} = 0.051\ \mathrm{kg{\cdot}m^2}$). Since T is a measure of the time constant of the system, it changes commensurately with J; that is, this case study indirectly also studies the robustness of the system to T, justifying why T is considered a tuning parameter. Note that these scenarios are hypothetical and, in practice, the change in parameter values is not likely to be of the same large magnitude. The parameters of the controllers are not changed. The transient response of the system speed subsequent to the aforementioned scenarios is shown in Figs. 14 and 15, respectively. Fig. 14 shows that SSPAACE reduces the overshoot from 50% to 0% and the settling time from 80 to 50 ms and increases the rise time from 15 to 28 ms; Fig. 15 shows that SSPAACE reduces the overshoot from 39% to 10% and the settling time from 0.4 to 0.2 s without compromising the speed of the system. This case study confirms the robustness of SSPAACE against substantial changes in the system parameters.

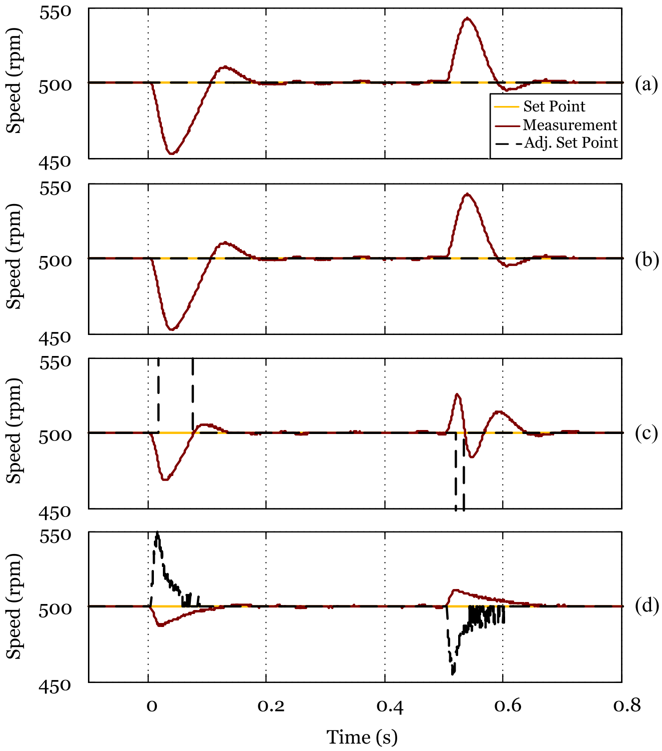

Fig. 13. Experimental results of the transient response of the speed of the dc motor subsequent to positive and negative step changes in i_{sq}. (a) base case, (b) prefilter, (c) SPAACE, and (d) SSPAACE.

E. Performance Comparison of SSPAACE With a PID Controller

Generally, adding a D term to a PI controller decreases the overshoot of a control system. In this case study, the performance of a PID controller is studied for different values of K_d and is compared with the performance of SSPAACE. A scenario

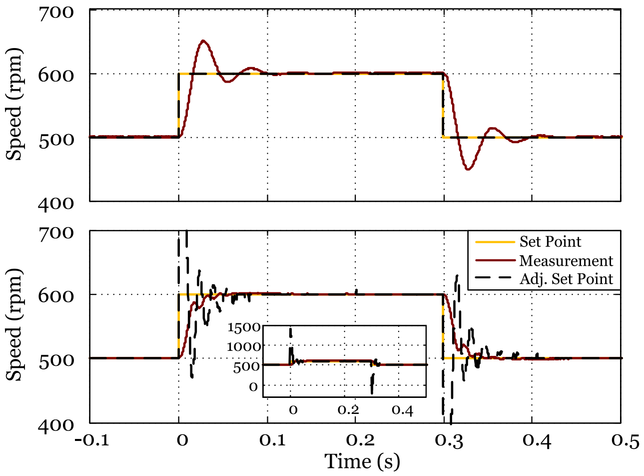

Fig. 14. Transient response of the speed of the dc motor with $J_{\mathrm{total}} = 0.0056\ \mathrm{kg{\cdot}m^2}$. (a) Base case and (b) SSPAACE.

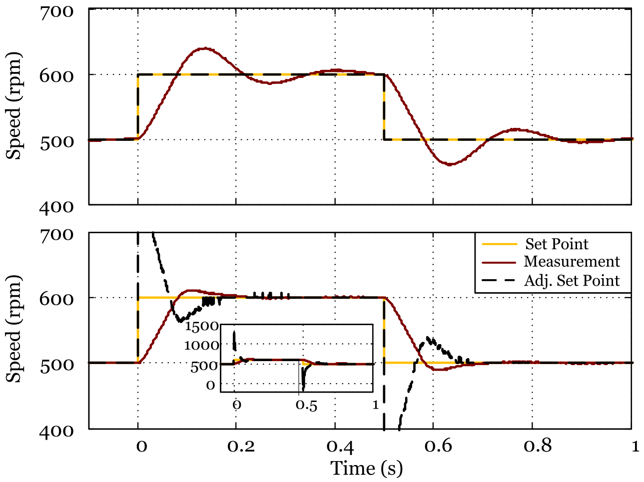

Fig. 15. Transient response of the speed of the dc motor with $J_{\mathrm{total}} = 0.051\ \mathrm{kg{\cdot}m^2}$. (a) Base case and (b) SSPAACE.

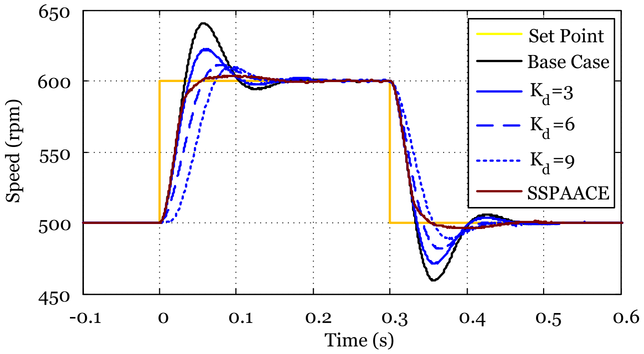

Fig. 16. Transient response of the speed of the dc motor subsequent to positive and negative step changes in ω_{ref} with a PID and SSPAACE controller.

similar to the case study of Section VI-A is performed for the PID controller. Fig. 16 shows the transient response of the PID controller for $K_d = 3, 6$, and 9 subsequent to the step changes in the speed set point. It can be seen that increasing K_d decreases the overshoot at the expense of decreasing the system speed, whereas SSPAACE reduces the overshoot more than the PID controller almost without compromising the system speed.

VII. CONCLUSION

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.

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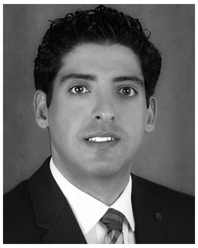

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