Extremum Seeking Approach for Real-Time Self-healing of Position Sensor Offset Error in PMSMs

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***Abstract*—The inherent advantages of permanent magnet synchronous machines (PMSMs) such as high efficiency have become a reason to use them more often in the industry including safety-critical applications such as transportation electrification. Among the number of factors, the accuracy of the rotor position is a key variable in achieving efficient and reliable field-orientation-based torque regulation. With the reliance on the rotor position signal being high, position sensor fault diagnosis and mitigation facilitates an added layer of safety. The proposed model-free extremum-seeking approach for position sensor fault compensation alleviates the reliance on motor parameters in detecting, quantifying, and compensating for position sensor error, which is known to vary based on various factors, introducing error. The theoretical framework for the proposed approach is presented in this paper along with simulation and experimental validation.**

***Index Terms*—Permanent magnet synchronous machine, Position measurement, Torque, Real-time control.**

Nomenclature

The next list describes several symbols that will be later used within the body of the document

$\lambda_m^{\prime r}$	Flux linkage constant of the PMSM
ω_c	Cut-off frequency
ω_{esc}	Angular frequency of the extremum seeking sinusoid
ω_r	rotor speed of the PMSM
ψ_{rotor}	Rotor magnetic flux
ψ_{stator}	Stator magnetic flux
θ_{comp}	Compensation angle for PSOE correction
θ_f	Angle between ψ_{stator} and ψ_{rotor}
θ_m	Measured rotor position
θ_{offset}	Difference between θ_r and θ_m
θ_r	True rotor position
A	Amplitude of the extremum seeking sinusoid
B	Integrator gain of the extremum seeking algorithm
I_{ds}^{r*}	d-axis current reference in rotor reference frame
I_{qs}^{r*}	q-axis current reference in rotor reference frame
I_{ds}^{r}	d-axis current in rotor reference frame
I_{qs}^{r}	q-axis current in rotor reference frame
I_{abc}	Three phase stator current vector
L_s	Stator phase inductance of the PMSM
r_s	Stator phase resistance of the PMSM
s	Laplace variable
T_{em}	Electromagnetic torque
V_{ds}^{r}	d-axis voltage in rotor reference frame
V_{qs}^{r}	q-axis voltage in rotor reference frame

I. Introduction

THE inherent advantages in permanent magnet synchronous machines (PMSMs) such as their compactness, efficiency, high torque density, and better thermal performance have led the demand growth in PMSMs in numerous fields. Among them, safety critical applications such as electrification in transportation and medical are significant [1]. The advancement in control strategies, fault diagnosis systems, and magnetic materials have further extended the scope of PMSM applications [2]–[4]. Open loop control, block commutation strategies, and field-oriented control (FOC) are primary control approaches for PMSMs. Of them, FOC is the most commonly used control strategy in systems that require high bandwidth torque response [5]. Accurate real-time rotor position measurement is a necessity for optimal and accurate torque generation in PMSMs. Considering both sensor-based (sensed or sensored) or sensor-less approaches for FOC, the sensed approach is preferred in torque regulating systems due to the transitory nature of speed and position signals under torque control [6].

Position sensing technologies are primarily classified as encoders, resolvers, or hall effect-based sensors that involve some form of mechanical assembly. The mounted sensor itself has an absolute zero position which needs to be aligned with the PMSM rotor zero position [7]. Recent research has illuminated a severe fault known as the position sensor offset error (PSOE), which maybe in the form of a dynamic or static nature, and is caused by factors such as manufacturing defects, environmental factors, or operating conditions. This fault is considered a critical fault in safety-critical systems such as electric powertrain and electric power steering systems, due to its ability to reverse electromagnetic torque generated by the machine. Researchers have proposed approaches to quantify PSOE under various conditions and strategies to compensate the PSOE as a means to mitigate the fault effect [6], [8]–[11]. However, all the proposed techniques rely on machine parameters resulting in pathways for further error under parameter variation. The effect of quantified PSOE under parameter variation has already been studied and therefore an approach capable of compensating PSOE effect without parameters dependency is crucial for safe operation of PMSM.

The proposed PSOE compensation strategy is independent of PMSM parameters and allows for real-time optimization and correction of PSOE through the use of extremum-seeking control (ESC) in a field-oriented controlled drive system.

In the next section of this paper, the effect of PSOE, PSOE quantification, and compensation methods are discussed. Section III elaborates on the use of ESC as a PSOE compensation method. Simulation validation of the suggested method is described in Section IV. In Section V, experimental results are presented to evaluate the ESC parameter effect on its performance and experimental validation of the suggested method and the paper is concluded in Section VI.

II. Fault Characteristics, Detection and Compensation

A. PSOE Fault Behaviour in FOC PMSM Drives

PMSMs are an AC synchronous machine type that uses permanent magnets as the rotor magnetic field. A Field-Oriented Controlled PMSM and its drive stage in a torque control application is depicted in figure 1. In FOC, the expectation is to place the stator flux orthogonal to the rotor flux and thus the accuracy of the rotor position is paramount. The resulting magnetic torque in a non-salient PMSM is expressed in (1), where the relative placement of the stator flux has a direct influence over the torque output. For example, $0° < \theta_f < 90°$ will result in an electromagnetic torque reduction, where as $-90° < \theta_f < 0°$ will cause a torque reversal. Therefore, θ_f need to be maintained at 90°, which is achieved through accurate rotor position measurement.

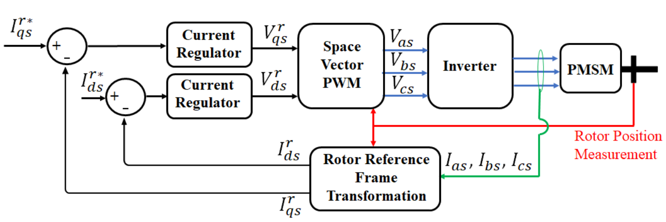

Fig. 1. Block diagram of a field-oriented controller for a PMSM

$$T_{em} \propto |\psi_{stator}||\psi_{rotor}|sin(\theta_f) \tag{1}$$

In sensed FOC implementations, a mechanical sensor position sensor or part of the position sensor is mounted on the rotor. During the manufacturing phase, either the sensor position zero is aligned to a known rotor position or calibrated to correct for any misalignment. However, environmental conditions such as temperature, humidity, vibrations, or corrosion in the mechanical interface lead to an uncalibrated offset that can be catastrophic in a system. This is known as Position Sensor Offset Error (PSOE). Figure 2 depicts three different scenarios that may occur, with the first two cases having no PSOE and the third case with PSOE. In addition to the influence on output torque, FOC masks the PSOE fault by regulating currents in an inaccurate frame of reference [6].

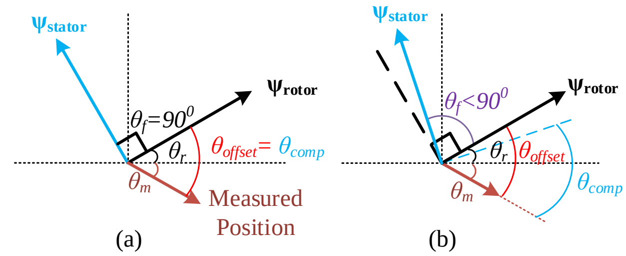

Fig. 2. FOC Flux vector placement with and without PSOE

B. PSOE Detection, Quantification and Compensation

Researchers have proposed different approaches to detect, quantify, and compensate PSOE. In [1], an open-loop self-calibration concept has suggested and proved the method utilizing analysis, simulation, and experimental results. Here, a current measurement-based strategy was followed to quantify the initial position sensor offset calibration required. The authors in [5] propose a current estimation based PSOE estimation in contrast to the voltage estimation-based approach proposed in [6]. Research in [9] elaborates how a dynamic PSOE can be detected, rather than a static PSOE which could occur while the machine is being operated. The results elaborated the complexity of the algorithm and the feasibility of practical implementation. Verification of PSOE calibration at startup is beneficial for safety-critical systems. Thus, [10] presents an approach that enables PMSM PSOE calibration, while the machine is in the system itself. The approach does require some form of mechanical rotation to be induced into the system for calibration to occur. The authors in [11] have suggested a self-correction strategy to the PSOE by combining the PSOE quantification method. However, all existing work on PSOE quantification and compensation relies on accurate machine parameters which may not be practical in all scenarios. Thus we propose an extremum seeking strategy that will enable the drive system to reach optimal position sensor aliment in real-time, which requires no machine parameters.

III. Extremum Seeking Control for PSOE Compensation

Extremum Seeking Control (ESC) is a non-linear adaptive control approach that is capable of reaching the maxima or minima by perturbing the system to extract gradient information. A generalized implementation of the proposed approach is illustrated in Fig. 3 below. The non-linear map with the extremum is assumed to be static and thus the extremum is assumed to be non-time varying [12]. The following is a simplified explanation of ESC for the reader and further details can be found at [12]. In implementing ESC, a minute-sinusoidal perturbation is injected into the control input, which is then allowed to propagate through the dynamic system. The perturbation that appears at the variable that is being optimized is extracted through a demodulation process and filtered to identify and remain at the extremum.

Considering a salient PMSM, the electromagnetic torque equation maybe expressed as in (2).

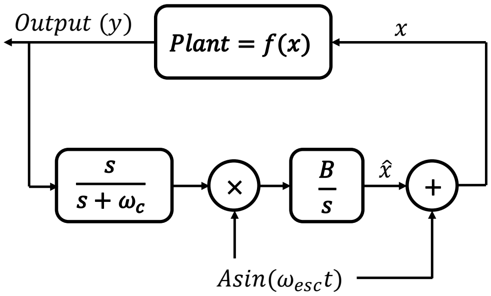

Fig. 3. Generic extremum seeking controller block diagram

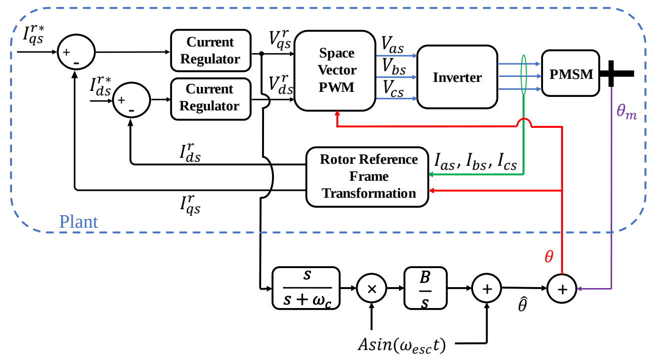

Fig. 4. Block diagram of the ESC implementation for PSOE compensation in field-oriented controlled PMSMs

$$T_{em} = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[\lambda_m'^r I_{qs}^r + (L_d - L_q) I_{qs}^r I_{ds}^r\right] \quad (2)$$

For a non-salient machine where $L_d \approx L_q$, and thus the electromagnetic torque is as in (3).

$$T_{em} = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_m'^r I_{qs}^r \quad (3)$$

From [8], the PSOE relation to electromagnetic torque in terms of the commanded q-axis current reference can be presented as (4), considering a non-salient machine $I_{ds}^r = 0$.

$$T_{em} = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_m'^r I_{qs}^{r*} cos(\theta_{offset}) \quad (4)$$

The above results conclude that θ_{offset} should be zero for the electromagnetic torque from the machine to reach maximum torque output for the commanded current reference. It can be shown that the q-axis voltage applied to an FOCed PMSM with a PSOE rotating in the clockwise direction is as in (5) [6].

$$V_{qs}^r = r_s I_{qs}^{r*} + \lambda_m'^r \omega_r cos(\theta_{offset}) \quad (5)$$

Close examination of (5) reveals that V_{qs}^r is a unimodal function of θ_{offset} in the interval $-\pi < \theta_{offset} < +\pi$, with the extremum (maximum) occurring at $\theta_{offset} = 0$. This conclusion was also validated with experimental results and presented under experimental results. Thus optimizing V_{qs}^r, indirectly optimizes the electromagnetic torque of a non-salient PMSM (assuming computational delays and inductive lag is negligible). The following extremum-seeking algorithm depicted in Fig. 4 is proposed to achieve this goal and later validated with simulation and experimental results.

Note: Equation (5) is considering the clockwise direction of rotation. A counterclockwise direction of rotation will cause V_{qs}^r with respect to θ_{offset} to have a minimum and therefore the extremum seeking algorithm should be appropriately modified to seek a minimum instead of a maximum.

IV. Simulation Results of the Proposed Algorithm

The proposed extremum-seeking PSOE optimization strategy was simulated with Matlab Simulink. The PMSM was field-oriented controlled as a torque actuator coupled to an ideal dynamometer that maintained the speed as desired. The PMSM parameters in the simulation were set to be the same as the experimental setup to be used later. Parameter values for the PMSM and the ESC are provided in Table 1. The effectiveness of the proposed method was evaluated at different operating conditions, including different speeds, currents, PMSM rotation direction (clockwise and counterclockwise), and PSOE polarity (positive and negative). The direction of rotation of the PMSM is a key property in properly choosing if the extremum-seeking algorithm is searching for a maxima or a minima. Hence provided results justify the algorithms' functionality regardless of the direction of rotation.

TABLE I
PMSM and ESC Parameters for Simulation

Parameter	Value
Phase Resistance (r_s)	71.4 mΩ
q-axis Inductance (L_q)	226.8 μH
Flux Linkage Constant ($\lambda_m'^r$)	76 mVs/rad
ESC Search Frequency (ω_{esc})	3 rad/s
ESC Search Signal Amplitude (r_s)	0.1
ESC Filter Cutoff Frequency (ω_c)	0.4 rad/s
ESC Integral Gain (B)	25

Figure 5 illustrates the results for clockwise rotation of the PMSM with step changes in PSOE, while Fig. 6 shows results for counter-clockwise rotation of the PMSM for the same PSOE step changes. The extremum-seeking algorithm is active and can be seen correcting the PSOE in real-time. The PSOE was changed in two steps; initially, it was changed from zero to 0.5 rad followed by 0.5 rad to 1 rad. Fig. 5 and 6 clearly illustrate the settling of the output torque at the optimal value, after a short duration following a PSOE change, indicating that the PSOE has been circumvented. Figures 5 and 6 also demonstrate the robustness of the proposed strategy towards current reference changes. At $t = 80$ seconds, the q-axis current reference is changed from 2A to 3A with no effect on the extremum-seeking algorithm compensation. Figures 7 and 8 illustrate simulation results for the same test cases with the injected PSOE being negative.

Simulations results being positive, an experimental implementation of the proposed ESC was carried out with details outlined in the next section.

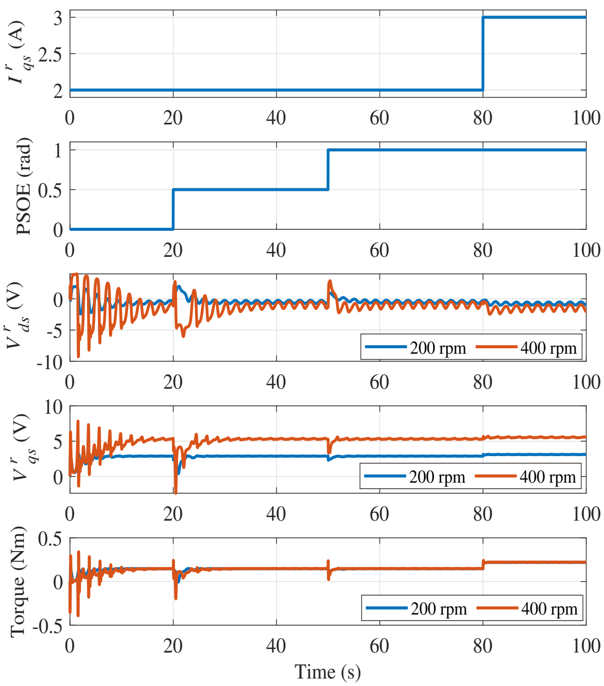

Fig. 5. Simulated ESC PSOE compensation at different operating points (Positive PSOE, Clockwise motor rotation)

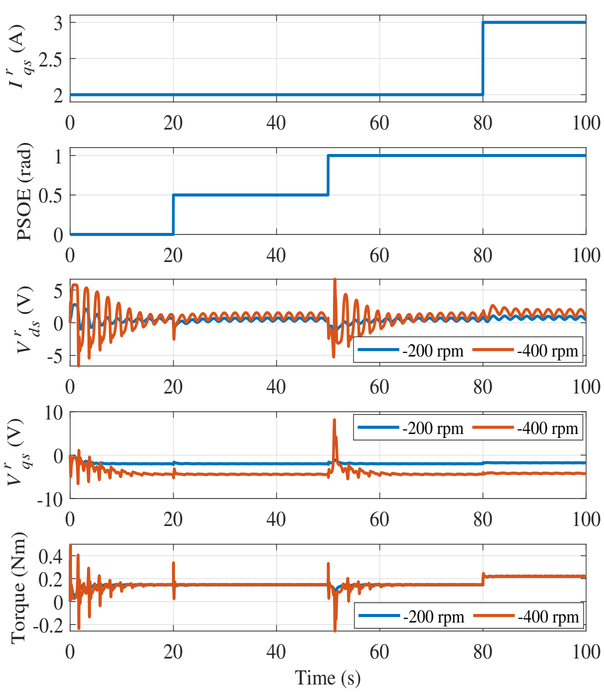

Fig. 6. Simulated ESC PSOE compensation at different operating points (Positive PSOE, Counter-Clockwise motor rotation)

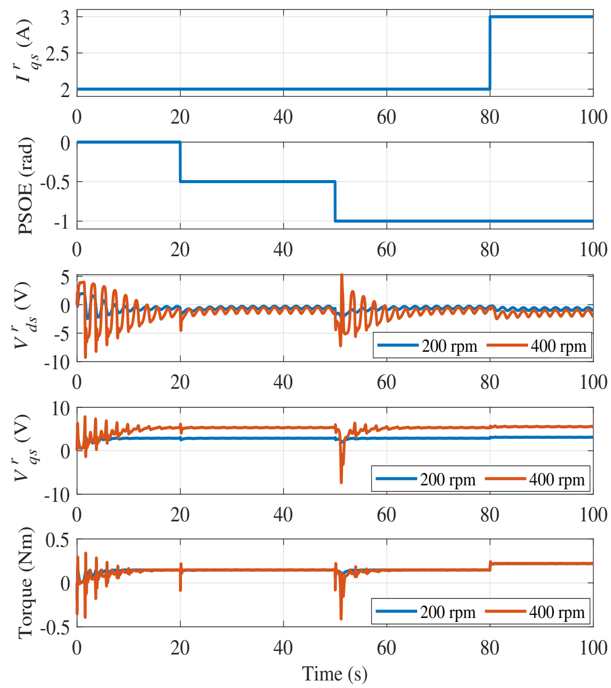

Fig. 7. Simulated ESC PSOE compensation at different operating points

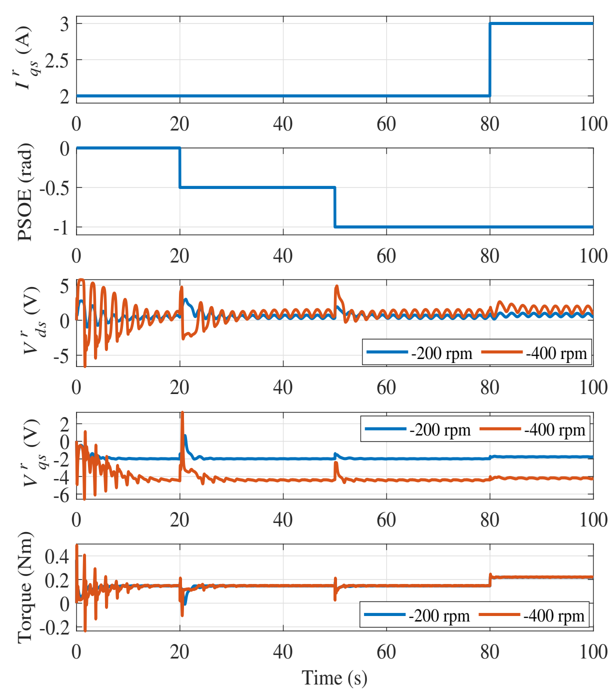

Fig. 8. Simulated ESC PSOE compensation at different operating points (Negative PSOE, Counter-Clockwise motor rotation)

V. Experimental Results

A dSPACE DS1104 platform coupled to a 250W PMSM-DC motor dynamometer setup depicted in Fig. 9 served as the platform to experimentally validate the proposed extremum-seeking controller for PSOE mitigation. The DC motor served as the speed regulator while the PMSM regulated torque using FOC. The hardware setup consists of a FUTEK torque sensor to validate the optimality of the output torque during the experiment.

A primary advantage of the proposed approach is the lack of a need for system parameters, including motor parameters to correct for the position sensor offset error that may occur unpredictably. To this end, both torque and q-axis voltage should demonstrate the same uni-modal characteristic with

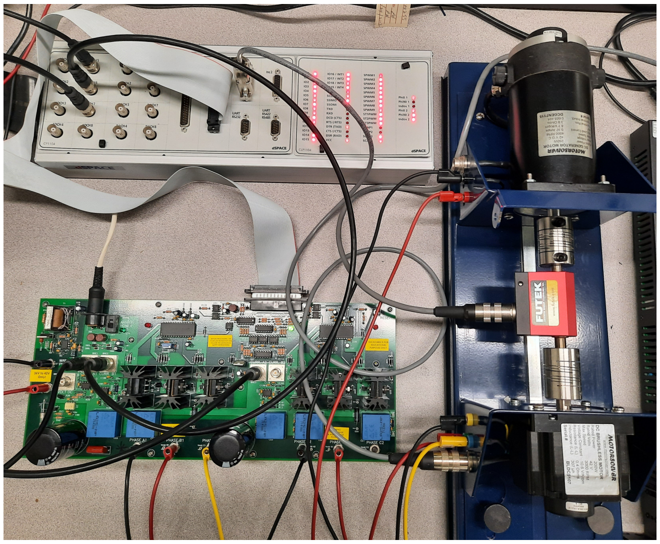

Fig. 9. Experimental setup used for validating the ESC-PSOE compensation strategy

respect to PSOE. Equations (4) and (5) are provided for an analytical explanation earlier with Fig. 10 proving this result experimentally.

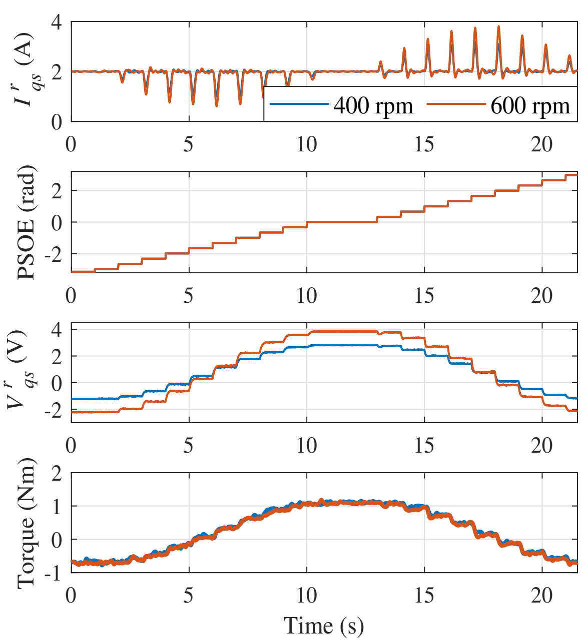

Fig. 10. Experimental validation of uni-modal nature of PMSM torque and V_{qs}^{r} under varying PSOE with I_{qs}^{r} = 2 A

Figure 10 illustrates the variation of torque and V_{qs}^{r} as PSOE is varied from $-\pi$ to $+\pi$ while the current reference and motor speed remained constant. The PSOE (subplot 2) is varied in 20 increments within the above interval. The experimental data concludes that both the torque and q-axis voltage are at their maxima, when PSOE reaches zero, making V_{qs}^{r} the ideal candidate for extremum-seeking-based PSOE compensation to maximize torque in a non-salient PMSM. The uni-modal nature of both V_{qs}^{r} and output torque with respect to PSOE is also evident in Fig. 10.

A. Effect of ESC Parameters on Algorithm Performance

The proposed ESC- PSOE compensation strategy includes a number of parameters that need to be optimized for rapid convergence of the algorithm. The effect of each parameter was experimentally evaluated and presented to help the reader select parameters suitable for a specific application. The parameters include ω_{esc}, A (search signal amplitude), ω_c and B (integrator gain). The transient and steady-state result of the ESC is demonstrated in figures 11 through 14, where the speed was maintained at 100 RPM, while I_{qs}^{r*} was set to 1 A. I_{ds}^{r*} was maintained at 0 A.

Fig. 11 shows the torque response with different ω_{esc}. In each case, the ESC was activated after PSOE injection. A PSOE of 1 rad is introduced at $t = 10$ seconds (subplot 3) followed by ESC being enabled at $t = 30$ seconds (subplot 4). According to Fig. 11, it can be observed that when the value of ω_{esc} is smaller, torque and V_{qs}^{r} show a considerable transient. For instance, ω_{esc} = 0.2 and 0.5 rad/s scenarios had a severe transient during the 80 - 100 Seconds period due to the PSOE step change. ω_{esc} = 1 rad/s scenario has shown a faster response followed by ω_{esc} = 5 rad/s scenario.

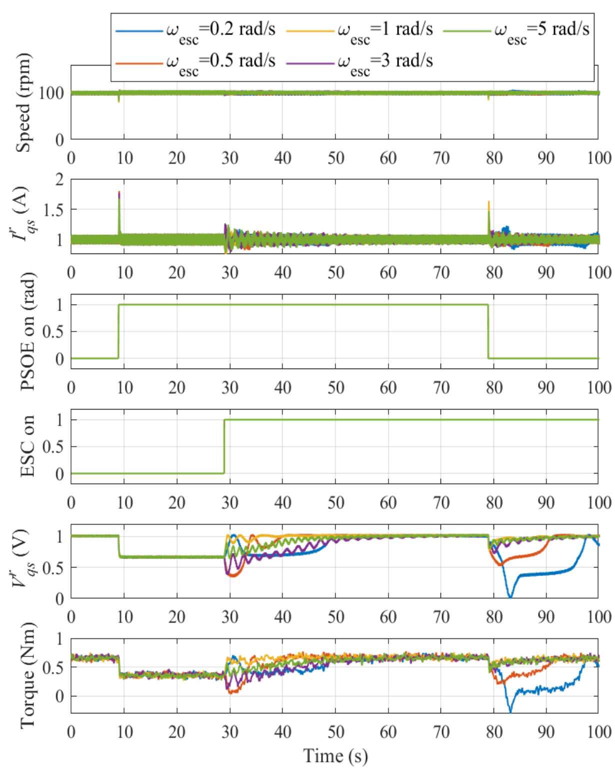

Fig. 11. Experimental result for ESC-PSOE compensation with varying ω_{esc} (A = 0.1, B = 25, ω_c = 0.4 rad/s)

The effect of the amplitude of the ESC search signal (A) on the overall system was studied next and presented in figure 12. When considering Fig. 12, it is evident that a too-small of an amplitude value cannot reach the optimum torque state. Even though the largest amplitude value helps reach the optimum torque faster, it also introduces considerable amounts of torque ripple during the transient. The A = 0.1 scenario demonstrates a smooth transient and reaches the optimal torque in a reasonable time.

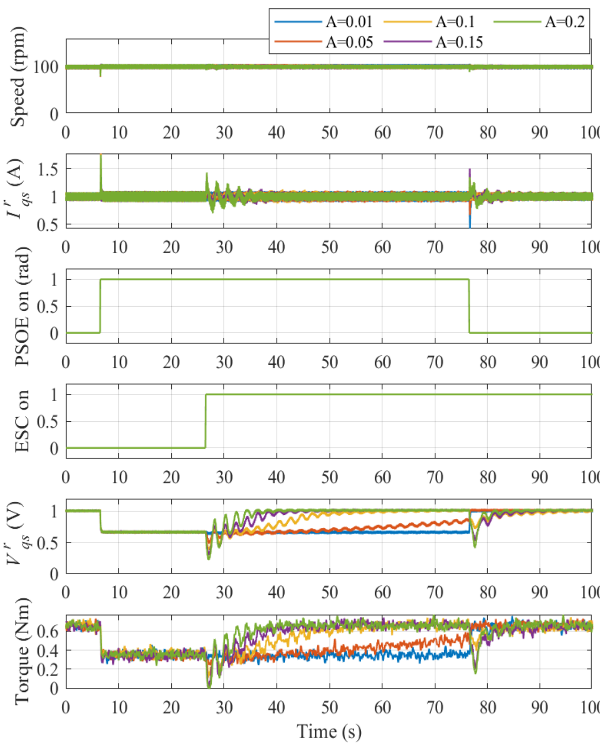

Fig. 12. Experimental result for ESC-PSOE compensation with varying A (ω_{esc} = 3 rad/s, B = 25, ω_c = 0.4 rad/s)

Based on the results in Fig. 13, it can be concluded that small B values do not reach the optimum torque or V^r_{qs}. Even though the largest B value (i.e. B = 50) has reached the optimum value, it has shown a significant transient, which may be undesirable in applications sensitive to torque transients. B = 25 scenario shows a much smoother transient and it has optimized torque and V^r_{qs} effectively.

Figure 14, is with varying high-pass filter cutoff frequencies. The time taken by the ESC to correct the PSOE error is much greater when the high-pass filter cutoff is too small (i.e. 0.02 rad/s) or too large (i.e. 10 rad/s). Furthermore, the smallest value has shown an oscillatory behavior in torque and V^r_{qs}. ω_c in the neighborhood of 0.4 rad/s leads to a smooth transient and it has converged to the optimum value of torque and V^r_{qs} with a less settling time compared to the other cases considered.

B. Validation of ESC-PSOE Compensation Under Transient Conditions

This section further evaluates the effectiveness and robustness of the ESC-PSOE compensation approach across different operating conditions, including transient behavior. Motor control systems in real life undergo different transient conditions and the robustness of fault compensation strategies are crucial. The algorithm was configured with $\omega_{esc} = 3 rad/s$, $A = 0.1$, $B = 25$ and $\omega_c = 0.4 rad/s$ for the following experimental

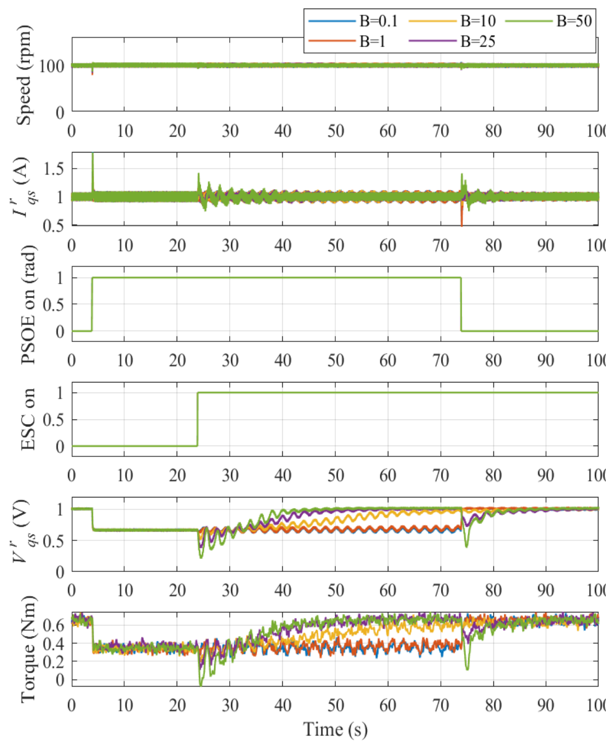

Fig. 13. Experimental result for ESC-PSOE compensation with varying B (ω_{esc} = 3 rad/s, A = 0.1, ω_c = 0.4 rad/s)

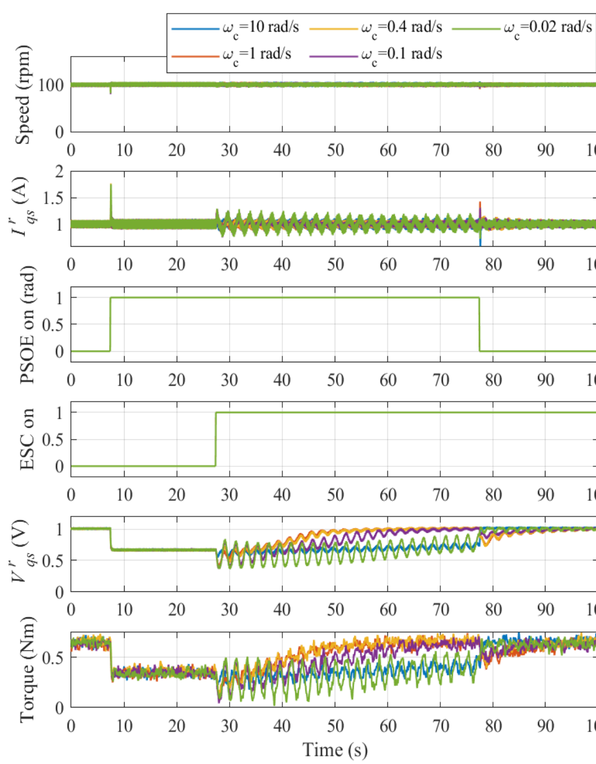

Fig. 14. Experimental result for ESC-PSOE compensation with varying ω_c (ω_{esc} = 3 rad/s, A = 0.1, B = 25)

cases. Figures 15 and 16 show results with positive PSOE changes and current reference changes in clockwise and counter-clockwise motor rotation, respectively. Figures 17 and 18 are results for negative PSOE values and current reference changes in clockwise and counter-clockwise motor rotation. Figure 19 demonstrates system behavior subjected to speed transients while under the influence of PSOE fault being compensated with the proposed ESC. In all scenarios, the ESC-PSOE compensation algorithm can be seen rapidly correcting for the injected PSOE enabling the system to circumvent the PSOE fault. The transients seem to have minimal to no effect on the ESC-PSOE compensation strategy, nor results in instabilities.

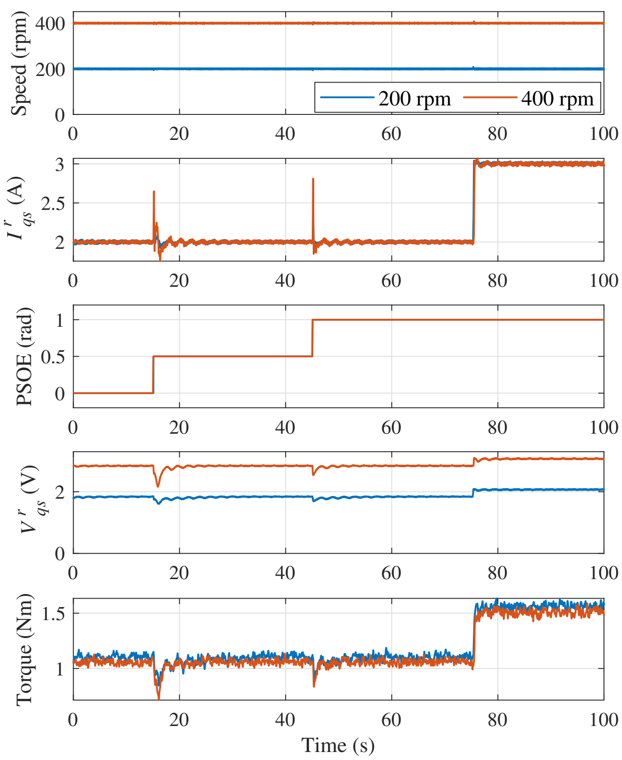

Fig. 15. Experimental evaluation of the ESC-PSOE compensation strategy under transients (Positive PSOE, Clockwise motor rotation)

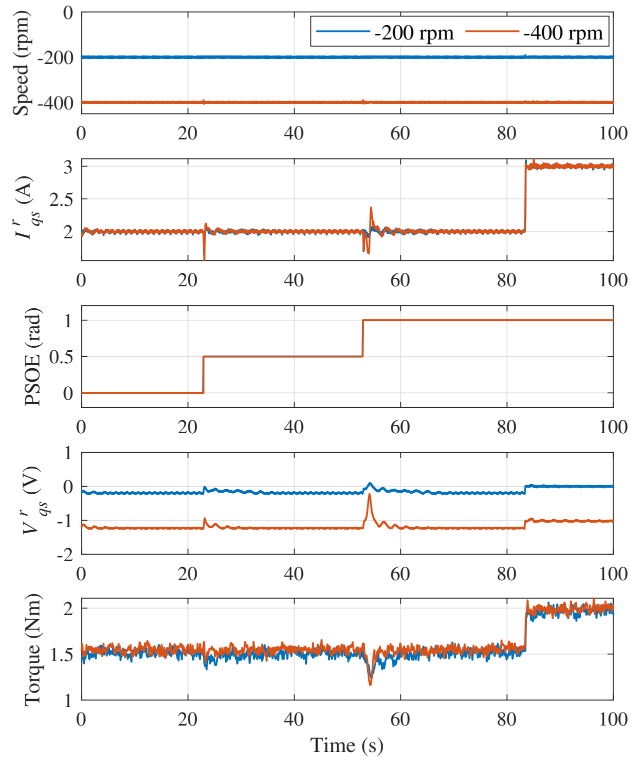

Fig. 16. Experimental evaluation of the ESC-PSOE compensation strategy under transients (Positive PSOE, Counter-Clockwise motor rotation)

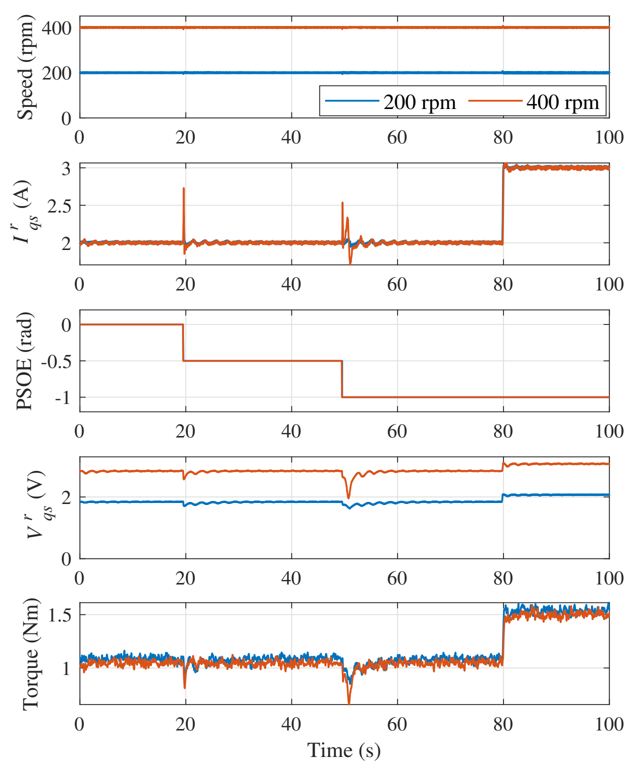

Fig. 17. Experimental evaluation of the ESC-PSOE compensation strategy under transients (Negative PSOE, Clockwise motor rotation)

VI. Conclusion

The accuracy of the position signal in a field-orientation-based torque-controlled permanent magnet synchronous machine being paramount, the offset errors on the position signal have been proven to be catastrophic. Existing position sensor offset error (PSOE) detection and compensation is laborious, computationally heav, and relies on accurate motor/system parameters to be effective. Therefore an extremum-seeking controller-based PSOE compensation strategy is proposed in this paper along with the theoretical background, and implementation results. Implementations results include both simulation and experimental results validating the effectiveness of the proposed algorithm under various operating points and transient conditions. The proposed algorithm indirectly optimizes the output torque, by optimizing the q-axis voltage

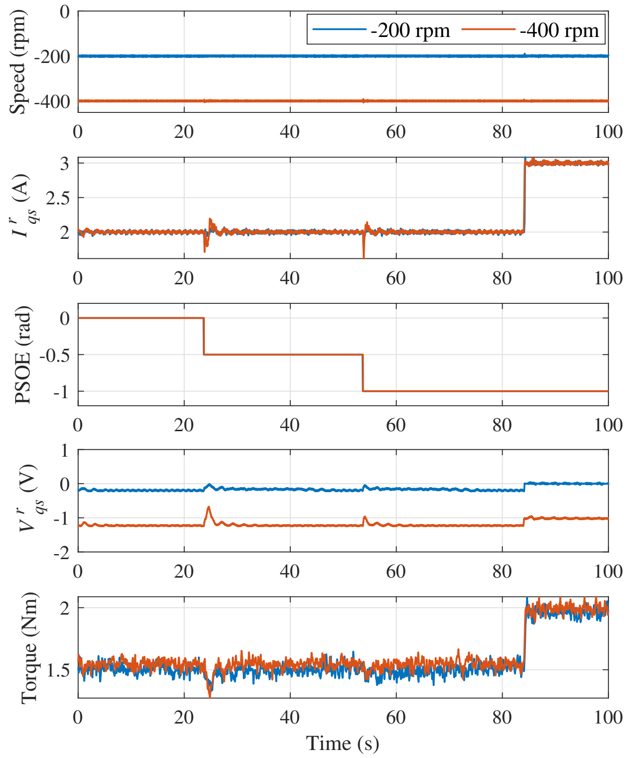

Fig. 18. Experimental evaluation of the ESC-PSOE compensation strategy under transients (Negative PSOE, Counter-Clockwise motor rotation)

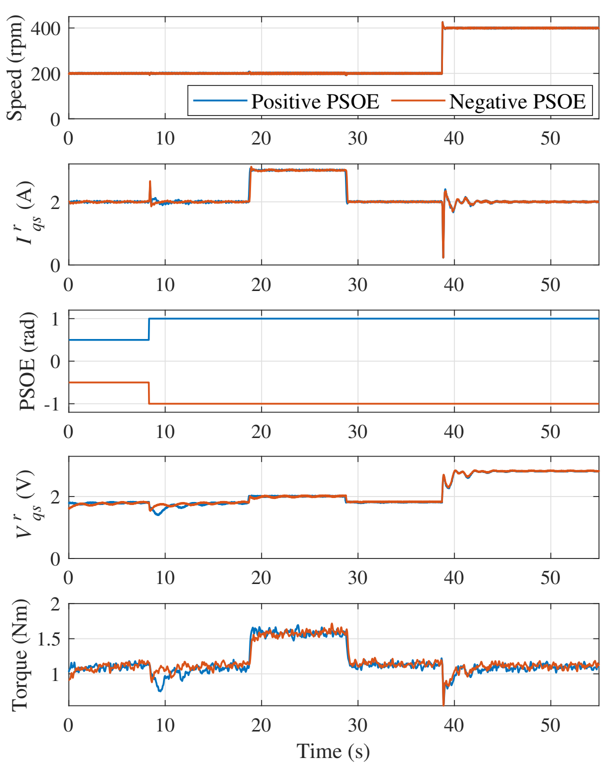

Fig. 19. Experimental evaluation of the ESC-PSOE compensation strategy under transients (Speed and Current Reference Changes)

using the extremum-seeking real-time optimization concepts. The presented results clearly justify the effectiveness as well as the robustness of the proposed approach.

ACKNOWLEDGMENTS

The authors would like to thank Professor Kartik Ariyur for introducing the concept of extremum-seeking control and helping demystify the concept.

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