JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 13(4), DECEMBER, 2025
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

Adaptive Model Predictive Current Control for Permanent Magnet Synchronous Motors under Poor Power Quality Conditions

Abel. E. Airoboman, Tidah Daniel Kurmi
Department of Electrical and Electronics Engineering,
Nigerian Defence Academy, Kaduna, Nigeria

ABSTRACT

This study investigates an adaptive model predictive current control strategy for permanent magnet synchronous motors exposed to poor power quality. The work focuses on operating conditions marked by voltage sags and harmonic distortion, which are common in weak-grid environments. The proposed framework brings three features into a single predictive control structure: real-time sag compensation, multivector harmonic mitigation, and thermal derating. A complete PMSM model that includes electrical, mechanical, and thermal behaviour was developed in MATLAB and Simulink and used to test the controller under controlled disturbance scenarios. These scenarios covered voltage sags at 0.75 and 0.74 per unit, injected harmonic orders of the fifth, seventh, eleventh, and thirteenth, and combined disturbances. The adaptive controller was compared with a baseline predictive controller and a simple open-loop drive. Under nominal conditions, it maintained a rotor speed of 1500 revolutions per minute, a torque of 30.24 newton metres, and an efficiency of 85.8 percent. During sag events, it limited speed droop to roughly 0.4 to 0.5 percent, which was better than the baseline controller and far superior to the large drops recorded in open-loop operation. Under harmonic injection, it kept speed variation within 1.6 to 1.9 revolutions per minute and reduced torque ripple to about 2.4 percent. In extended operation it restricted the winding temperature rise to 20.9 degrees Celsius, which demonstrates improved thermal management. The findings show that the adaptive predictive controller offers stronger resilience, better efficiency, and safer thermal behaviour than the other methods. It represents a practical option for PMSM drives used in electric transport, industrial equipment, and renewable energy systems where grid quality is unreliable.

ARTICLE INFO
Article History
Received: June, 2025
Received in revised form: August, 2025
Accepted: October, 2025
Published online: December, 2025

KEYWORDS
Permanent Magnet Synchronous Motor (PMSM), Model Predictive Current Control (MPCC), Power Quality, Voltage Sag, Adaptive Control

INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) are cornerstone components in modern electromechanical systems such as electric vehicles, renewable energy systems, and industrial automation due to their high-power density, efficiency, and precise torque control [1]. However, their performance is highly susceptible to degradation in regions with poor power quality, such as Nigeria, where unstable grids are plagued by frequent voltage sags, harmonic distortions, and voltage unbalance [2], [15]. These disturbances lead to increased torque ripple, current overshoots, elevated copper and iron losses, and excessive thermal stress, which can reduce motor lifespan and reliability [3], [16].

Conventional control strategies like Field-Oriented Control (FOC) and Direct Torque Control (DTC) perform adequately under ideal grid conditions but are ill-suited for dynamic, disturbance-prone environments [4]. FOC's dependency on accurate motor parameters

Corresponding author: Abel. E. Airoboman
airobomanabel@nda.edu.ng
Department of Electrical and Electronics Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

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makes it vulnerable to parameter drift [17], while DTC suffers from significant torque and flux ripples under voltage instability [18]. Model Predictive Current Control (MPCC) has emerged as a powerful alternative, leveraging a discrete-time model of the motor and inverter to predict future states and select optimal switching actions in real-time, offering enhanced dynamic performance and inherent constraint handling [5], [19].

Conventional MPCC lacks specific mechanisms to counteract the compounded effects of voltage sags, harmonic pollution, and thermal stress simultaneously. While some studies have addressed these issues in isolation [6], [7], a unified adaptive framework tailored for the specific multi-disturbance profiles of weak grids remains a research gap. This study, therefore, aims to develop an adaptive MPCC framework that integrates real-time voltage sag compensation, harmonic mitigation, and thermal derating to ensure robust, efficient, and safe PMSM operation under poor power quality conditions, with validation conducted through comprehensive MATLAB/Simulink simulations.

Permanent Magnet Synchronous Motors (PMSMs) have become very popular in modern electric drive applications, favoured for their compact design, high torque-to-current ratio, and superior efficiency [8], [20]. Unlike induction motors, PMSMs utilise permanent magnets to establish the rotor's magnetic field, eliminating the need for external excitation and enabling rapid dynamic response and high-power density [9], [10].

Modelling of PMSMs typically adopts the synchronous d–q reference frame, where the two orthogonal current components are controlled independently to regulate torque and flux. Equations describing stator currents in this transformed coordinate system relate the rate of change of current to stator voltages, resistance, inductances, electrical angular speed, and magnet flux [11]. Control strategies for PMSMs have evolved significantly. Field-Oriented Control (FOC) has long been the baseline, but its reliance on linear decoupling and sensitivity to parameter variations and grid disturbances limits robustness under real-world conditions [4]. Direct Torque Control (DTC) offers faster response but suffers from higher torque ripple and lacks precise current shaping [18]. As digital control technology and processing power have advanced, Model Predictive Control (MPC), particularly Model Predictive Current Control (MPCC), has emerged as a powerful alternative [12]. MPCC exploits the predictive motor model to forecast future current trajectories under different inverter voltage vector options, minimising a cost function based on current error to select the optimal switching action without requiring pulse-width modulation [12], [13], [14].

The aim of this study is to develop an adaptive predictive current control strategy that brings sag compensation, harmonic mitigation, and thermal derating into a single control structure. The controller adjusts its behaviour in real time and maintains stable motor performance when the supply is degraded. A detailed PMSM model that includes electrical, mechanical, and thermal processes was implemented in MATLAB and Simulink and used to assess the method under controlled tests. The results demonstrate the advantages of the adaptive approach and highlight its relevance for applications that depend on reliable motor operation under uncertain grid conditions.

MATERIALS AND METHODS

PMSM System Modelling

A holistic model of the PMSM was developed, integrating electrical, mechanical, and thermal subsystems to accurately simulate its behaviour under disturbances.

Electrical Subsystem

The electrical dynamics of the PMSM were modelled in the synchronous rotating d-q reference frame to simplify control design. The stator voltage equations are given by [8]:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (1)$$

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$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_m \quad (2)$$

where vd,*vq* are dq-axis voltages, *id*,*iq* are dq-axis currents, Rs*Rs* is stator resistance, *Ld*,*Lq* are dq-axis inductances, *ωe* is electrical angular speed, and *λm* is permanent magnet flux linkage. The electromagnetic torque *Te* is derived as:

$$T_e = \frac{3}{2} p[\lambda_m i_q + (L_d - L_q) i_d i_q] \quad (3)$$

where *p* is the number of pole pairs.

Mechanical Subsystem

The mechanical rotor dynamics are governed by:

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \quad (4)$$

where *J* is the moment of inertia, *ωm* is mechanical angular velocity, *TL* is the load torque, and *B* is the viscous friction coefficient.

Thermal Subsystem

A first-order lumped-parameter thermal network was used to model the winding temperature rise:

$$C_{th} \frac{dT_w}{dt} = P_{\text{loss}} - \frac{T_w - T_{\text{amb}}}{R_{th}} \quad (5)$$

where *Tw* is winding temperature, T_{amb} is ambient temperature, C_{th} is thermal capacitance, R_{th} is thermal resistance, and P_{loss} represents total losses, primarily copper losses $P_{cu}=\frac{3}{2}R_8\left(i\frac{2}{d}+i\frac{2}{q}\right)$.

Disturbance Modelling

To simulate poor power quality, two primary disturbances were modelled:

1. **Voltage Sags:** Implemented as a temporary reduction in the RMS supply voltage by a sag factor *ksag* (e.g., 0.75 pu) for a defined duration.
2. **Harmonic Distortions:** Introduced by superimposing higher-order sinusoidal components (e.g., 5th, 7th, 11th harmonics) onto the fundamental supply voltage waveform.

Control Strategy Design

Baseline Model Predictive Current Control (MPCC)

The baseline MPCC uses a discrete-time model of the PMSM, derived from Eqs. (1) and (2) using the forward Euler method, to predict the future stator currents (*id*(*k*+1), *iq*(*k*+1)) for each of the eight possible inverter switching states. The optimal state is selected by minimizing a cost function *g*:

$$\begin{aligned} g &= w_d(i_d^*(k+1) - i_d(k+1))^2 \\ &+ w_q(i_q^*(k+1) - i_q(k+1))^2 \\ &+ w_8 \,.\, Switching\ Penalty \end{aligned} \quad (6)$$

where i_d^*, i_q^* are the reference currents, and w_d ,w_q,w_8 are weighting factors.

Adaptive MPCC Framework

The baseline MPCC was enhanced with three adaptive modules:

1. **Voltage Sag Compensation:** Detects sag events via continuous DC-link voltage monitoring. Upon detection, it scales the available voltage vectors in the predictive model and dynamically adjusts the q-axis current reference to maintain stability within the reduced voltage limit.
2. **Harmonic Mitigation:** Employs a feedforward compensation technique where detected harmonic components are subtracted from the measured voltage before prediction. The cost function is also augmented with a term penalizing predicted harmonic currents.
3. **Thermal Derating:** Monitors the estimated winding temperature. If a predefined threshold is exceeded, it

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dynamically reduces the allowable current limit (Imax)(*Imax*) to prevent overheating, thereby trading off performance for thermal protection.

4. **Simulation Setup**: The PMSM model and control strategies were implemented in MATLAB/Simulink R2018b. The motor parameters used for simulation are listed in Table 1. A fixed-step ode3 solver with a sampling time of 50-100 µs was used. Performance was evaluated under nominal load, voltage sags, harmonic injections, combined disturbances, and extended operation.

Table 1: PMSM Simulation Parameters

Parameter	Symbol	Value	Unit
Stator Resistance	R_s	0.40	Ω
d-axis Inductance	L_d	0.0057	H
q-axis Inductance	L_q	0.0125	H
Flux Linkage	λ_m	0.3125	Wb
Number of Pole Pairs	P	4	-
Rotor Inertia	J	0.0005	kg.m²
Load Torque	T_L	30.24	Nm
Thermal Resistance	R_{th}	0.07	°C/W
Thermal Capacitance	C_{th}	18000	J/°C

RESULTS AND DISCUSSION

The performance of the Open-Loop, Baseline MPCC, and Adaptive MPCC strategies was compared across multiple scenarios. Main results are summarized in the tables below.

Nominal Operation

Under ideal conditions, all strategies achieved the target speed and torque. The MPCC strategies demonstrated superior efficiency and lower q-axis current, as shown in Table 2.

Table 2: Performance Comparison under Nominal Conditions

Control Strategy	Speed (RPM)	Torque (Nm)	Iq (A)	Efficiency (%)
Open-Loop	1500.0 ± 0.0	30.24	45.72	79.0
Baseline MPCC	1500.0 ± 3.1	30.24	32.28	85.7
Adaptive MPCC	1500.0 ± 2.4	30.24	32.28	85.8

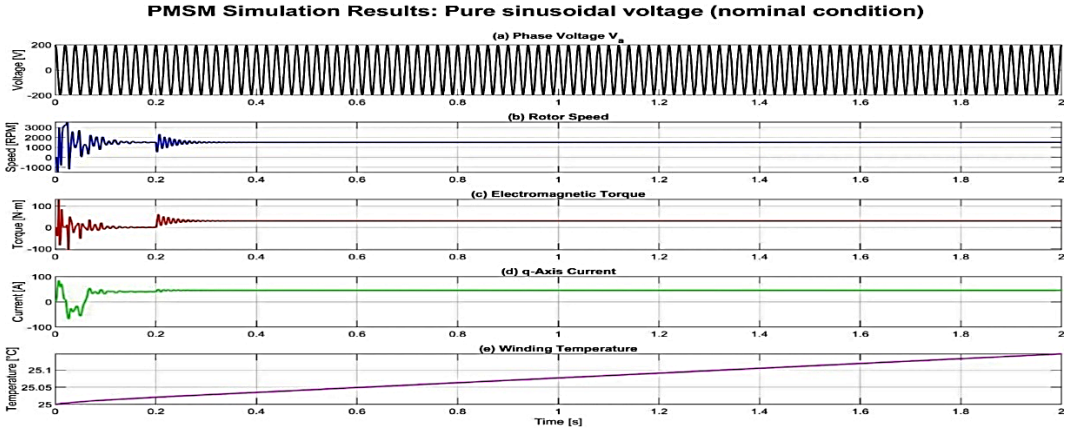

Figure 1. Open-Loop Nominal Response

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airobomanabel@nda.edu.ng
Department of Electrical and Electronics Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

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Fig.1 (a) displays the pure sinusoidal phase voltage (Va) applied to the PMSM, confirming the ideal input conditions. Fig. 1(b) shows the rotor speed, which quickly settles to the synchronous speed of 1500 RPM after an initial transient, demonstrating the system's ability to reach its target speed. Fig. 1(c) presents the electromagnetic torque, which also stabilizes at the rated load torque of 30.24 Nm with minimal oscillations after the initial startup. Fig. 1(d) illustrates the q-axis current (Iq), which is the primary component responsible for torque generation. It shows a stable current flow after the initial transient. Finally, Fig.1(e) depicts the winding temperature, which exhibits a gradual and minimal increase, indicating low power losses during nominal operation. The stable steady-state values across all parameters confirmthe system's stability under ideal conditions, with the torque aligning with the load and back-EMF interaction as expected from the model equations.

Voltage Sag Conditions

The adaptive MPCC showed exceptional robustness during voltage sags, significantly limiting speed droop compared to the other strategies (Table 3).

Table 3: Performance Comparison under Voltage Sag Conditions

Control Strategy	Sag Case 1 (0.75 pu) Droop (%)	Sag Case 2 (0.74 pu) Droop (%)
Open-Loop	123.4	135.7
Baseline MPCC	0.6	0.7
Adaptive MPCC	0.4	0.4

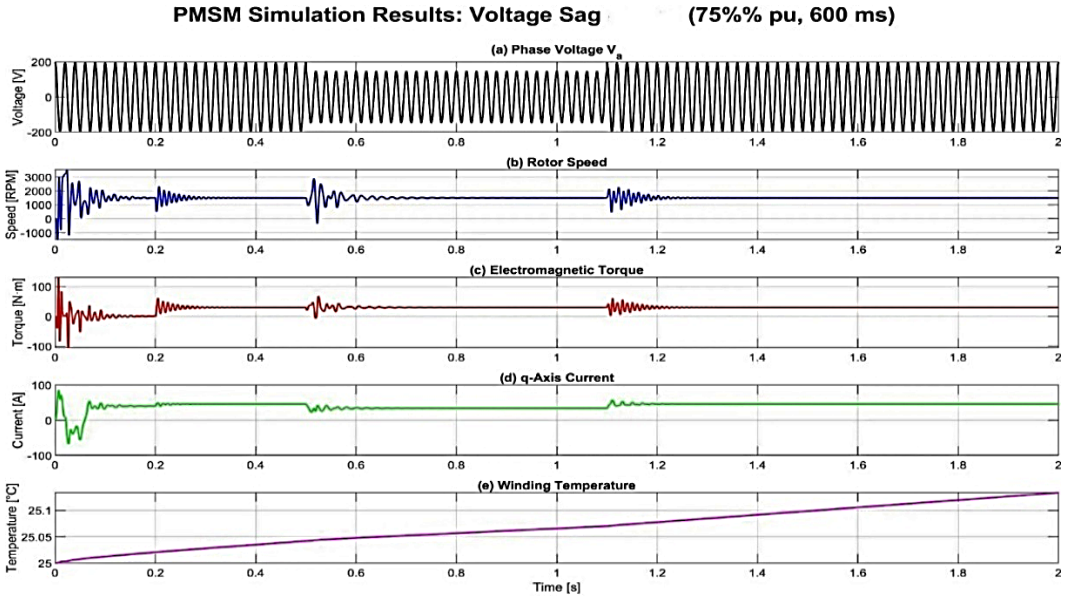

Figure 2: Open-Loop Voltage Sag Response

Fig. 2(a) clearly shows the applied phase voltage (Va) with the distinct sag event occurring from 0.5 seconds to 1.1 seconds, where the voltage amplitude is reduced. Fig. 2(b) illustrates the rotor speed, which experiences a severe drop into negative values during the sag, highlighting the system's vulnerability to voltage disturbances in open-loop operation. The speed then recovers to 1500 RPM after the sag clears. Fig. 2(c) shows the electromagnetic torque, which also exhibits significant fluctuations during the sag but eventually returns to its stable value. Fig. 2(d) displays the q- axis current (Iq), which decreases

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airobomanabel@nda.edu.ng
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during the sag due to the reduced voltage but recovers afterward. Fig. 2(e) indicates a minimal change in winding temperature. The large speed droop observed underscores the PMSM's sensitivity to voltage reduction without active control, consistent with established findings on open-loop PMSM behaviour under sags.

Harmonic Injection Conditions

The adaptive MPCC effectively suppressed oscillations caused by harmonic distortions, resulting in the lowest speed variations and torque ripple (Table 4).

Table 4: Performance Comparison under Harmonic Conditions

Control Strategy	Harmonic Case A Speed Variation (RPM)	Harmonic Case B Speed Variation (RPM)	Torque Ripple (%)
Open-Loop	21.5	17.7	6.26 - 7.03
Baseline MPCC	3.0	3.7	~2.60
Adaptive MPCC	1.6	1.9	~2.38

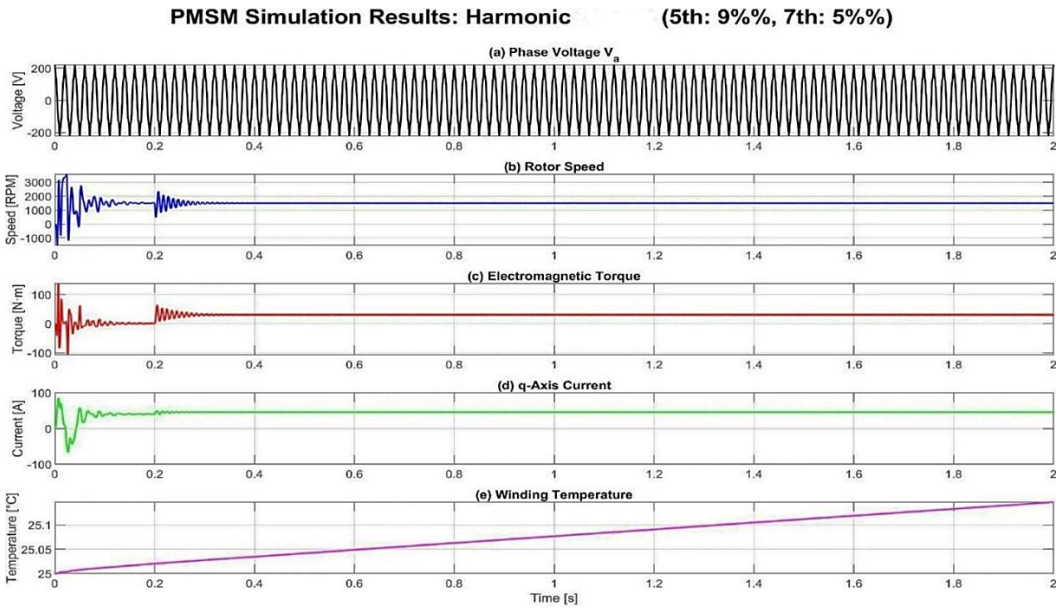

Figure 3. Open-Loop Harmonic Case A Response

Fig.3(a) shows the distorted phase voltage (Va) due to the presence of 5th and 7th harmonics, which deviate from a pure sinusoidal waveform. Fig. 3(b) illustrates the rotor speed, which, while averaging 1500 RPM, exhibits noticeable oscillations around the mean, reflecting the impact of voltage harmonics on speed stability. Fig. 3(c) displays the electromagnetic torque, showing significant ripple content, which is a direct consequence of the harmonic distortions in the supply. Fig. 3(d) presents the q-axis current (Iq), which also shows variations corresponding to the torque ripple. Fig. 3(e) indicates a minimal temperature rise. The observed torque ripple and stator current THD are direct indicators of the harmonic impact, with the THD value approaching the limits specified by IEEE Std 519-2014

Combined Disturbance Conditions

Under simultaneous sag and harmonic events, the adaptive MPCC maintained the most stable operation, confirming its ability to handle complex, real-world power quality issues (Table 5).

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airobomanabel@nda.edu.ng
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Table 5: Performance Comparison under Combined Disturbances

Control Strategy	Combined Case A Droop (%)	Combined Case B Droop (%)
Open-Loop	122.3	132.9
Baseline MPCC	0.7	0.8
Adaptive MPCC	0.5	0.4

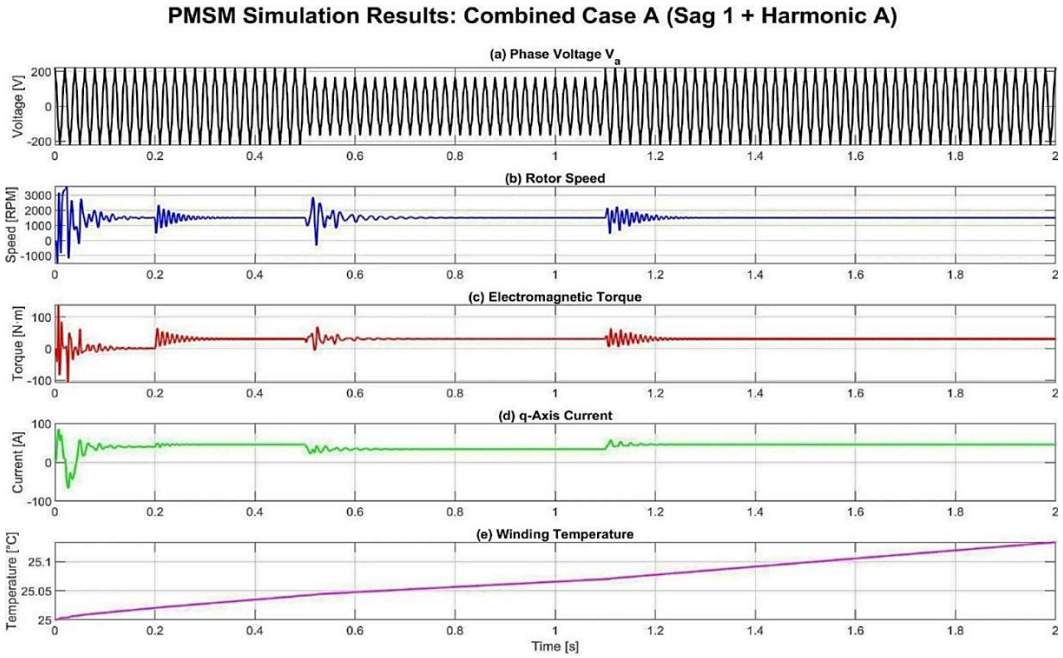

Figure Error! No text of specified style in document.**:** Open-Loop Combined Case Response

Fig. 4. (a) shows the phase voltage (Va) exhibiting both the sag event and the harmonic distortions, demonstrating the simultaneous presence of both types of disturbances. Fig. 4(b) illustrates the rotor speed, which experiences a significant droop during the sag, similar to the individual sag cases, but also displays continuous oscillations due to the harmonics. The combination of these effects leads to a more complex and unstable speed response. Fig. 4(c) displays the electromagnetic torque, showing both the transient impact of the sag and the persistent ripple from the harmonics. Fig. 4(d) presents the q-axis current (Iq), reflecting the combined effects on current. Fig. 4(e) shows a minimal temperature rise. The exacerbated instability observed in this combined scenario underscores the challenges of maintaining system performance under multiple simultaneous disturbances.

Extended Operation and Thermal Performance

During a 10-minute simulation under continuous harmonic injection, the adaptive MPCC's thermal derating strategy resulted in the lowest temperature rise, showcasing its long-term reliability (Table 6).

Table 6: Performance Comparison during Extended Operation

Control Strategy	Final Speed (RPM)	Temp. Rise (°C)
Open-Loop	1489.6	33.4
Baseline MPCC	1500.0	21.0
Adaptive MPCC	1500.0	20.9

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airobomanabel@nda.edu.ng
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The discussion of these results confirms the critical vulnerability of open-loop PMSM drives to power quality disturbances. The baseline MPCC provides a substantial improvement, offering stable operation and basic disturbance rejection. The adaptive MPCC, demonstrates a superior level of intelligence and robustness. Its integrated compensation mechanisms proactively mitigate the effects of sags and harmonics, while its thermal awareness ensures operational safety under prolonged stress, making it a comprehensively optimized solution for challenging grid environments.

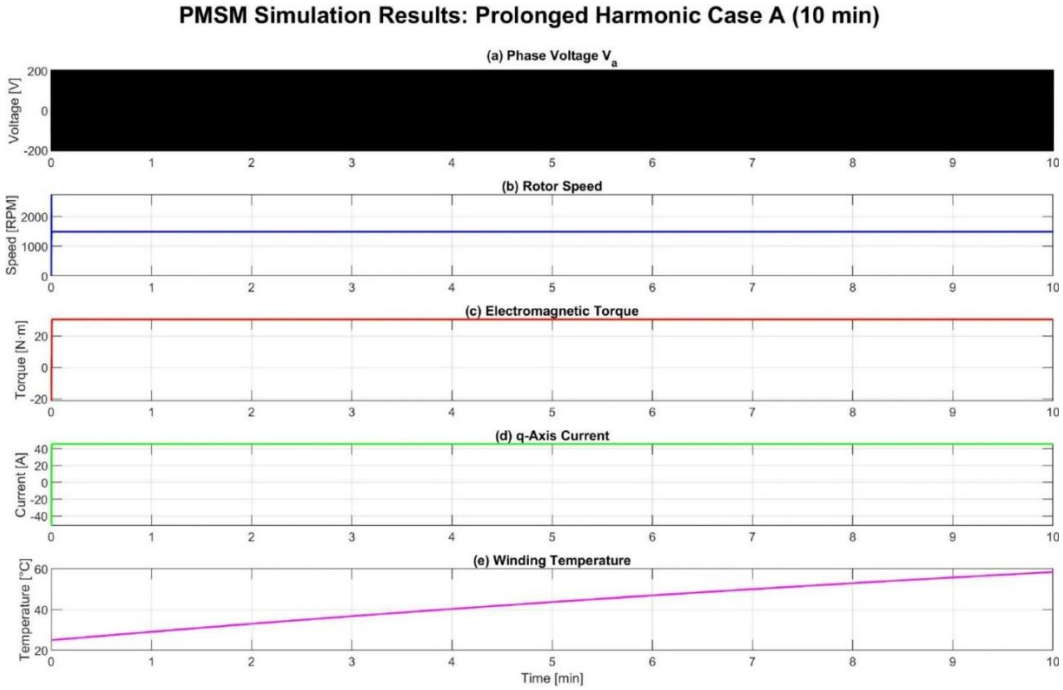

Figure Error! No text of specified style in document.**.3:** Open-Loop Extended Harmonic Case A Response

Figure 5(a) shows the distorted phase voltage (Va) over the extended 10-minute period, indicating the continuous presence of harmonics. Figure 5(b) illustrates the rotor speed, which, while relatively stable, shows a slight offset from the 1500 RPM reference, indicating a steady-state error introduced by prolonged harmonic exposure. Figure 5(c) displays the electromagnetic torque, which remains stable with minimal ripple over the long duration. Figure 5(d) presents the q-axis current (Iq), also showing stable behaviour. However, Figure 5(e) clearly demonstrates a significant and continuous increase in winding temperature over the 10-minute period, reaching a much higher steady-state value. This substantial temperature rise is a critical finding, indicating increased thermal stress and potential long-term degradation of the motor due to sustained harmonic losses, emphasizing the importance of thermal management and harmonic mitigation in practical applications.

CONCLUSION

This study successfully developed and validated an adaptive Model Predictive Current Control (MPCC) framework for Permanent Magnet Synchronous Motors (PMSMs) operating under poor power quality conditions. The main innovation lies in the seamless integration of real-time voltage sag compensation, multivector harmonic mitigation, and thermal derating within a single predictive control structure. Simulation

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airobomanabel@nda.edu.ng
Department of Electrical and Electronics Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

results conclusively demonstrate that the proposed adaptive MPCC framework significantly enhances PMSM resilience, efficiency, and thermal safety compared to both open-loop operation and a standard MPCC strategy. It effectively limits speed droop to below 0.5% during severe voltage sags, reduces speed variations to under 2 RPM under harmonic distortion, and minimizes long-term temperature rise. This makes the adaptive MPCC a highly suitable and recommended control solution for PMSM applications in electric vehicles, industrial automation, and renewable energy systems, particularly in regions with unstable and poor-quality power grids.

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Corresponding author: Abel. E. Airoboman
airobomanabel@nda.edu.ng
Department of Electrical and Electronics Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

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airobomanabel@nda.edu.ng
Department of Electrical and Electronics Engineering, Nigerian Defence Academy, Kaduna, Nigeria.