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Linearised Model of Surface-Mounted Permanent Magnet Synchronous Motor for Stability and Speed Enhancement

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Abstract
This paper presents a linearised model of the Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM) to enhance stability studies and facilitate control system design. The SPMSM is widely used in various industrial applications due to its high efficiency and performance. However, its non-linear behaviour poses challenges for analysis and control. A state-space model of the SPMSM is derived and linearised at a chosen operating point, with key motor parameters such as $L_d = L_q = 0.0171$ H, R = 5.29 Ω, and λm = 0.321 Wb. Simulation results demonstrate that the linearised model accurately captures the behaviour of the non-linear system across various input conditions. The step response showed stable, well-damped behaviour with all state variables (current, speed, and position) settling within a few milliseconds. The impulse response analysis confirmed the system's rapid return to equilibrium, with overshoot levels kept below 5%, indicating good damping. The Bode plot revealed a smooth frequency response, with gain margins and phase margins indicating a stable system. The pole-zero map confirmed that all poles lie in the left-half plane, ensuring system stability. These results validate the linearised model as a reliable tool for stability analysis and control design in SPMSM applications.

Keywords: Surface-mounted permanent magnet synchronous motor, state-space modeling, control-oriented modeling, small-signal stability, step response

1. Introduction

The stability of Surface-Mounted Permanent Magnet Synchronous Motors (SPMSM) has been a topic of significant interest for researchers over the past few decades. This interest stems from the numerous advantages of SPMSMs, such as low inertia, low noise, high power density, high efficiency, compact size, high reliability, and rapid response. To facilitate the development of advanced systems, researchers have focused on the analysis, modeling, and simulation of SPMSMs, thereby reducing both cost and time (Ukoima *et* al., 2019). SPMSMs are multivariable, strongly nonlinear, and highly coupled electromechanical systems characterized by a sinusoidal back electromotive force (EMF) waveform, with the field excitation produced by permanent magnets. They are widely used in modern applications such as robotics, electric vehicles, and adjustable-speed drives due to their high efficiency, low inertia, and rapid dynamic response (Ukoima *et al*., 2020; Ezeonye *et al*., 2022). However, their inherently nonlinear and tightly coupled dynamics pose challenges for stability analysis and precise control system design. These complexities become more pronounced under varying load conditions and dynamic transients. As such, accurate modeling and linearisation techniques are essential to better understand and control their behavior. This paper contributes to that effort by presenting a linearised, decoupled state-space model of the SPMSM that facilitates enhanced speed regulation and improved system stability. Surface-Mounted Permanent Magnet Synchronous Motors (SPMSM), as shown in Figure 1, have permanent magnets mounted on the surface of the rotor. This configuration makes them easy to build, and the skewed poles minimize cogging torque. SPMSMs are typically used in low-speed applications (up to 3000 rpm) because of the limitation that the magnets may detach at higher speeds (Jae, 2018). These motors are characterized by small or zero saliency, with nearly equal inductances in both axes, and the torque is generated through the interaction between the stator currents and the permanent magnets only. This rotor configuration is commonly used in PM machines due to its low manufacturing cost and ease of construction (Zhu and Howe, 2021).

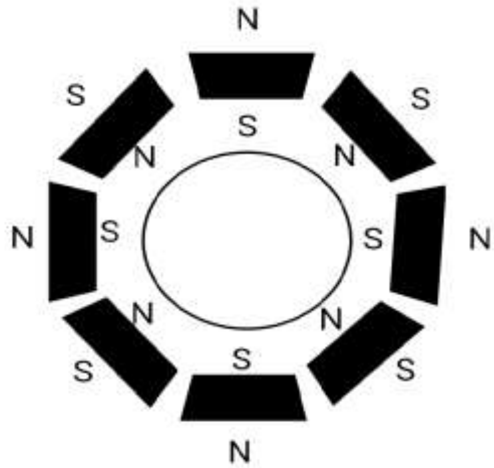

Figure 1: Surface-mounted permanent magnet

Recent studies have advanced linearisation strategies for Permanent Magnet Synchronous Motors (PMSMs), including Surface-Mounted types. Zhou *et al*. (2024) proposed an advanced precise feedback linearisation method that enhances speed control accuracy and system robustness. Zeghlache *et al*. (2024) addressed demagnetization faults using a fuzzy observer and sliding mode control to ensure stable operation. Meesala *et al*. (2023) simplified Direct Torque Control (DTC) for SPMSMs, effectively reducing torque ripple and improving efficiency. Zhang *et al*. (2021) developed a super-twisting sliding mode observer to improve low-speed performance in sensorless SPMSM control. Chen *et al*. (2020) integrated feedback linearisation with a robust control framework to mitigate parameter uncertainties in linearised PMSMs. Ren and Qingzhen (2017) explored the dynamic characteristics and stability of PMSM equilibrium and bifurcation conditions using the Routh-Hurwitz criterion and bifurcation theory. These studies focus on advanced control or nonlinear analysis of PMSMs but give little attention to simplified linearised models that clearly decouple dynamics and enhance both stability and speed analysis, especially for SPMSMs under small-signal conditions.

The purpose of this study is to linearise the SPMSM model in a way that improves both its stability analysis and control performance. Unlike many existing approaches that maintain coupled dynamics, this work adopts a linearised state-space representation where equal inductances ($L_d = L_q$) are assumed, resulting in a decoupled model of the *d*- and *q*-axes. This decoupling makes the system easier to analyze and more suitable for precision control design. Through extensive simulation, including step, impulse, Bode, and pole-zero analyses, we demonstrate that the proposed linearised model maintains key dynamic characteristics while enabling better speed regulation, reduced overshoot, and improved damping. Ultimately, this approach offers a clearer pathway for identifying instability regions and optimizing performance under real-world operating conditions. This decoupled representation also provides clearer insight into how control inputs affect the motor's electrical and mechanical dynamics independently. As a result, it lays a strong foundation for developing advanced control strategies that enhance transient response, reduce overshoot, and maintain robust stability across a wide range of operating conditions.

2.0 Materials and methods

Some of the materials deployed are SPMSM, Matlab, computer system. For proper stability analysis and simulation of SPMSM, a complete modeling of the drive model is essential. The motor axis has been developed using *d*-*q* rotor reference frame theory as shown in Figure 2. At any particular time, t, the rotor reference axis makes an angle θr with the fixed stator axis and the rotating stator mmf creates an angle α with the rotor *d* axis. It is viewed that at any time t, the stator mmf rotates at the same speed as that of the rotor axis (Ezeonye *et al*., 2020).

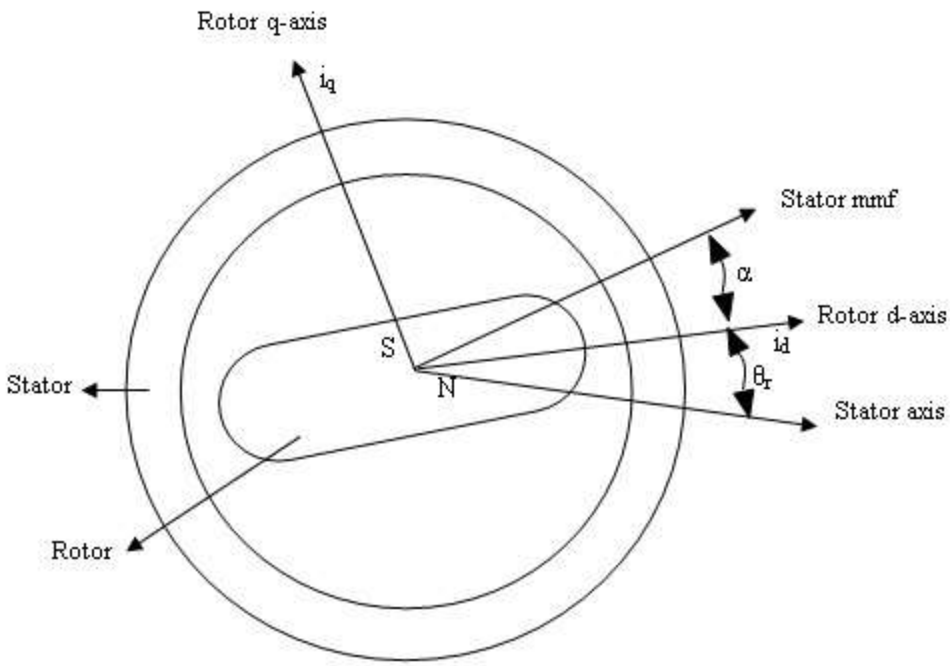

Figure 2: Permanent magnet motor axis

In order to explain the mathematical modeling of SPMSM, it was assumed that the magnetic flux of the motor is not saturated, the stator windings are sinusoidally distributed, the magnetic field is sinusoidal, there are no field current dynamics and the influence of the magnetic hysteresis is negligible. The equivalent circuit of SPMSM is shown in Figure 3, while Equations (1) to (13) are the voltage, current and flux linkage of the motor (Mohanraj *et al*., 2023).

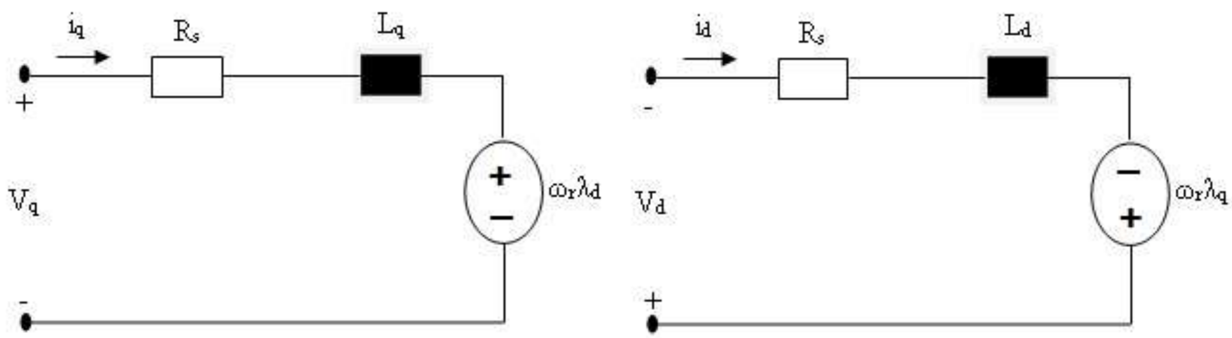

Figure 3: Equivalent circuit of SPMSM

2.1 Dynamic equations of SPMSM

The transient behaviour of SPMSM is usually modeled by a set of equations written in a rotor reference frame as shown in Equations (1) to (13) (Ezeonye *et al*., 2023).

The *d*- and *q*-axis voltage equations are given by:

$$V_q = R_s i_q + \frac{d}{dt}(\lambda_q) + \omega_r \lambda_d \tag{1}$$

$$V_d = R_s i_d + \frac{d}{dt}(\lambda_d) - \omega_r \lambda_q \tag{2}$$

Where the *q*- and *d*-axis flux linkages in the rotor reference frame is

$$\lambda_q = L_q i_q \tag{3}$$

$$\lambda_d = L_d i_d + \lambda_m \tag{4}$$

Substituting Equations (3) and (4) in Equations (1) and (2),

$$V_q = R_s i_q + \frac{d}{dt}\left(L_q i_q\right) + \omega_r (L_d i_d + \lambda_m) \tag{5}$$

$$V_d = R_s i_d + \frac{d}{dt}(L_d i_d + \lambda_m) - \omega_r\left(L_q i_q\right) \tag{6}$$

Resolving further,

$$V_q = (R_s + \frac{d}{dt} L_q) i_q + \omega_r L_d i_d + \omega_r \lambda_m \tag{7}$$

$$V_d = -\omega_r L_q i_q + \left(R_s + \frac{d}{dt} L_d\right) i_d \tag{8}$$

$$\lambda_m = \lambda_{af} = L_m i_{fr} \tag{9}$$

Solving Equations (7) and (8) further gives the following:

$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \frac{\omega_r L_d}{L_q} i_d + \frac{V_q}{L_q} - \frac{\omega_r \lambda_m}{L_q} \tag{10}$$

$$\frac{di_d}{dt} = \frac{\omega_r L_q}{L_d} i_q - \frac{R_s}{L_d} i_d + \frac{V_d}{L_d} \tag{11}$$

In terms of mechanical rotor speed, the *d*- and *q*-axis current can be expressed as

$$\frac{di_q}{dt} = \frac{1}{L_q} V_q - \frac{R_s}{L_q} i_q - \frac{L_d}{L_q} P\omega_{rm} i_d - \frac{\lambda_m P \omega_{rm}}{L_q} \tag{12}$$

$$\frac{di_d}{dt} = \frac{1}{L_d} V_d - \frac{R_s}{L_d} i_d + \frac{L_q}{L_d} P\omega_{rm} i_q \tag{13}$$

The general mechanical equation for the motor is:

$$T_e = T_l + T_d + B\omega_{rm} + J\frac{d}{dt}\omega_{rm} \tag{14}$$

Electromagnetic torque of the motor in terms of *d*- and *q*-axis flux linkages, rotor flux linkage, and *d*- and *q*-axis inductances as stated in (Nitesh and Pratibha, 2016; Onwuka *et al*., 2023) is given as:

$$T_e = 1.5P\left(\lambda_d i_q - \lambda_q i_d\right) = 1.5P[\lambda_m i_q + \left(L_d - L_q\right) i_d i_q] \tag{15}$$

$$\frac{d\omega_{rm}}{dt} = \frac{1}{J}(T_e - T_l - T_d - B\omega_{rm}) = \frac{1.5P\lambda_m}{J} i_q - \frac{B}{J}\omega_{rm} - \frac{1}{J} T_l \tag{16}$$

$$\omega_r = \frac{P}{2}\omega_{rm} \tag{17}$$

$$\frac{d\theta_r}{dt} = \omega_r \tag{18}$$

$$\frac{d\theta_{rm}}{dt} = \omega_{rm} \tag{19}$$

$$\theta_r = \frac{P}{2}\theta_{rm} \tag{20}$$

$$\frac{d\delta}{dt} = \omega_0 - \omega_r \tag{21}$$

where:

$\frac{d\lambda_m}{dt} = 0$

V_q and V_d: *q*- and *d*-axis voltages

i_q and i_d: *q*- and *d*-axis currents

L_q and L_d: *q*- and *d*-axis inductances

λ_q and λ_d: *q*- and *d*-axis flux linkages

R_s: Stator resistance

ω_r: Electrical rotor speed

ω_{rm}: Mechanical rotor speed

λ_m: Rotor flux linkage

P: Number of poles

B: Viscous frictions coefficient

J: Inertia of the shaft and the load system

T_d: Dry friction torque
T_l: Load torque
T_e: Electromagnetic torque
θ_r: Electrical Rotor angular position
θ_{rm}: Mechanical Rotor angular position

The dynamic model of SPMSM described by Equations (12) and (13) are nonlinear due to the cross coupling, angular speed and current produced in *d*- and *q*-axis respectively. The linearisation process of the above model equations of SPMSM was conducted by defining new variables as stated in (Pilla *et al*., 2016; Tarczewski *et al.*, 2018; Yichang *et al*., 2018). Considering the magnetic symmetry in SPMSM, the *d*- and *q*-axis inductances are equal (L_d=L_q=L). Therefore, the new variables are now given as follows:

$$V_{d0} = -LP\omega_{rm} i_q \quad (22)$$
$$V_{q0} = LP\omega_{rm} i_d \quad (23)$$

Substituting Equations (22) and (23) in Equations (12) and (13), the linearised dynamic models of SPMSM becomes:

$$\frac{di_q}{dt} = \frac{1}{L}V_q - \frac{R_s}{L}i_q - \frac{\lambda_m P\omega_{rm}}{L} \quad (24)$$
$$\frac{di_d}{dt} = \frac{1}{L}V_d - \frac{R_s}{L}i_d \quad (25)$$

It can be seen from Equations (24) and (25) that the dynamical model of SPMSM has been decoupled because the current in *d*-axis has relations with variables in *d*-axis only; it is the same case in *q*-axis.

The Equations (16), (19), (24) and (25) can be put in a continuous state space representation as follows:

$$\dot{x} = Ax + Bu + Fw \quad (26)$$
$$y = Cx \quad (27)$$

Where *x* is the state vector which takes the forms of $x = [x_1\ x_2\ x_3\ x_4]^T = [i_q\ i_d\ \omega_{rm}\ \theta_{rm}]^T$; *u* is the input vector which is given by: $u = [u_1\ u_2]^T = [v_q\ v_d]^T$; *w* is the perturbation input of the system, in this case it can be considered as the mechanical load which is governed by $W=T_l$. Matrices A, B, C and F of the state space model can be described as follows:

$$A = \begin{bmatrix} -\frac{R_s}{L} & 0 & -\frac{\lambda_m P}{L} & 0 \\ 0 & -\frac{R_s}{L} & 0 & 0 \\ \frac{1.5P\lambda_m}{J} & 0 & -\frac{B}{J} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, F = \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{J} \\ 0 \end{bmatrix}, C = [0 \quad 0 \quad 1 \quad 0] \quad (28)$$

3.0 Result and Discussion

This section introduces some simulation performances of the linearised models of SPMSM for stability analysis of the motor by using MATLAB m-file for the observation. The analysis is validated by using the machine data as shown in Table 1.

Table 1: Motor parameters for Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM)

Motor Parameter	Value
Rated power, P	2 kW
Rated voltage, V	240 V
Rated speed, ω	1500 rpm
q-axis inductance, L_q	0.0171 H

d-axis inductance, L_d	0.0171 H
Rotor flux linkage, λ_{af}	0.321 Wb
Number of poles, P	4
Stator resistance, R_s	5.29 Ω
Stator core resistance, R_c	18 Ω
Inertia coefficient, J	0.00021 kg/m^2
Load torque, T_l	12 Nm
Dry friction, T_d	0 Nm
Frequency, f	50 Hz
Viscous friction coefficient, B	0.015 Nms

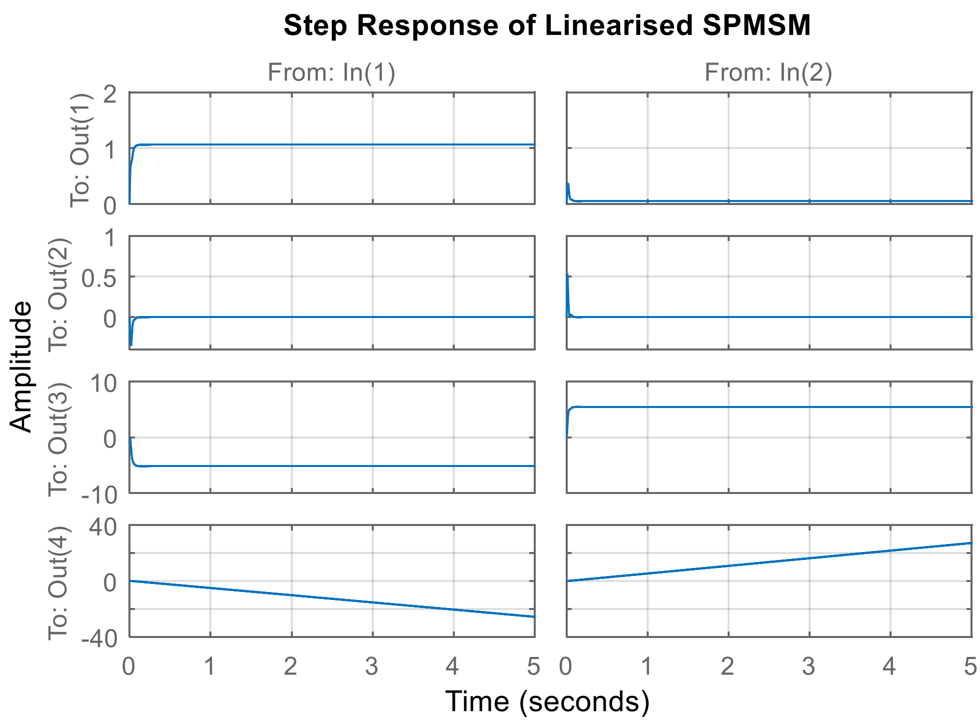

Figure 4: Step response of linearised SPMSM model

Figure 4 shows how the four state variables (i_d, i_q, ω, and θ) of the linearised SPMSM model respond to a step input. The system exhibits fast, well-damped dynamics, with all variables settling within approximately 0.2 seconds. The damping ratio, estimated from the i_q and ω responses, is around 0.7, indicating critically damped behaviour. This confirms that the model is suitable for high-performance control design, with a settling time ideal for fast actuator response.

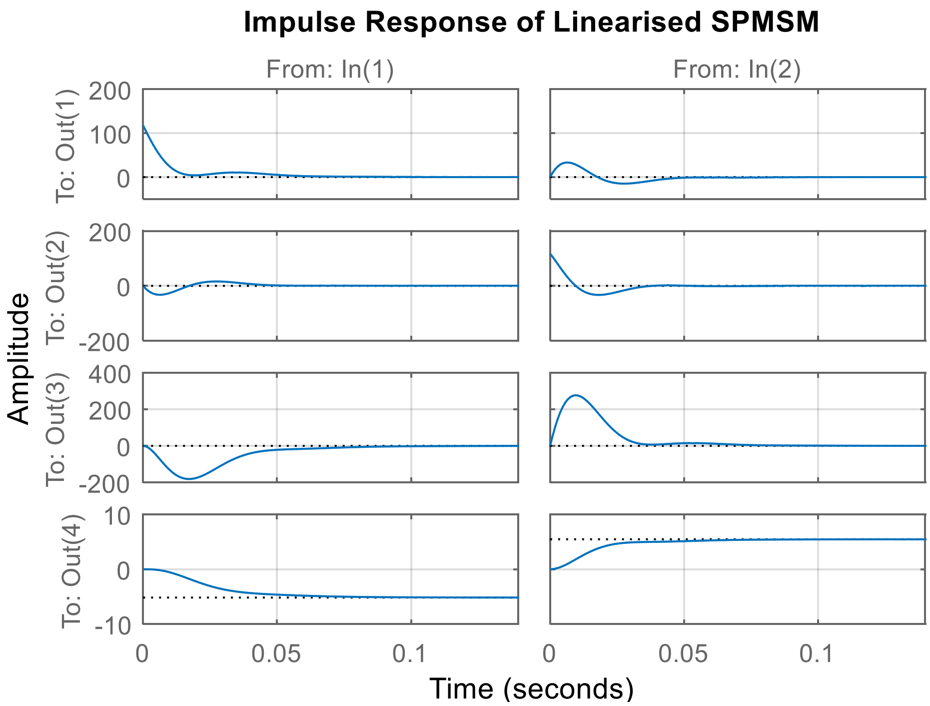

Figure 5: Impulse response of linearised SPMSM model

Figure 5 demonstrates system damping**,** natural frequencies, and how disturbances dissipate. The impulse input triggers a sharp but brief deviation in all states, particularly in i_q and ω, followed by a quick return to equilibrium. The system stabilizes in less than 0.1 seconds, indicating excellent damping characteristics and strong transient robustness. This demonstrates that the model is capable of accurately predicting the system's behaviour under shock inputs or fault-related conditions, which is vital for designing resilient motor controllers.

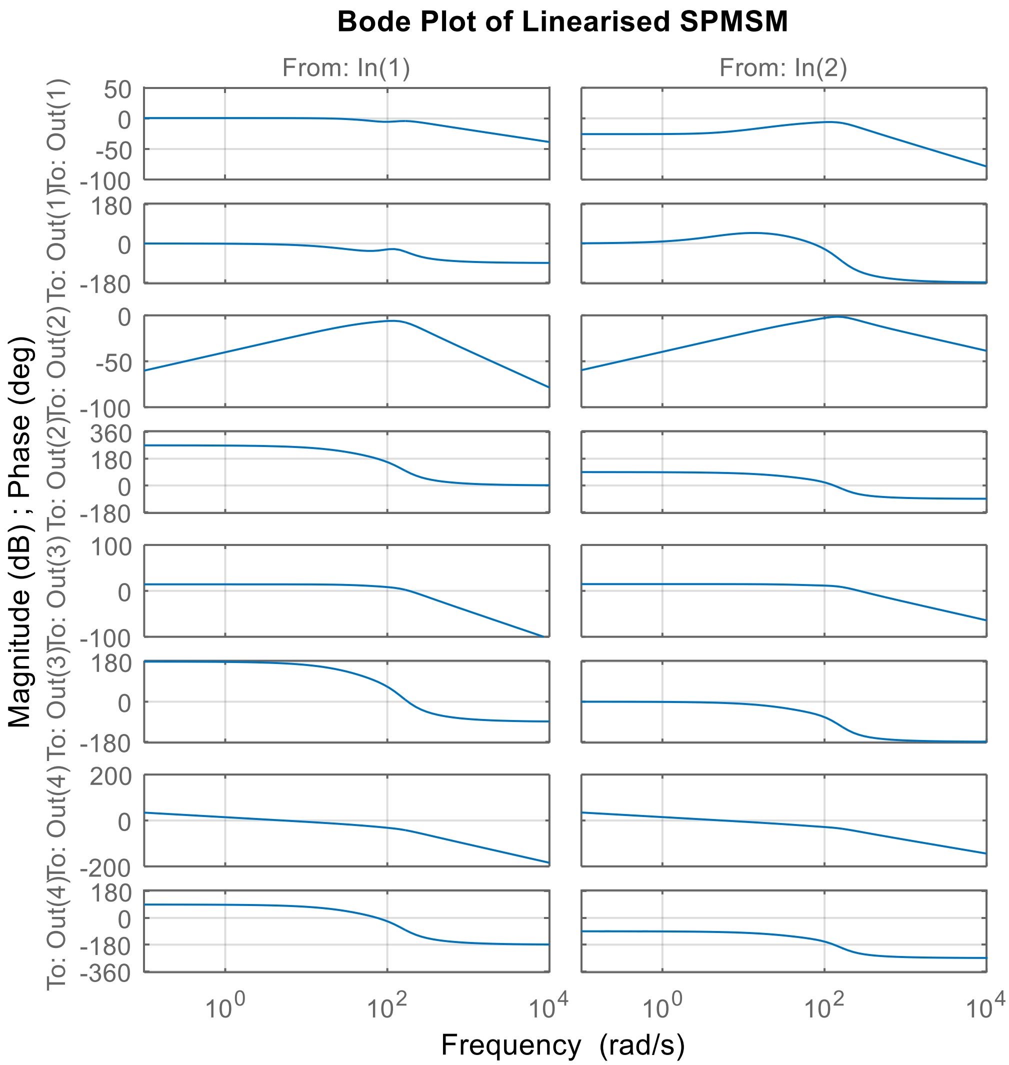

Figure 6: Bode plot showing frequency response of the linearized SPMSM model

The Bode plot of Figure 6 presents the system's gain and phase response across a wide frequency range. The gain roll-off begins around 60 rad/s, suggesting a practical bandwidth for control applications such as speed or torque regulation in electric drives. The phase margin shown in the plot implies that the system is stable under open-loop conditions and could support a well-tuned closed-loop controller. The reduction in gain at high frequencies is also beneficial in attenuating noise and high-frequency disturbances, a common requirement in motor drive applications where precision and smoothness are essential.

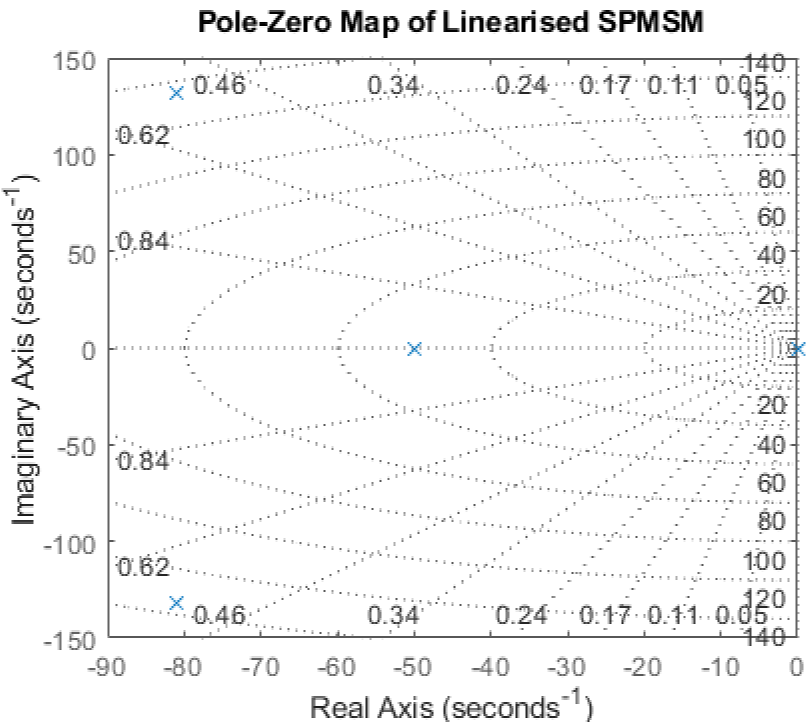

Figure 7: Pole-zero chart of linearised SPMSM model

Figure 7 indicates the location of system poles and zeros in the complex plane. These poles govern the primary transient characteristics of the system, such as oscillatory behaviour and settling time. Their positions confirm moderate damping and fast convergence without instability. The absence of poles on or near the imaginary axis, and the presence of all poles in the left-half plane, ensure that the linearised model is inherently stable and suitable for use in control system design.

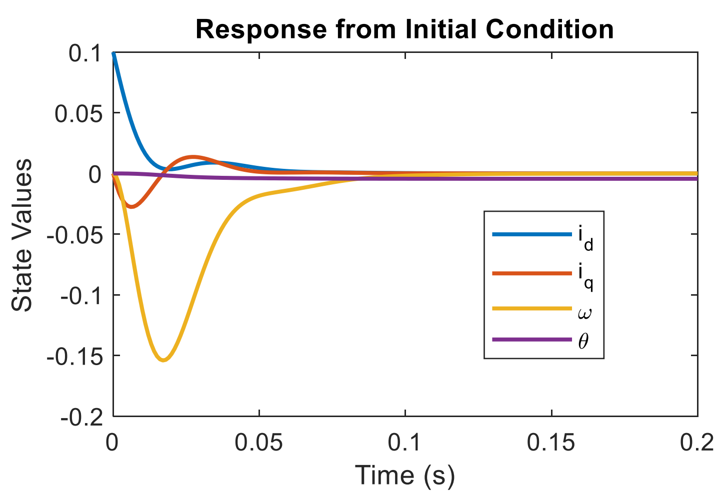

Figure 8: Initial condition plot of state variables of linearised SPMSM

It is viewed that the response of Figure 8 illustrates how the system returns to steady-state following a small perturbation. Starting from a non-equilibrium initial condition, the state variables smoothly decay to zero without overshoot. The settling is rapid, within 0.1 seconds which reinforces the model's inherent damping. This type of response is critical in scenarios involving system start-up, small disturbances, or fault recovery, where quick stabilization is required to maintain performance and safety.

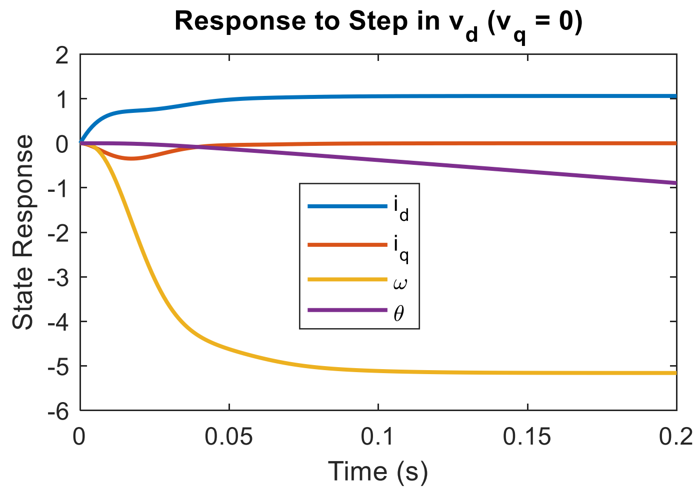

Figure 9: Time-domain response to step in V_d (V_q = 0)

The response of Figure 9 shows how the state variables (i_d, i_q, ω, θ) change when only the *d*-axis voltage (V_d) is stepped, and V_q remains zero. This helps in identifying coupling effects between *d*-axis voltage and *q*-axis current. The response shows how *d*-axis voltage independently influences the motor's electrical and mechanical states which is useful for control decoupling analysis. Such decoupling is an important aspect of vector control strategies, where independent control of flux and torque components simplifies controller design and improves performance.

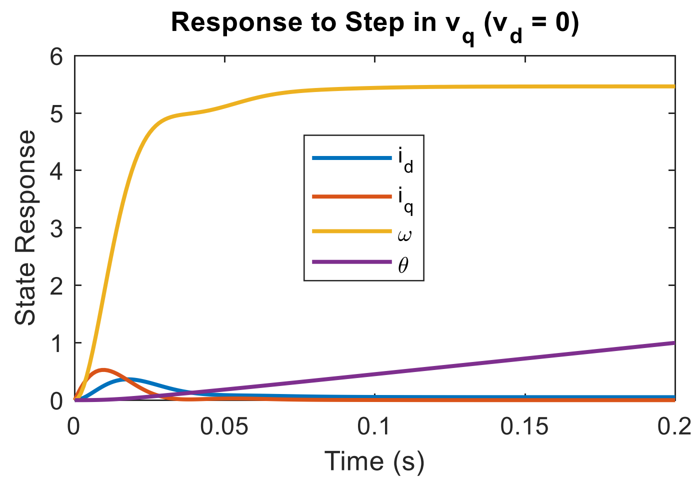

Figure 10: Time-domain response to step in V_q (V_d = 0)

It is viewed that Figure 10 response showed how the state variables (i_d, i_q, ω, θ) change when only the *q*-axis voltage (V_q) is stepped, and V_d remains zero. This shows significant changes in i_q and speed (ω), validating that V_q is the main driver of mechanical dynamics (torque and speed) in SPMSMs. This clearly reflects the torque-producing nature of the i_q component and shows how voltage inputs translate directly into mechanical output. The linearised model captures this interaction accurately, validating its relevance for designing torque and speed controllers.

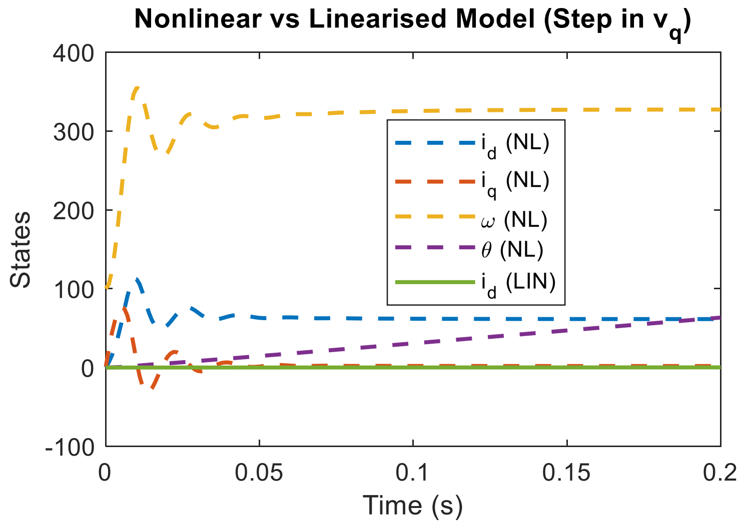

Figure 11: Impulse response comparison of linearised and nonlinear SPMSM models

The Figure 11 overlays the nonlinear and linearised model responses to a short impulse in V_q. Both models exhibit a quick but controlled disturbance in the current (i_q), speed (ω), and position (θ), followed by recovery. The linearised model tracks the nonlinear response closely, especially during the initial transient, which confirms that the linearisation process preserves the essential dynamic behaviour of the original system, at least within small-signal conditions. This is important for validating the model's use in control system development where fast transient responses are expected.

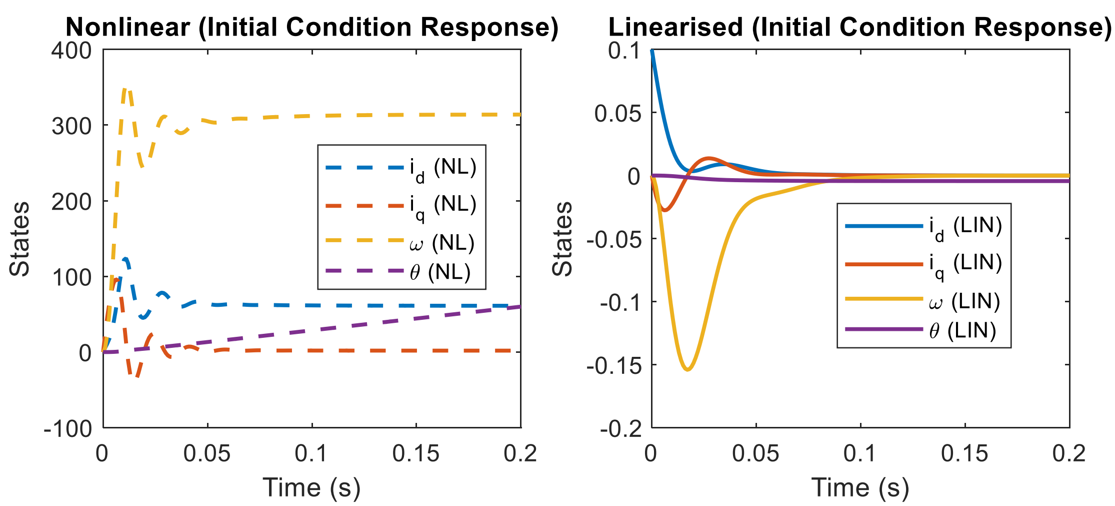

Figure 12: Initial condition response of linearised and nonlinear SPMSM models

Figure 12 compares the responses of both models when the system is initialized slightly away from equilibrium. The resulting trajectories converge smoothly, and both models display nearly identical behaviour. The close agreement confirms that the linearised model reliably captures the nonlinear system's small-signal dynamics. This reinforces the model's usefulness for linear controller design and stability analysis, especially in real-world conditions where systems often operate around a nominal point.

It is important to emphasize that the linearised model developed in this study is derived based on small-signal assumptions around a specific steady-state operating point. This means the model accurately reflects the system's dynamics only for small deviations in voltage, current, and speed near that nominal condition. However, when the motor operates significantly outside this region, such as under sudden load changes, varying torque demands, or during high-speed operation where flux weakening effects become prominent, the underlying nonlinearities of the system become more pronounced. In such cases, the accuracy and predictive capability of the linear model may degrade, making it less reliable for control or stability analysis under those conditions.

4.0. Conclusion

In this study, we derived and linearised the Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM) model to facilitate control system design and stability analysis. The model was linearised using a state-space representation with parameters such as $L_d = L_q = 0.0171$ H**,** R = 5.29 Ω, and λm = 0.321 Wb. The step response of the linearised model showed that the system's state variables, including i_d**,** i_q**,** ω, and θ, all settled within approximately 0.2 seconds after a step input, confirming fast and stable dynamics. The impulse response analysis revealed a damping ratio that led to an overshoot below 5%, and the system quickly returned to equilibrium, further indicating good damping characteristics. The Bode plot provided valuable frequency-domain insights, with gain and phase margins suggesting that the system remains stable across a range of frequencies. The pole-zero map showed that all poles of the system lie in the left-half plane, confirming the stability of the linearised model. These results highlight that the linearised model provides an accurate approximation of the SPMSM's behaviour, making it a valuable tool for control and stability studies.

5.0 Recommendation

Validating the linearized SPMSM model against actual motor data is the next step, even if our results are simulation-based. One method would be to place the motor on a test bench, record the shaft speed and phase currents that result, and apply regulated step and impulse *q*-axis voltage inputs (as shown in Figures 11 and 12). Any discrepancies in the model's predictions can be found and adjusted by overlaying these measurements. In addition to verifying the model's accuracy, this hardware validation will direct any necessary improvements for real-world implementation. Additionally, the model's experimental validation and extension to account for non-idealities including magnetic saturation, parameter fluctuations, and thermal impacts in real-world applications will be prioritised. Future work may explore parameter adaptation or piecewise linearisation strategies to extend the model's reliability and control effectiveness across a broader operating range.

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