Improved Hybrid Current Regulation for Interior PMSM Drives Subjected to Internal/External Distortions

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***Abstract*—This paper designs a hybrid control strategy for interior permanent magnet synchronous motors (IPMSM) in the presence of internal/external disturbances. It combines two control approaches, i.e., adaptive control that is activated during the steady-state condition and iterative learning control (ILC) which is activated only at the transient condition. Therefore, the proposed hybrid control merges the robustness of the adaptive control against system uncertainty while the ILC improves the tracking performance hence achieving improved dynamic and steady-state control performance regardless the changing disturbances. Contrary to the conventional method, the proposed method maintains a satisfactory control operation (e.g., fast dynamic response, small steady-state error, etc.) by stabilizing the state errors to approach zero and compensating for the model parameter variations. To prove the effectiveness of the proposed control approach, it is simulated on a PSIM simulation tool and implemented on a prototype of PMSM drive powered by 2 level (2L)-inverter.**

***Index Terms*—External distortion, hybrid current control, internal distortion, interior permanent magnet synchronous motors.**

I. INTRODUCTION

Interior permanent magnet synchronous motors (IPMSMs) are becoming incredibly popular in a variety of commercial applications due to their appealing characteristics such as minimal maintenance cost, small construction, great efficiency, high power density [1]–[3], etc. However, IPMSM drives must have excellent control performance for such applications, e.g., rapid dynamic response and excellent trajectory tracking, and resilience against system perturbation and parameter fluctuations. Nonetheless, there are several limitations to their control performance (e.g., model parameter uncertainties, nonlinear motor parameters, etc.) [4] that must be considered in order to maintain appropriate control performance.

A variety of advanced control systems have previously been designed to maintain high-performance standards, such as deadbeat control [5], [6] fuzzy logic control (FLC) [7], [8] adaptive control [96], model predictive control (MPC) [10], [11] , iterative learning control (ILC) [12]–[14], etc. have been extensively studied. First, the deadbeat control [4] considerably refines dynamic performance; however, it heavily dependent on system parameters that cause it to be sensitive for parameter mismatch. To ensure a satisfactory control performance, precise knowledge of the IPMSM variables should be taken into account. Next, in view of fuzzy logic capability, FLC [5] has emerged as a promising control approach among advanced control methods. Nonetheless, its precision is largely associated with the designed fuzzy rules, which complicates the control algorithm. In [6], adaptive control is known for its capability to compensate for parameter variation, but it relatively complicates the overall control structure. MPC has outstanding tracking competencies where it can forecast future system behavior by employing a predictive model [9]. The smooth and accurate monitoring of reference signals is made possible by this predictive capability, which also efficiently rejects disturbances. This contributes to superior motor performance and stability[10]. Nevertheless, it is model dependent that may lead to poor control performance when the system parameters deviate from their nominal values. Iterative learning control (ILC) [7] has lately gained popularity due to its potential to improve overall control performance by revising the control commands by stored data. As a consequence, the ILC is extensively employed in a range of industrial applications where perturbations occur on a regular basis. Unfortunately, if the IPMSM drives are exposed to large parameter fluctuations, this control technique can be adversely deteriorated. To keep appropriate control effectiveness of the ILC approaches, an adaptive control regulation can be included to correct for system mismatch.

This research work designs a hybrid control approach for IPMSM drives. It combines the great features of the adaptive control to tackle the system uncertainties by compensating for the parameter variation and the attractive characteristics of ILC to enhance the dynamic response. The adaptive control is activated during steady-state so it can ensure low THD, minimized steady-state error, etc., while the ILC is activated during the dynamic response so it can confirm fast-tracking capability with less overshoot. The observed findings obtained verify the superiority of the proposed control strategy over the conventional one.

II. PROPOSED HYBRID CURRENT CONTROL FOR PMSM DRIVES

This section describes the dynamic model of IPMSM and the control design of the proposed method.

A. Dynamical Model of IPMSM

The model of the IPMSM drives in the rotating d–q reference frame can be regarded in form of continuous-time domain as follows [4], [12]:

$$\begin{aligned} d\omega/dt &= \frac{3}{2}\frac{1}{J}\frac{p^2}{4}\lambda_m i_{qs} - \frac{B}{J}\omega_r - \frac{p}{2J}T_L + \frac{3}{2}\frac{1}{J}\frac{p^2}{4}(L_d - L_q) i_{ds} i_{qs} + d_\omega \\ di_{ds}/dt &= -\frac{R_s}{L_d} i_{ds} + \frac{1}{L_d}U_{ds} + \frac{L_q}{L_d}\omega_r i_{qs} + d_{ds} \\ di_{qs}/dt &= -\frac{R_s}{L_q} i_{qs} + \frac{1}{L_q}U_{qs} - \frac{L_d}{L_q}\omega i_{ds} - \frac{\lambda_m}{L_q}\omega + d_{qs} \end{aligned} \quad (1)$$

where ω, T_L, i_{ds}, i_{qs}, u_{ds}, u_{qs}, d_d, and dq are the rotor speed, load torque, dq-axis stator currents, the dq-axis stator voltages; p, λ_m, L_d and L_q, J, R_s, and B represent the number of poles, magnetic flux linkage, stator inductances, the rotor inertia, stator resistance, and friction coefficient, respectively.

B. Design of Improved Hybrid Control for IPMSM Drives

The overall proposed hybrid current control can be deduced as follows:

$$\begin{aligned} U_{ds} &= \underbrace{-\varsigma_d \bar{i}_{ds}}_{fb\_T} + \underbrace{\hat{l}_{ids} x_{ids}}_{Adap\_T} + \underbrace{\psi_{dILC}}_{ILC\_T}, \\ U_{qs} &= \underbrace{-\varsigma_q \bar{i}_{qs}}_{fb\_T} + \underbrace{\hat{l}_{iqs} x_{iqs}}_{Adap\_T} + \underbrace{\psi_{qILC}}_{ILC\_T} \end{aligned} \quad (2)$$

where it combines three control terms, feedback control terms (, adaptive terms, and ILC terms, i.e., *fb_T*, *Adap_T*, and *ILC_T*, respectively.

Then these terms are designed as follows:

First, the feedback terms can be expressed as given below:

$$\begin{aligned} u_{ds}(j+1) &= t_s g_{Pd} e_{ids}(j) + u_{ds}(j) + t_s g_{Id} e_{ids}, \\ u_{qs}(j+1) &= t_s g_{Pq} e_{iqs}(j) + u_{qs}(j) + t_s g_{Iq} e_{iqs} \end{aligned} \quad (3)$$

where g_{pd}, g_{Id}, g_{pq}, and g_{Iq} are the feedback control gains while eids and eiqs are the current state errors that can be defined as follows:

$$\begin{aligned} e_{ids}(j) &= i_{dsr}(j) - i_{ds}(j) \\ e_{iqs}(j) &= i_{qsr}(j) - i_{qs}(j) \end{aligned} \quad (4)$$

where i_{dsr} and i_{qsr} are the dq-axis reference currents where i_{qsr} can be set manually while the iqsr is calculate from i_{qsr} as follows:

$$i_{dsr}(j) = -\frac{1}{\lambda_m}\left(L_q - L_d\right) \times i_{qsr}^2(j). \quad (5)$$

Then, the adaptive terms are designed utilizing the well-known Lyapunov control law as follows:

$$\hat{l}_{ids} = -(x_{ids} i_{ds})/G_{ids}, \; \hat{l}_{iqs} = -(x_{iqs} i_{qs})/G_{iqs} \quad (6)$$

where G_{ids} and G_{iqs} are the adaptive control gains.

Last, the ILC terms are designed as follows:

$$u(k, j+1) = u(k, j) + \mathrm{M}e(k+1, j) \quad (7)$$

where M is the ILC gain.

Then, the switching condition for the proposed hybrid current control can be given by

$$\begin{array}{ll} \text{if } e_{ss} >= 0.15 \times i_{qsd} & U_{ds}, U_{qs} = U_{ds,ILC}, U_{qs,ILC} \\ \text{else} & U_{ds}, U_{qs} = U_{ds,adap}, U_{qs,adap} \end{array} \quad (8)$$

where $e_{ss} = \bar{i}_{qs}$, i.e., the maximum *q-axis* stator current error, and $U_{ds,ILC}$, $U_{qs,ILC}$, $U_{ds,adap}$, and $U_{qs,adap}$ are command signal that generated from the adaptive control and ILC respectively, while the 15% of the i_{qsd} to switch between the adaptive control and ILC is chosen by extensive simulation and experimental results.

Fig. 1 describes the proposed method that has two objectives, i.e., adaptive control to ensure satisfactory steady-state performance while the ILC method provided a faster dynamic capability that is similar to that offered by the conventional method.

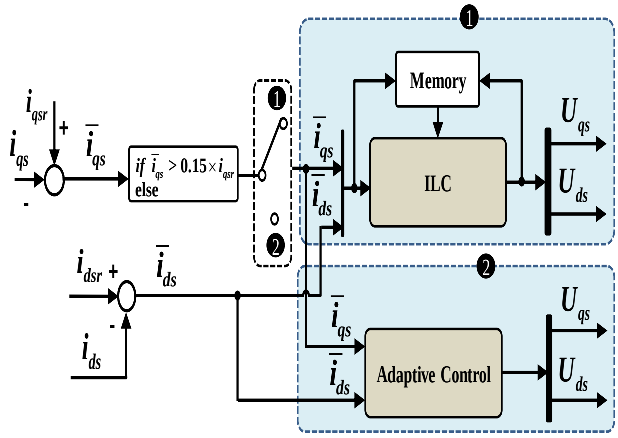


Fig. 1: Proposed block diagram hybrid current control for IPMSM drives.

Fig. 2 elaborates on the flowchart of the proposed hybrid current control for IPMSM drives. As can be observed from this figure, to establish the hybrid control method, the listed below step has to be done sequentially:

a) Convert the continuous-time model into its discrete form to easily capture the stored data, i.e., preceding state current errors.
b) Obtain the state errors e_{ids} and e_{iqs} to be regulated either by the adaptive control law or by the ILC law.

c) Check the percentage of the steady-state error, i.e., *ess*, to decide the switching between the adaptive control law and ILC.
d) If control performance (i.e., fast transient response and reduced THD) is acceptable, end the process, otherwise, repeat step c).

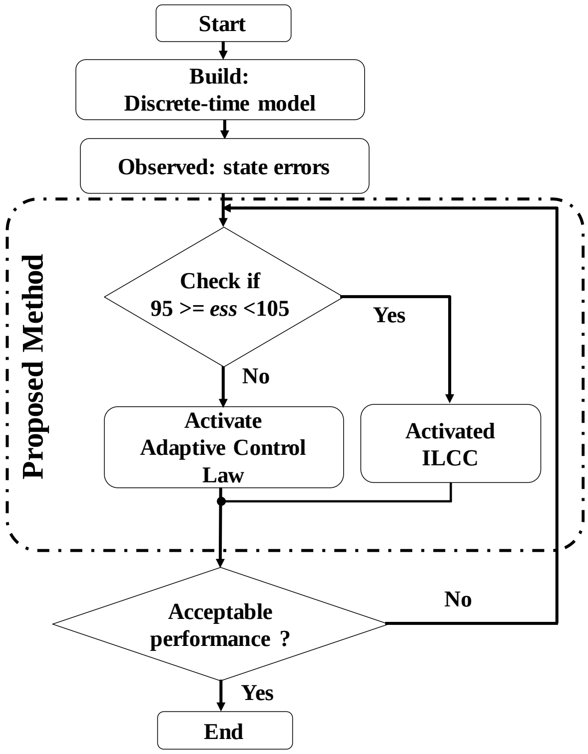


Fig. 2: Flowchart of proposed hybrid current control for IPMSM drives.

III. Performance Verification Results

To verify the efficacy of the proposed method, first, the i_{qsr} is stepped changed from 1 to 5 A at a constant speed 300 RPM (Scenario 1). Next, the i_{qsr} is stepped changed from 3 to 12 A at a constant speed 1000 RPM (Scenario 2). Note that all scenarios are test while the system is subjected to parameter variation, i.e., +60% of the stator resistance and –20% of both the stator inductances L_d and L_q. It can be observed from the simulation results of scenarios (1) and (2), i.e., Figs. 3 and 4.

Fig. 3 demonstrates the comprehensive control block diagram to regulate the stator currents and generates the control signals that drive the three-level inverter that fed the IPMSM. Meanwhile, Table I lists the system parameters for the simulation and experimental validation while Table II provides the summary of the observed results.

The performance criteria (i.e., settling time, overshoot, steady-state error, and THD) observed by simulation and experimental results for the conventional method are (0.5, no overshoot, 3.8%, and 2.5%) and (0.6, no overshoot, 3.9%, and 2.6%), respectively, while the observed findings offered by the proposed method are (0.47, no overshoot, 0.8%, and 1.5%) and (0.48, no overshoot, 0.9%, and 1.4%), respectively. To this end, the proposed method ensured better control performance over the traditional method.

TABLE I

System parameters for simulations and experiments

System Parameters	Values
Rated power	5[kW]
Rated torque	27.3 [N·m]
Rated current	17.23 [A]
Rated speed	1750 [r/min]
Sampling time	100 [μs]
Switching frequency	10 [kHz]
R_s	0.158 [Ω]
p	8
L_{ds}	0.00729 [H]
L_{qs}	0.00725 [H]
λ_m	0.264 [Wb]
J	0.0066 [kg·m^2]

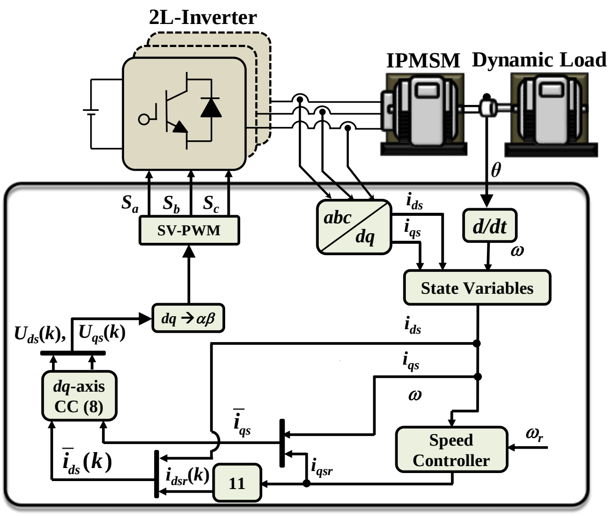
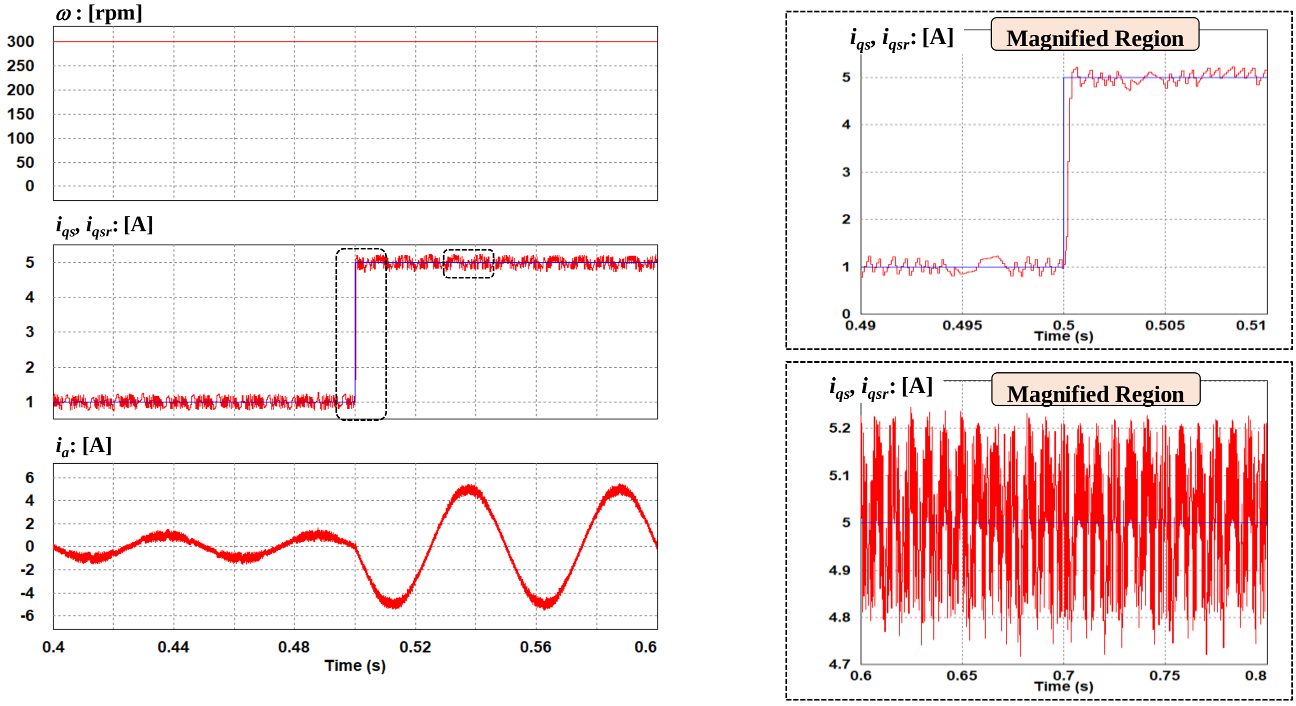
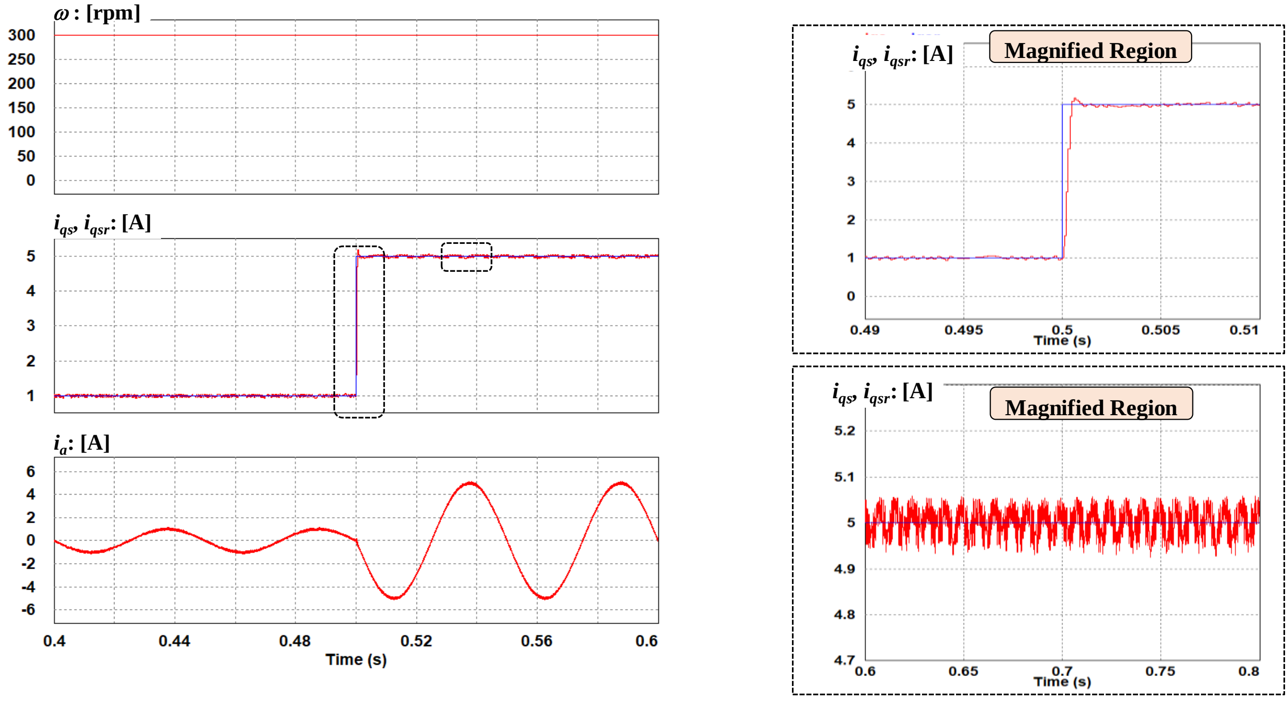


Fig. 3. Comprehensive control block diagram.

To ensure the potency of the proposed method, the proposed method is experimentally tested by IPMSM test rig fed by three-level inverter. It can be disclosed from Fig. 5 the conventional method displays a poor control performance (i.e., settling time of 1.67 ms, no overshoot, steady-state error of 6.5%, and THD of 3%) while the proposed method exhibits accepted transient and steady-state performance (i.e., settling time of 1.65 ms, no overshoot, steady-state error of 2%, and THD of 1.8%). This concluded the influence of the proposed method on offering improved control criteria compared to the classical method in both the transient and steady-state performance owing to the compensating for system uncertainty during the steady state while maintaining a faster tracking capability at the transient state. This is can be achieved by smoothly switching between the adaptive control law and ILC law, respectively.

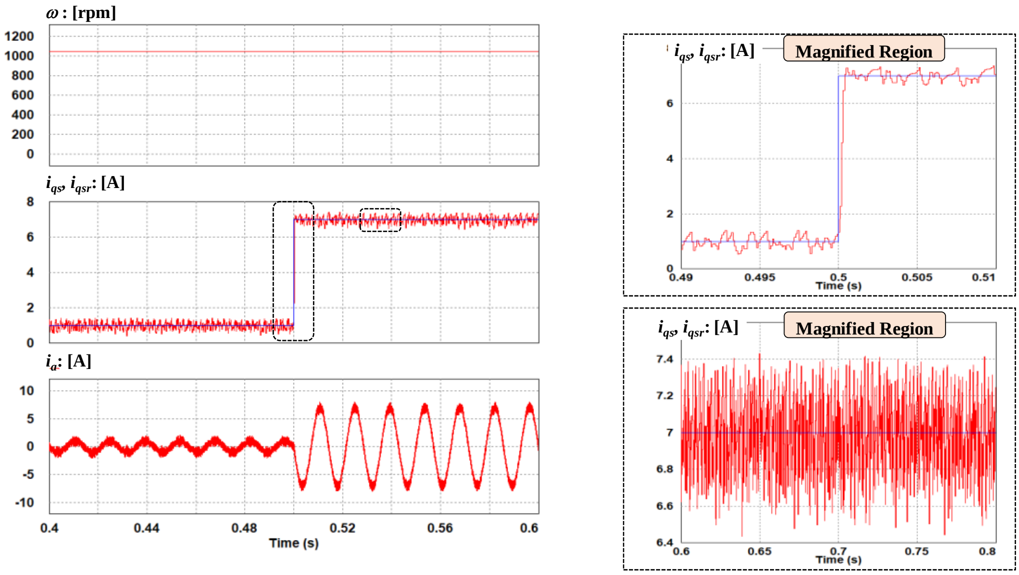


(a)

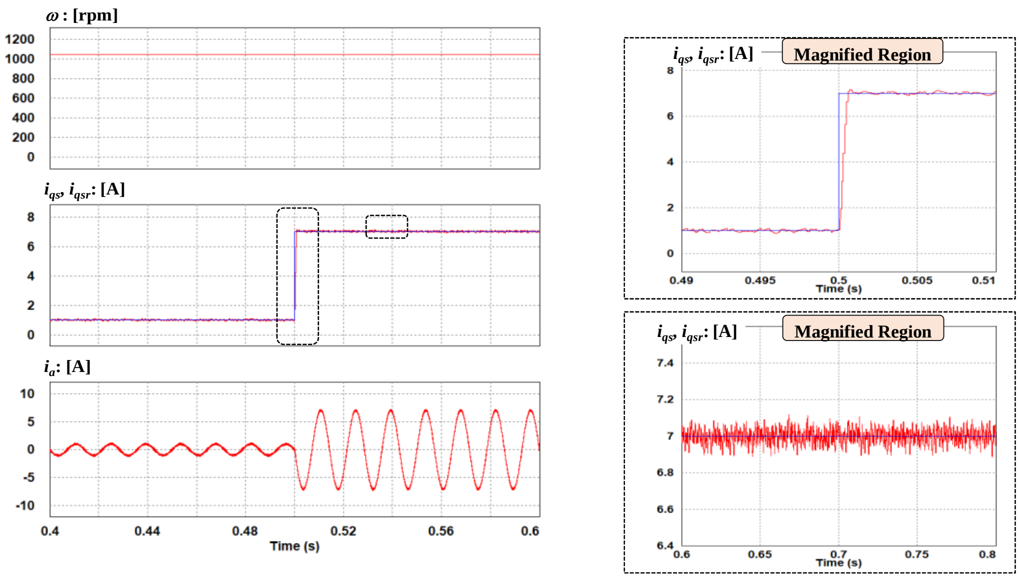


(b)

Fig. 4: Simulation performance verification when i_{qsr} is stepped changed from 1 to 5 A at a constant speed 300 RPM (Scenario 1). (a) Conventional method. (b) Hybrid current control.

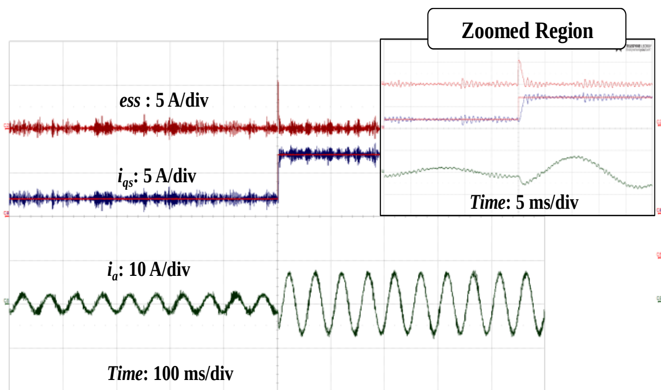


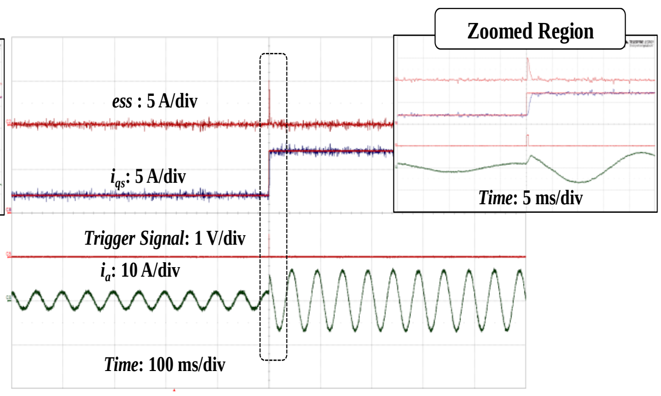
(a)



(b)

Fig. 5: Simulation performance verification when i_{qsr} is stepped changed from 1 to 7 A at a constant speed 1050 RPM (Scenario 2). (a) Conventional method. (b) Hybrid current control.





(a) (b)

Fig.6: Experimental performance verification. (a) Conventional method. (b) Hybrid current control.

TABLE II
SIMULATION/EXPERIMENTAL OBSERVATIONS

Control Method	Settling Time (ms)	Overshoot (%)	THD (%)	Steady-State Error (%)
Conventional Simulations	0.5	No	3.8	2.5
Conventional Experiments	1.67	No	6.5	3
Proposed Simulation	0.47	No	0.8	1.5
Proposed Experiments	1.65	No	2	1.8

IV. CONCLUSION

This paper designed a hybrid control approach for IPMSM where it is subjected to internal/external disturbances. The proposed method has two functionalities, i.e., adaptive control which is activated at the steady-state condition and ILC which is activated at the transient condition. As a result, the proposed hybrid control integrates the adaptive control's resilience against system uncertainty with the ILC's tracking capability, resulting in better dynamic and steady-state control performance independent of changing disturbances. In contrast to the conventional method, the proposed method retains acceptable control performance by stabilizing the state errors and compensating for model parameter variations. The simulation/experimental results ensured the effectiveness of the proposed method over the conventional one.

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