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Control of a Five-Phase Induction Motor Drive with High-Torque Density and Voltage Overmodulation

Luca Vancini, Michele Mengoni, Gabriele Rizzoli, Luca Zarri, Angelo Tani

Dept. of Electrical, Electronic and Information Engineering "G. Marconi"
University of Bologna
Bologna, Italy

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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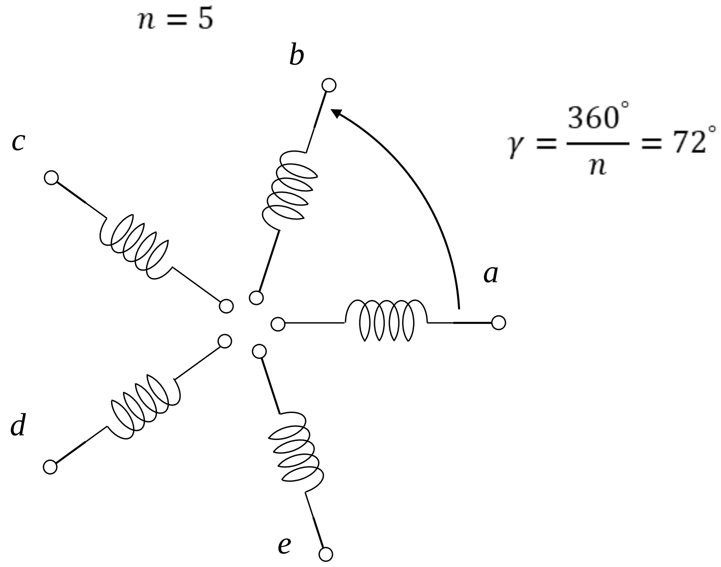
MULTIPHASE MACHINES

Multiphase drives are based on inverters and machines with more than three phases.

Nowadays, there is an increasing interest in multiphase motor drives for medium and high-power applications, such as naval and railway propulsion systems.

Compared to three-phase machines, multiphase motors have some advantages, such as:

- ❑ reducing the current per phase
- ❑ increasing the level of fault tolerance
- ❑ controlling high-order spatial harmonics of the magnetic field.



ABSTRACT

- The torque of a multiphase machine increases if the 3rd-order spatial harmonic of the magnetic field in the air gap is correctly synchronized with the fundamental one (high-torque density control).
- However, as the speed increases, the voltage required to sustain the harmonic component of the field in the air gap rises. Just below the base speed, the control strategy for high-torque density should be abandoned.
- This paper shows that, above the base speed, the performance can improve further if a voltage harmonic component is used to extend the modulation range of the fundamental voltage. In the field weakening region, an increase in the magnitude of the stator voltage vector significantly improves the motor power (by 40%).
- Experimental tests with a five-phase induction motor drive confirm the feasibility and effectiveness of the developed control scheme.

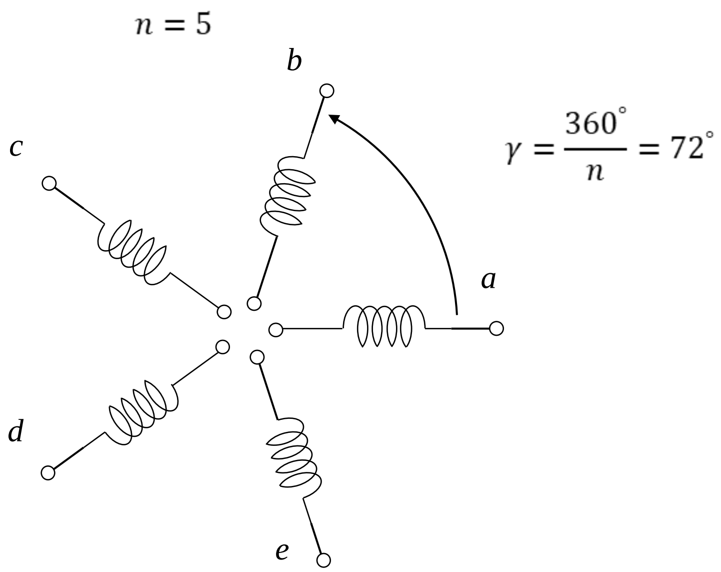
OUTLINE

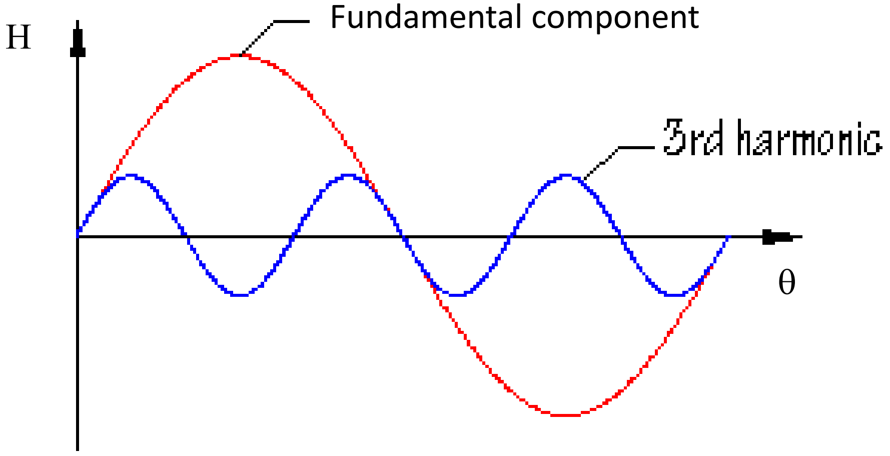
- Equations of a five-phase induction machine.
- Fundamentals of high-torque density multiphase drives.
- Fundamentals of overmodulation for multiphase drives.
- Combined control strategy over the entire speed range.
- Control scheme.
- Experimental tests.
- Conclusion.

MODEL OF A FIVE-PHASE INDUCTION MACHINE

- Let's consider a five-phase induction machine. The stator and rotor windings are assumed symmetrically distributed in the slots and star-connected.

- The behavior of this machine can be described with a mathematical model that considers the fundamental and the 3rd-order spatial harmonics of the air-gap magnetic field.





VECTOR SPACE DECOMPOSITION

Given set of five real variables $x_1, x_2, \ldots, x_5$, the Vector Space Decomposition (VSD) is a transformation that generates a new set of variables and generalizes the concept of space vector.

Space Vectors

$$\bar{x}_\rho = \frac{2}{5}\sum_{k=1}^{5} x_k \bar{\alpha}_k^\rho \qquad (\rho = 1,3)$$

Zero-Sequence Component

$$x_0 = \frac{1}{5}\sum_{k=1}^{5} x_k$$

where

$$\bar{\alpha}_k = e^{j\frac{2\pi}{5}(k-1)}$$

VECTOR SPACE DECOMPOSITION

Given $x_0, \bar{x}_1$ and $\bar{x}_3$, the original set of variables $x_1, x_2, \ldots, x_5$ can be found again through the following inverse relationships:

$$x_k = x_0 + \bar{x}_1 \cdot \bar{\alpha}_k + \bar{x}_3 \cdot \bar{\alpha}_k^3 \qquad (k = 1,2, \ldots, 5)$$

where the symbol "$\cdot$" is the dot product between two complex numbers, defined as the real part of product of the first number and complex conjugate of the second number.

The vector space decomposition is essential to develop the model of a five-phase machine.

MODEL OF A FIVE-PHASE INDUCTION MACHINE

The interaction of the stator and the rotor through the fundamental spatial component of the magnetic field leads to the following set of equations, which is equal to that of a three-phase motor.

$$\bar{v}_{S1} = R_S \bar{\imath}_{S1} + j\omega_1 \bar{\varphi}_{S1} + \frac{d\bar{\varphi}_{S1}}{dt}$$

$$0 = R_{R1} \bar{\imath}_{R1} + j(\omega_1 - \omega_m) \bar{\varphi}_{R1} + \frac{d\bar{\varphi}_{R1}}{dt}$$

$$\bar{\varphi}_{S1} = L_{S1} \bar{\imath}_{S1} + M_1 \bar{\imath}_{R1}$$

$$\bar{\varphi}_{R1} = M_1 \bar{\imath}_{S1} + L_{R1} \bar{\imath}_{R1}$$

Subspace d_1-q_1

where $\bar{\imath}_{S1}$ and $\bar{\imath}_{R1}$ are the stator and rotor current vectors, $\bar{\varphi}_{S1}$ and $\bar{\varphi}_{R1}$ are the stator and rotor flux vectors, ω_m is the electrical speed of the rotor and ω_1 is the angular speed of the reference frame $d_1 - q_1$.

MODEL OF A FIVE-PHASE INDUCTION MACHINE

The interaction of the stator and the rotor through the 3rd-order spatial harmonic of the magnetic field leads to another set of equations, which represents a three-phase motor rotating at speed $3\omega_m$.

$$\bar{v}_{S3} = R_S \bar{i}_{S3} + j\omega_3 \bar{\varphi}_{S3} + \frac{d\bar{\varphi}_{S3}}{dt}$$

$$0 = R_{R1} \bar{i}_{R1} + j(\omega_1 - 3\omega_m)\bar{\varphi}_{R3} + \frac{d\bar{\varphi}_{R3}}{dt}$$

$$\bar{\varphi}_{S3} = L_{S3} \bar{i}_{S3} + M_3 \bar{i}_{R3}$$

$$\bar{\varphi}_{R3} = M_3 \bar{i}_{S3} + L_{R3} \bar{i}_{R3}$$

Subspace d_3-q_3

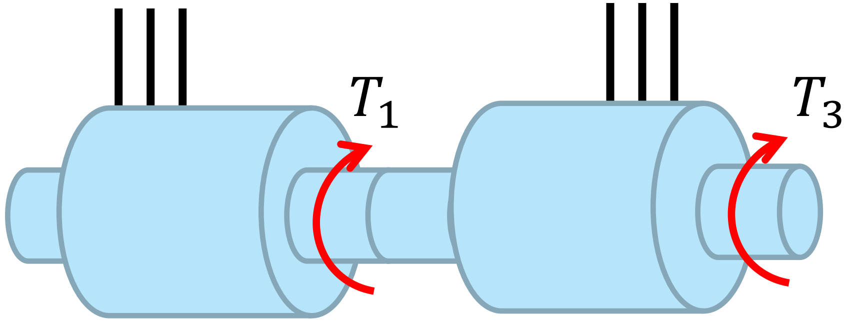
where $\bar{i}_{S3}$ and $\bar{i}_{R3}$ are the stator and rotor current vectors, $\bar{\varphi}_{S3}$ and $\bar{\varphi}_{R3}$ are the stator and rotor flux vectors, and ω_3 is the angular speed of the reference frame $d_3 - q_3$.

MODEL OF A FIVE-PHASE INDUCTION MACHINE

The electromagnetic torque T can be written as a sum of two terms, T_1 and T_3, which correspond to the contributions of the two virtual three-phase motors.

Virtual motor
(p pairs of poles)

Fundamental
spatial component of the field



Virtual motor
($3p$ pairs of poles)

3rd-order
spatial component of the field

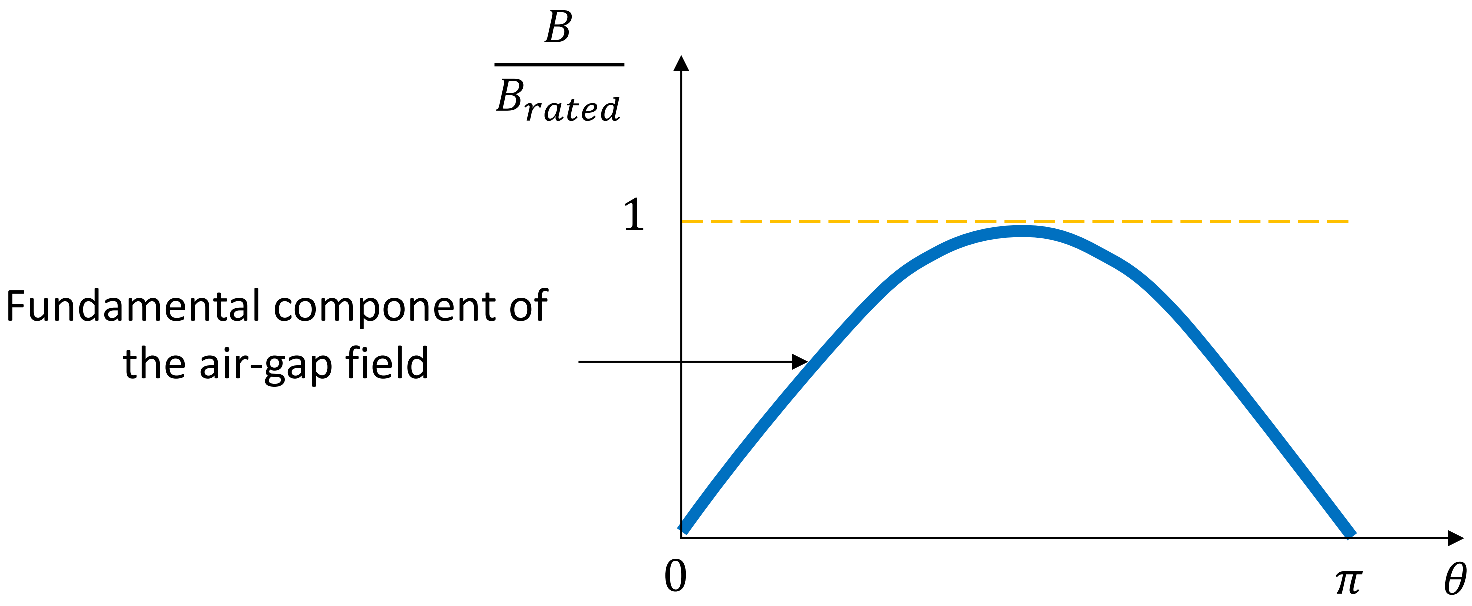
$$T_1 = \frac{5}{2} p \, \bar{\imath}_{S1} \cdot j\bar{\varphi}_{S1} \qquad T_3 = \frac{5}{2}(3p) \, \bar{\imath}_{S3} \cdot j\bar{\varphi}_{S3}$$

where p is the number of pairs of poles.

A five-phase machine is formally equivalent to two machines, respectively with p and $3p$ pairs of poles, coupled to the same shaft.

HIGH-TORQUE DENSITY

In electric machines, the fundamental component of the air-gap field is sinusoidal, and its rated amplitude is constrained by iron saturation and losses.



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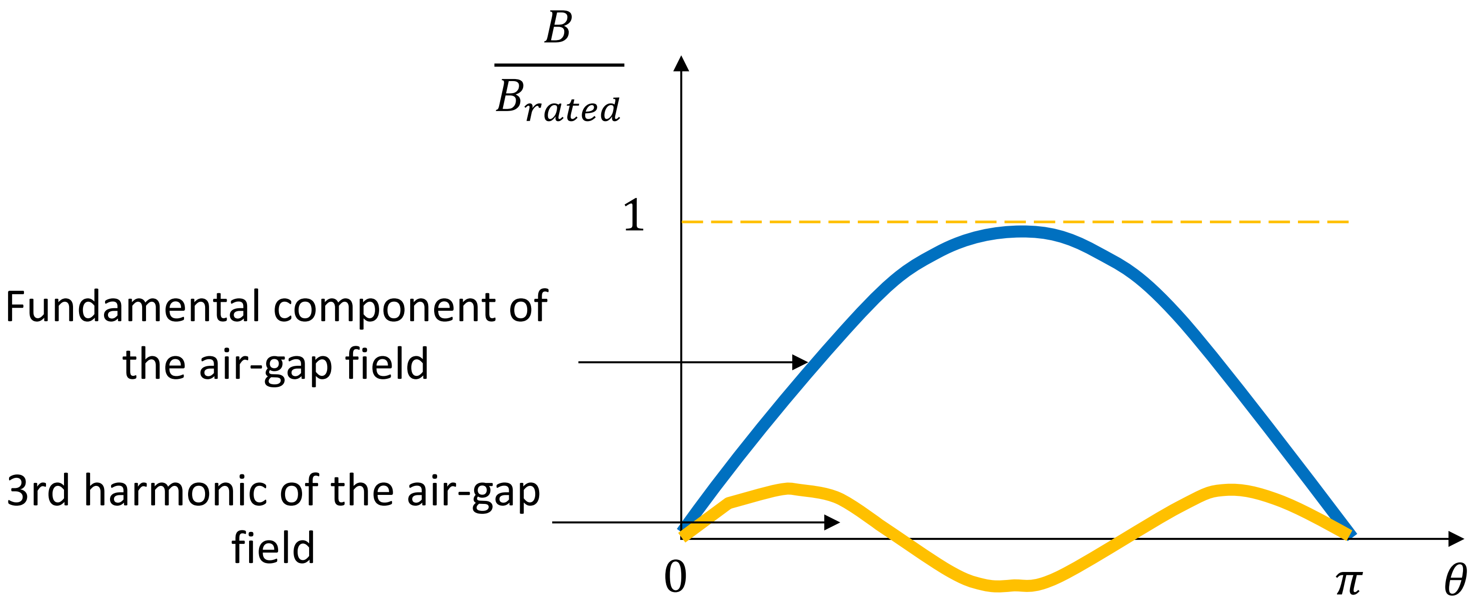

If a suitable 3rd-order spatial harmonic component is added to the air-gap magnetic field and synchronized with the fundamental component, the peak value of the resulting field decreases by roughly 15%.

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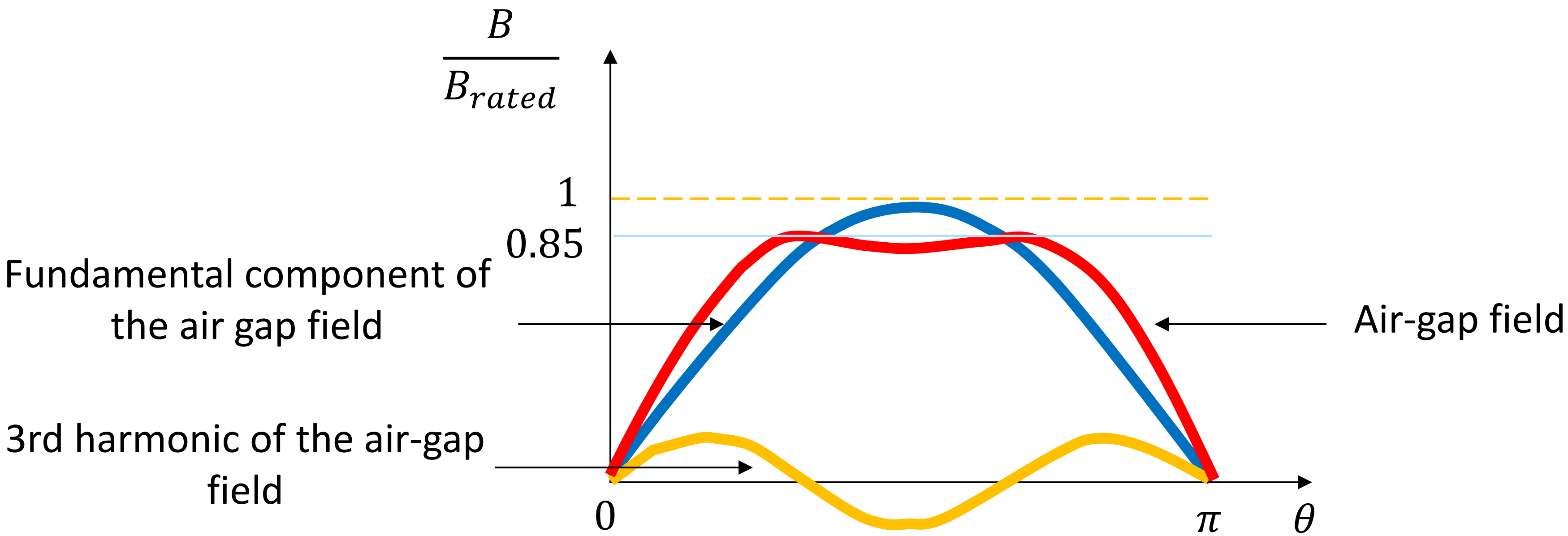
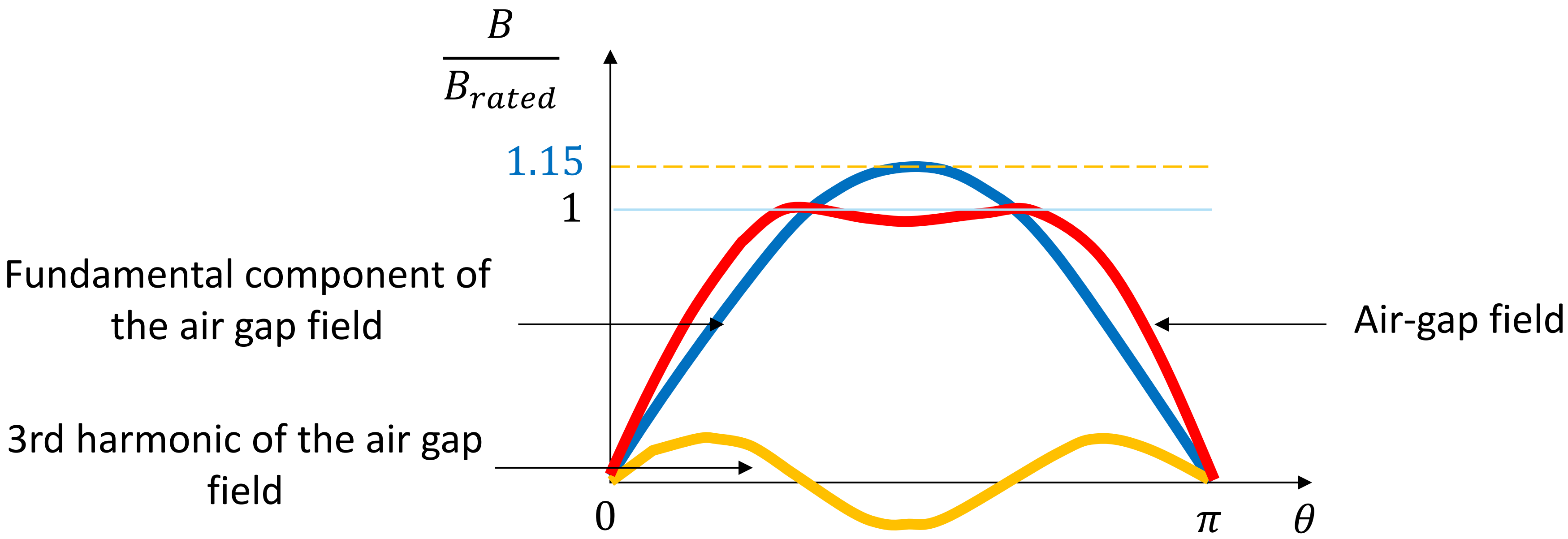


If a suitable 3rd-order spatial harmonic component is added to the air-gap magnetic field and synchronized with the fundamental component, the peak value of the resulting field decreases by roughly 15%.

HIGH-TORQUE DENSITY

In conclusion, the amplitude of the fundamental component can increase up to 115% without overcoming the rated peak value of the flux density.



An increase in the amplitude of the fundamental component of the air-gap field generates a higher torque T_1 without increasing the RMS value of the stator current.

HIGH-TORQUE DENSITY

Let's suppose that the d-axes of reference frames d_1-q_1 and d_3-q_3 have the same directions of rotor flux vectors $\bar{\varphi}_{R1}$ and $\bar{\varphi}_{R3}$ (rotor flux-oriented control).

Since the third spatial harmonic of the magnetic field *must move synchronously* with the fundamental component, its electric angular speed is triple that of the fundamental wave.

$$\omega_3 = 3\omega_1$$

Approximately, if the leakage flux is neglected, the conditions for high-torque density control are met when the following relationships between the space vectors $\bar{\imath}_{S1}$ and $\bar{\imath}_{S3}$ hold:

$$i_{S1d} = \frac{2}{\sqrt{3}} i_{Sd,rated}$$

$$i_{S3d} = \frac{1}{2} i_{S1d}$$

$$i_{S3q} = 3 \frac{\tau_{R3}}{\tau_{R1}} \frac{i_{S3d}}{i_{S1d}} i_{S1q}$$

CURRENT AND VOLTAGE CONSTRAINTS

The motor operation is limited by the inverter current rating or the machine thermal rating, $I_{S,max}$.

$$i_{S1}^2 + i_{S3}^2 \leq I_{S,max}^2$$

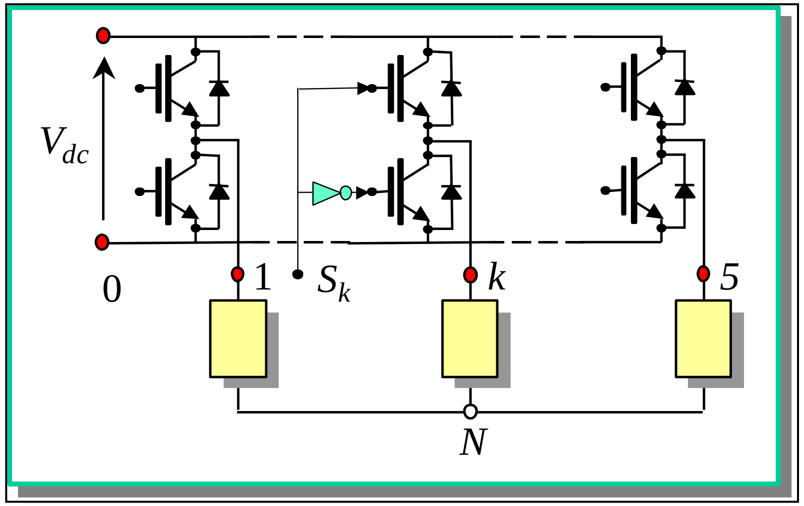
Also, the voltage generated by the inverter is constrained by the available DC-link voltage.

The high-torque density control can be used only if the voltage required to generate the air-gap field is sufficient. When the speed increases, the voltage constraint of the inverter becomes the most binding one and the current injection is not feasible because the available voltage is just enough to sustain only the fundamental component of the field.

CURRENT AND VOLTAGE CONSTRAINTS

The schematic of a five-phase inverter connected to a passive load is shown below.

The signals s_1, …, s_5 are the switching commands and can have only two values, 0 and 1 (1 means that the upper switch is enabled, 0 means that the lower switch is enabled).



The control system calculates the reference voltage vectors $\bar{v}_{S1,ref}$ and $\bar{v}_{S3,ref}$. The duty-cycles $m_1, \dots, m_5$ of the inverter legs can be calculated as follows:

$$m_k = \frac{1}{E_{DC}} \left(\bar{v}_{S1,ref} \cdot \bar{\alpha}_k + \bar{v}_{S3,ref} \cdot \bar{\alpha}_k^3 + v_{0,ref} \right) \quad k = 1,2, \dots, 5$$

The zero-sequence voltage $v_{0,ref}$ is a degree of freedom that the designer can choose to improve the performance of the modulation strategy.

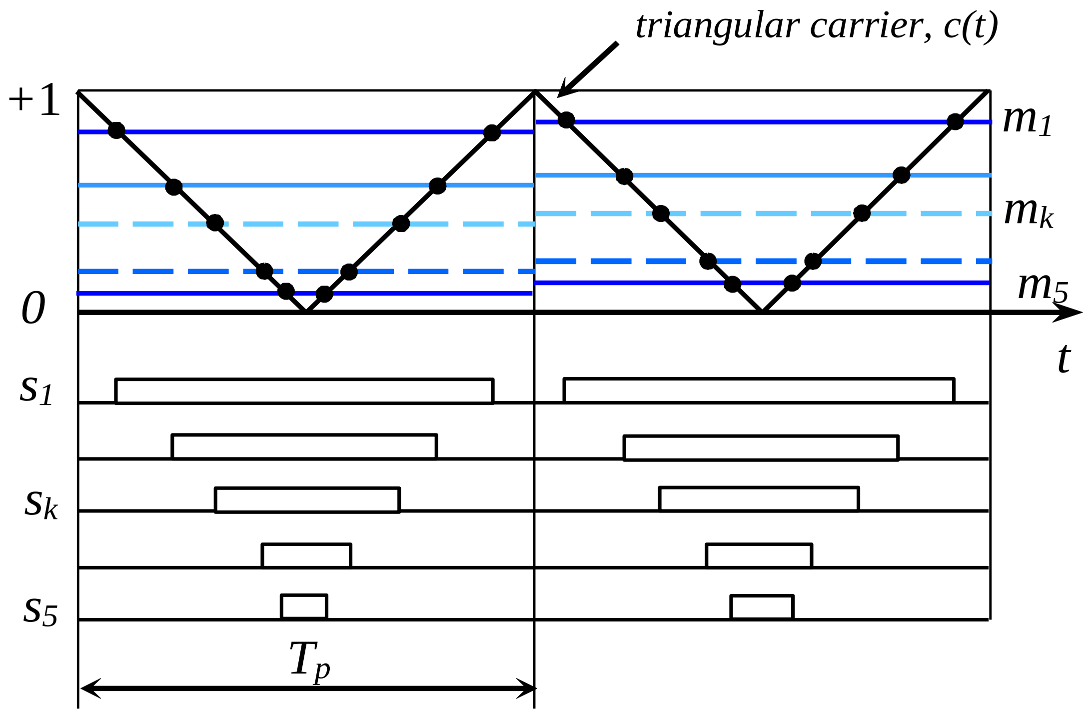
CURRENT AND VOLTAGE CONSTRAINTS

❑The inverter command signals s_k (k = 1, 2, ... , 5) are generated by comparing a triangular carrier signal varying in the range [0, 1] with five regularly-sampled (i.e., constant over a switching period) modulating signals, obtained from m_k (k = 1, 2, ... , 5).

❑The modulating signals must satisfy the following constraints:

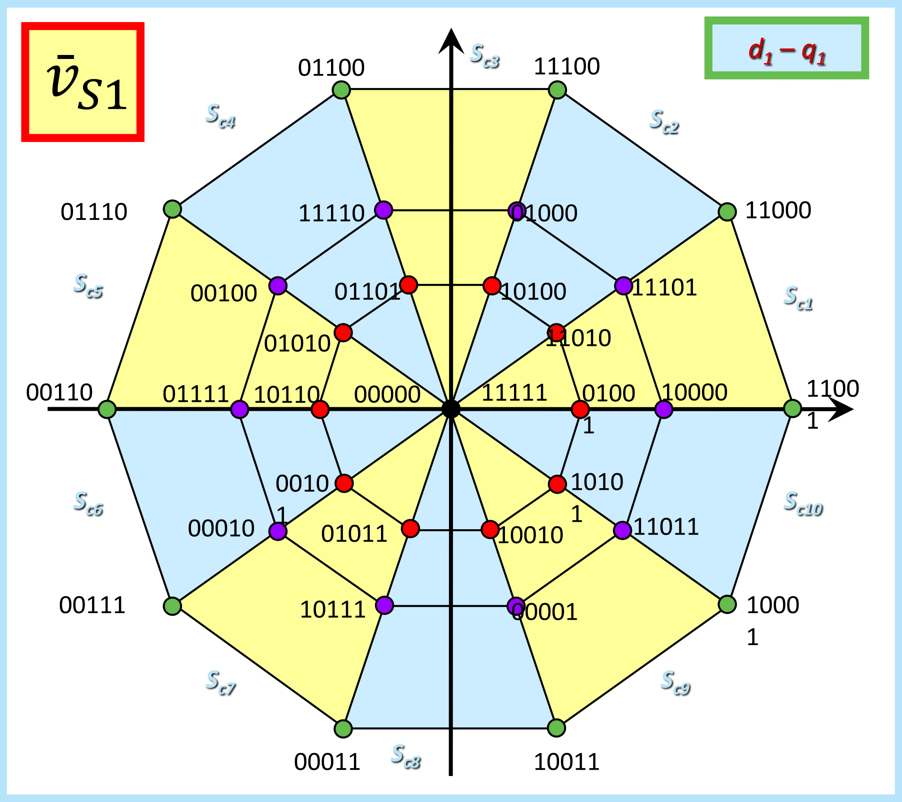
$$m_k \in [0,1] \quad k = 1,2,\dots,5$$

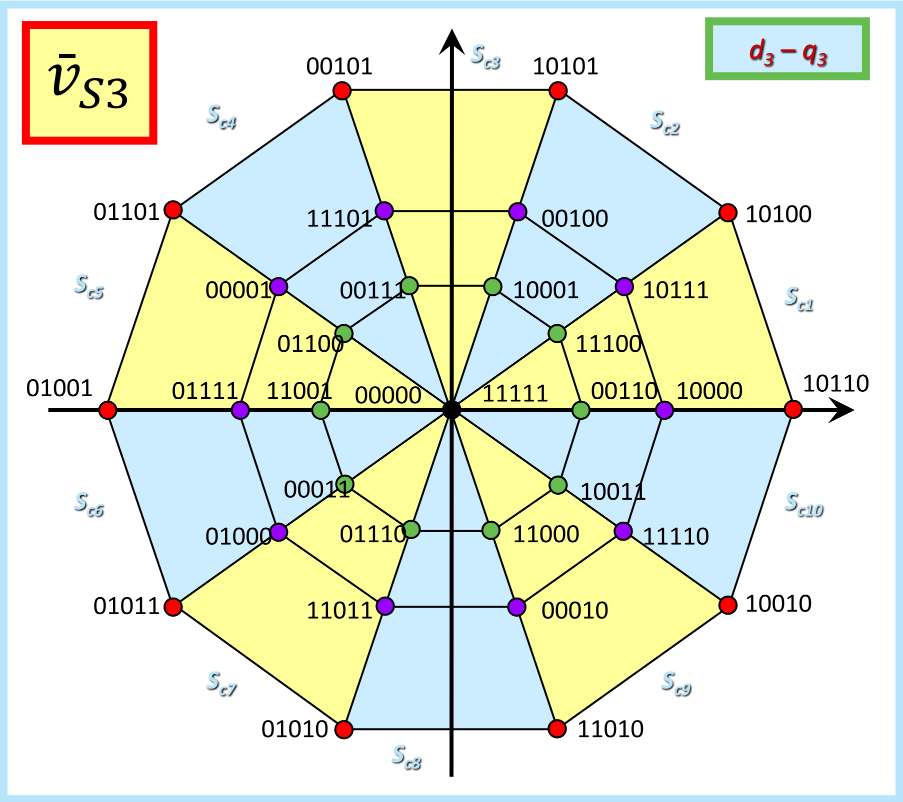
We assume that the adopted modulation strategy can fully exploit the dc-link voltage and generate all the admissible combinations of voltage vectors in the two subspaces.



CURRENT AND VOLTAGE CONSTRAINTS

The reference voltage vectors $\bar{v}_{S1,ref}$ and $\bar{v}_{S3,ref}$ must remain inside two decagonal regions. However, not all combinations of $\bar{v}_{S1,ref}$ and $\bar{v}_{S3,ref}$ are admissible.



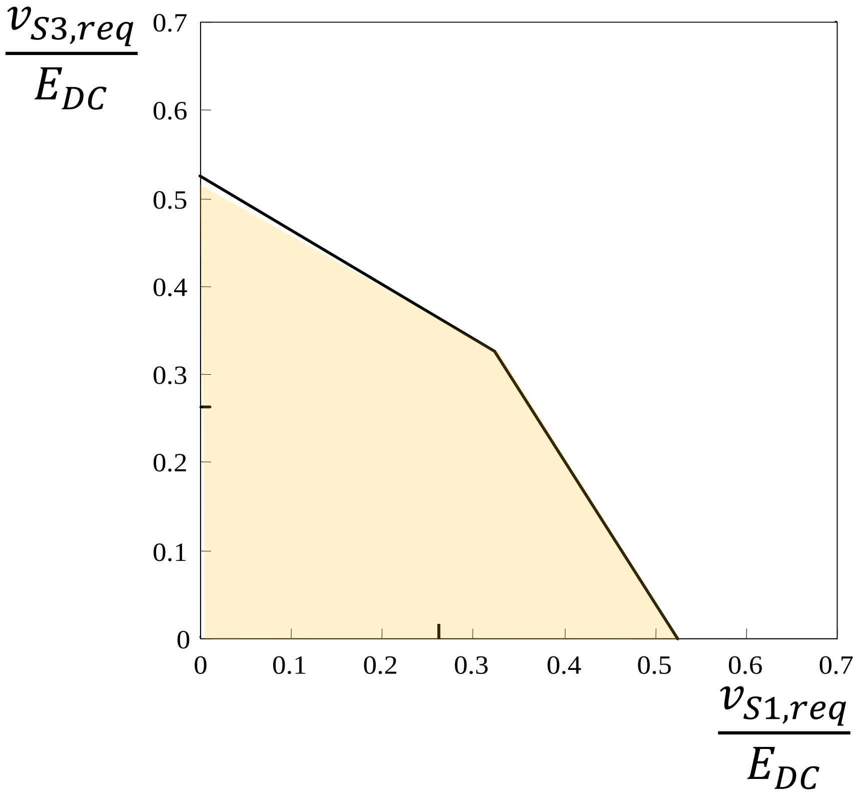


CURRENT AND VOLTAGE CONSTRAINTS

It is possible to find a range of amplitudes where the reference voltages $\bar{v}_{S1,ref}$ and $\bar{v}_{S3,ref}$ are independent (linear modulation range).

$$\begin{cases} |\bar{v}_{S1,req}| cos\left(\frac{\pi}{10}\right) + |\bar{v}_{S3,req}| cos\left(\frac{3\pi}{5}\right) \leq E_{DC} \\ |\bar{v}_{S1,req}| cos\left(\frac{3\pi}{10}\right) + |\bar{v}_{S3,req}| cos\left(\frac{\pi}{10}\right) \leq E_{DC} \end{cases}$$

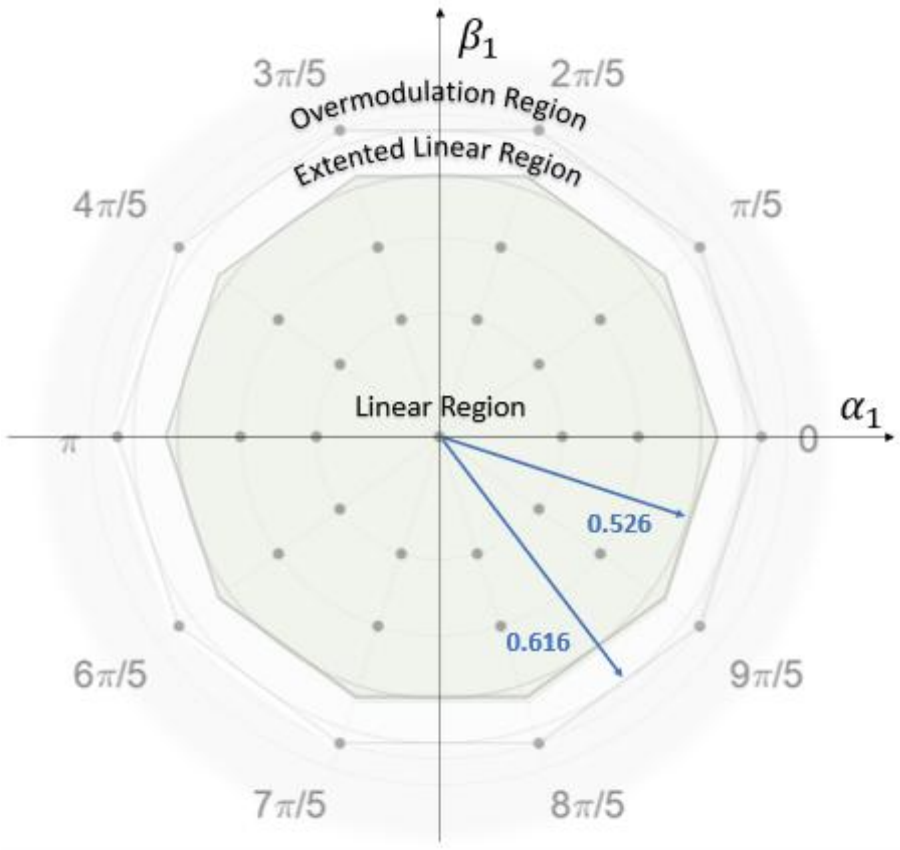
At steady state, the maximum voltage $0.526 E_{DC}$.



CURRENT AND VOLTAGE CONSTRAINTS

In the field-weakening region, the current injection aiming to generate the third-harmonic component of the air-gap field has a detrimental effect, and the available voltage should be used to support only the fundamental component of the magnetic field.

Although $\bar{v}_{S3,ref}$ should not be used for current injection, it can be used to extend the admissible range of $\bar{v}_{S1,ref}$ (extended linear region).

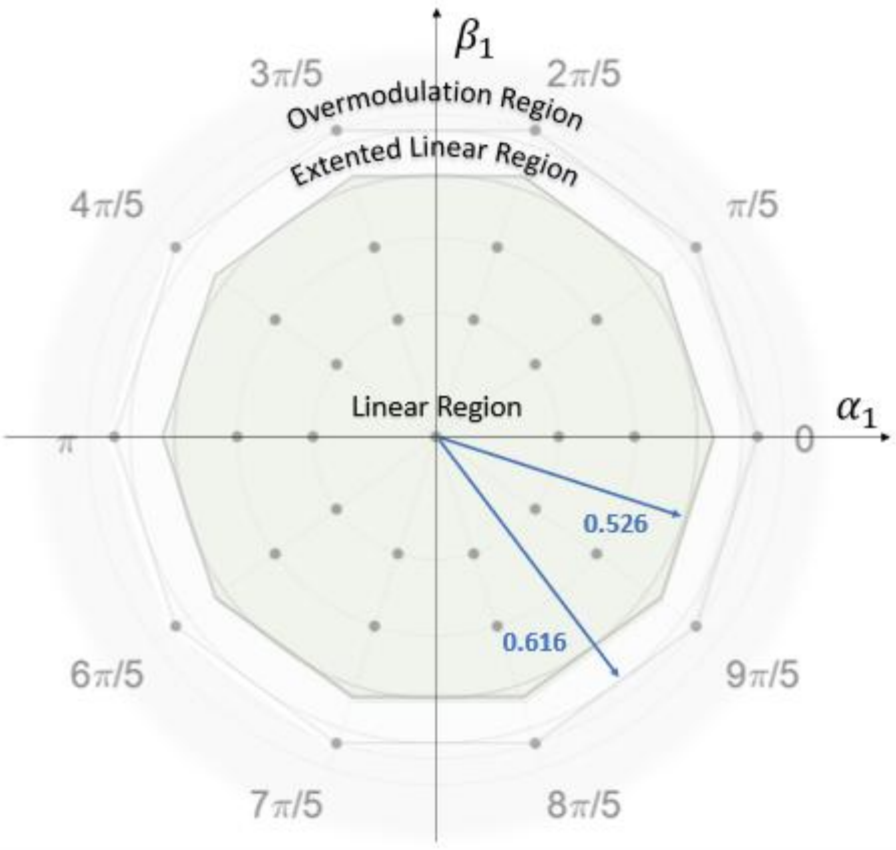


CURRENT AND VOLTAGE CONSTRAINTS

The key idea is that the voltage vector $\bar{v}_{S3,ref}$ and the zero-sequence $v_{0,ref}$ can be specifically chosen to maintain the duty-cycles in the range [0,1] even for magnitudes of $\bar{v}_{S1,ref}$ greater than $0.526E_{DC}$.

$$m_k = \frac{1}{E_{DC}}\left(\bar{v}_{S1,ref} \cdot \bar{\alpha}_k + \bar{v}_{S3,ref} \cdot \bar{\alpha}_k^3 + v_{0,ref}\right) \in [0,1]$$

This technique allows reaching a maximum modulation index of 0.616 in the extended linear modulation. Above this threshold, the inverter enters the conventional overmodulation mode, and the desired value of $\bar{v}_{S1}$ cannot be obtained anymore.



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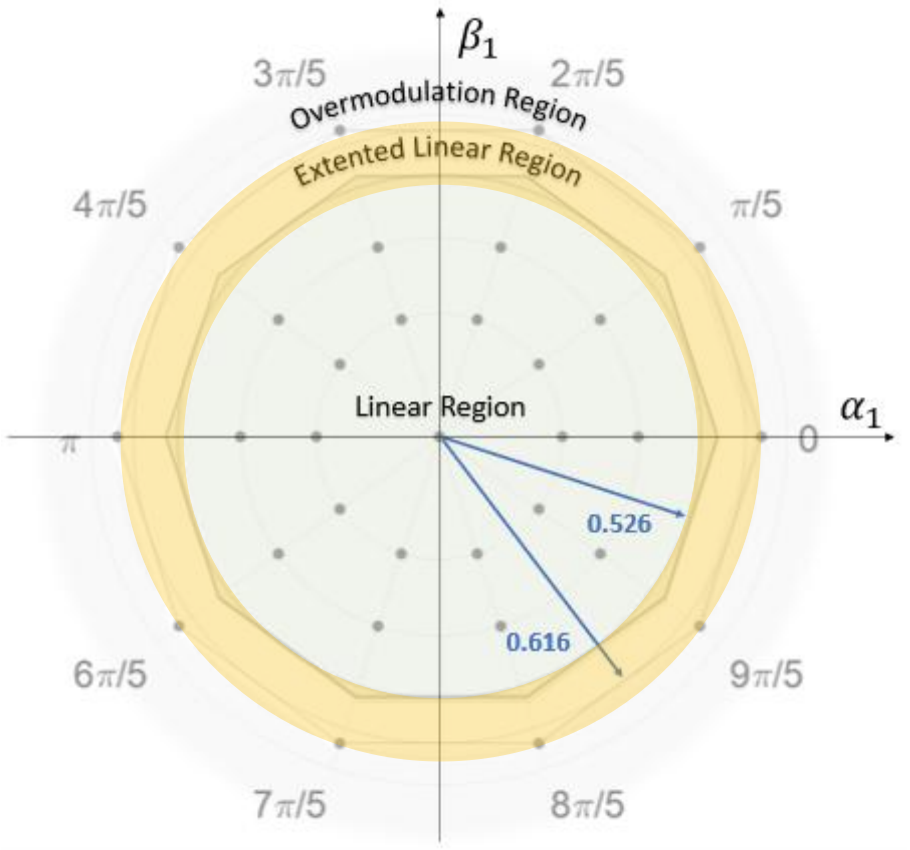

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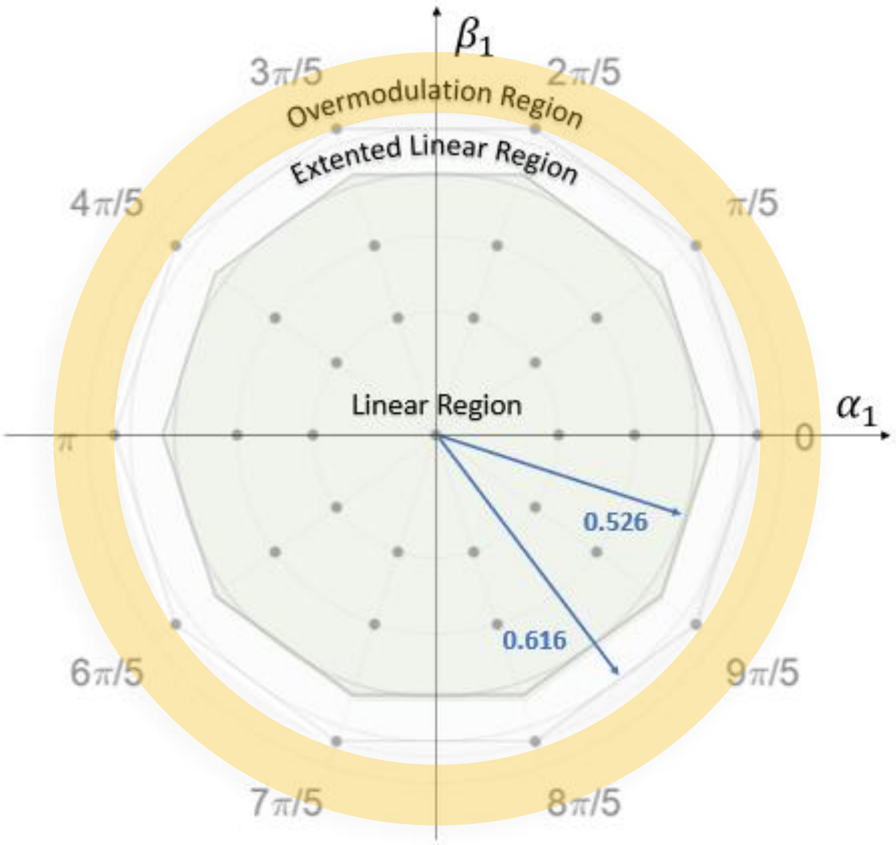
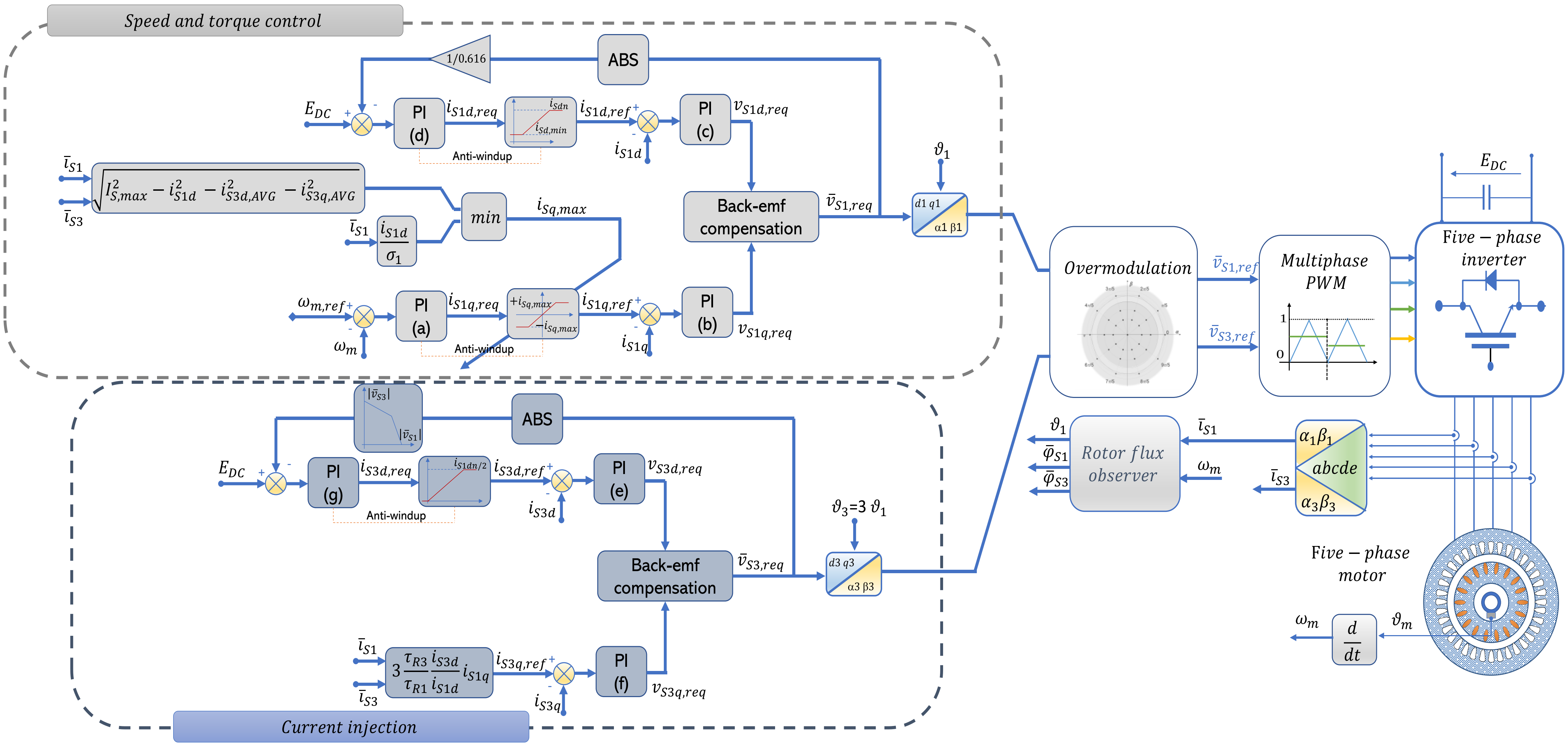


CONTROL SCHEME



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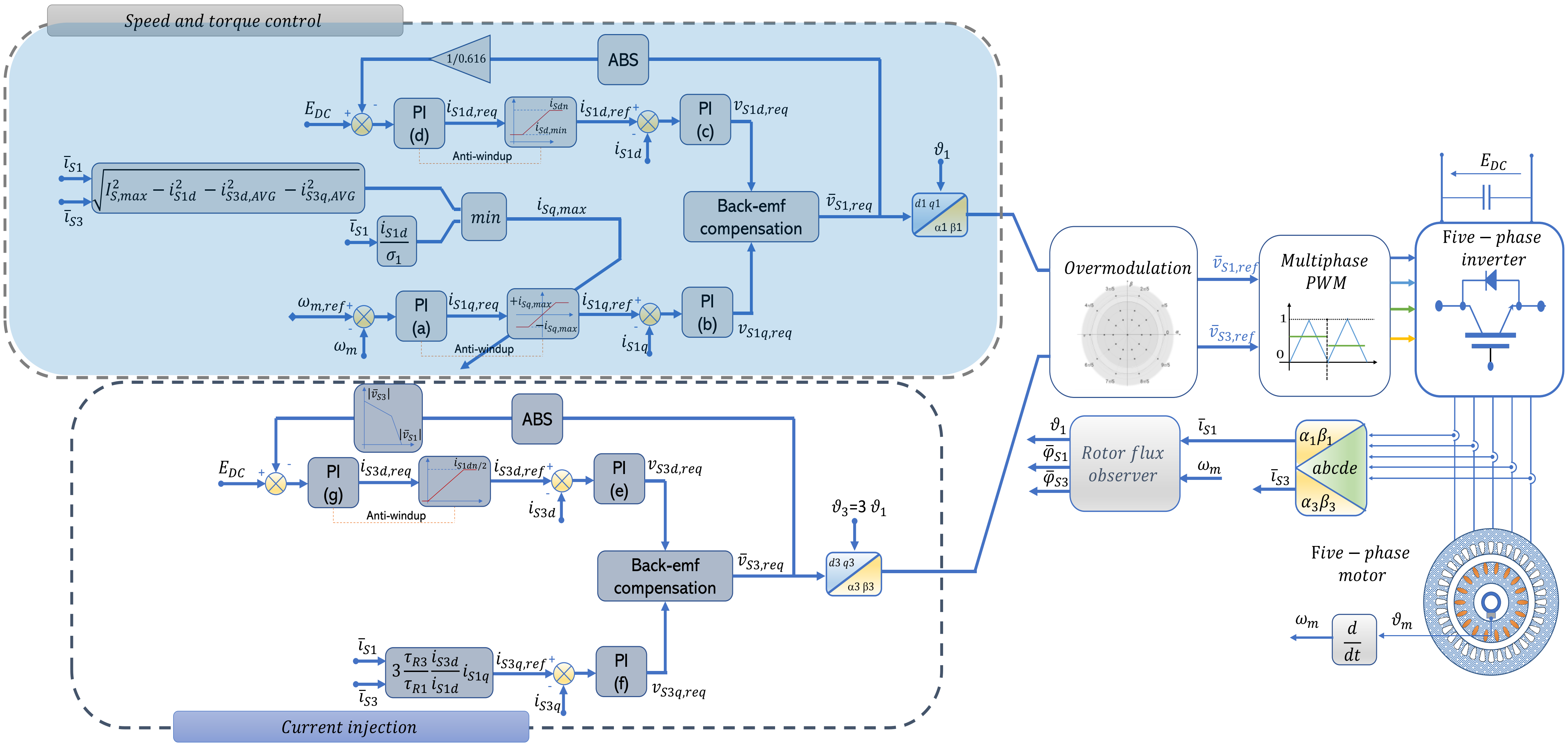

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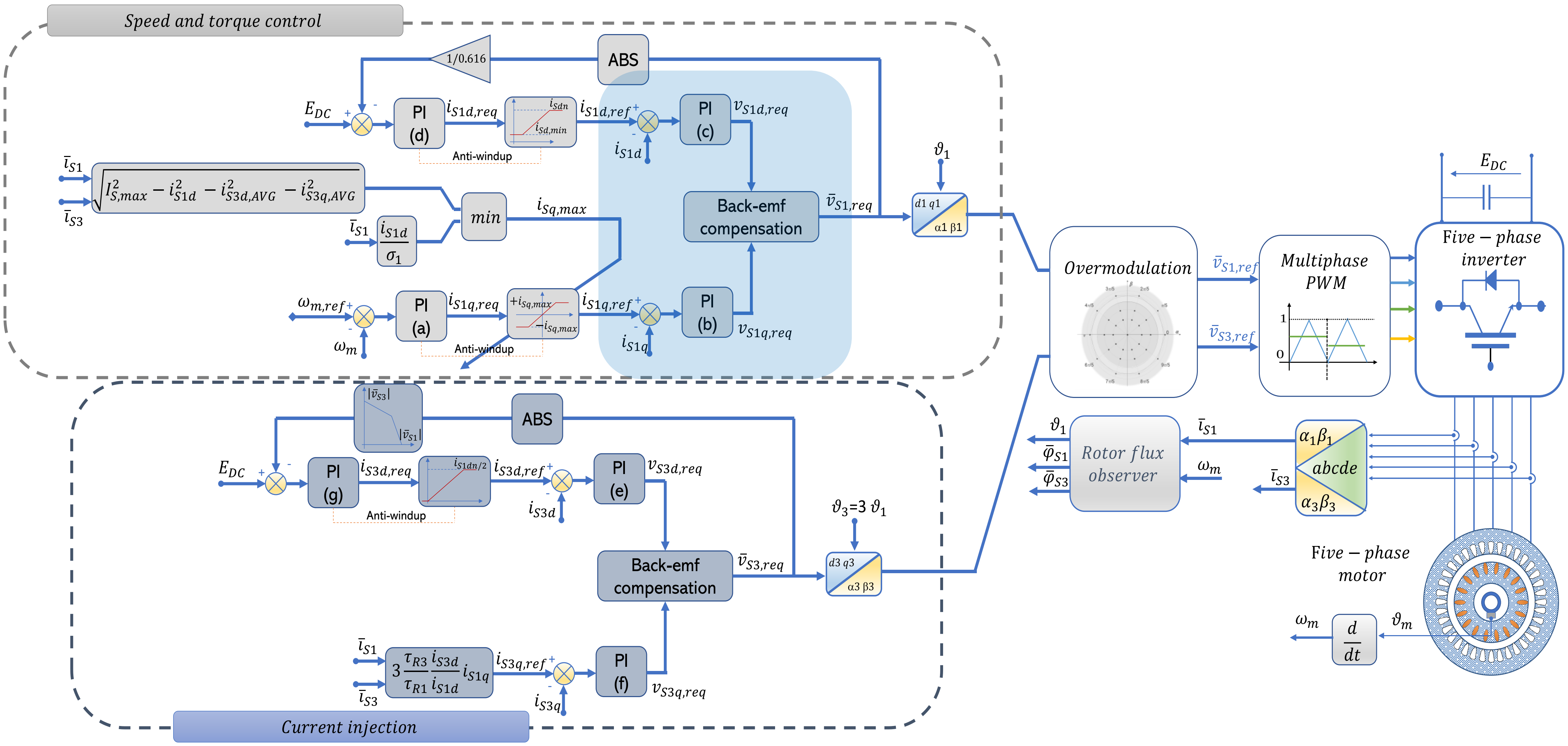

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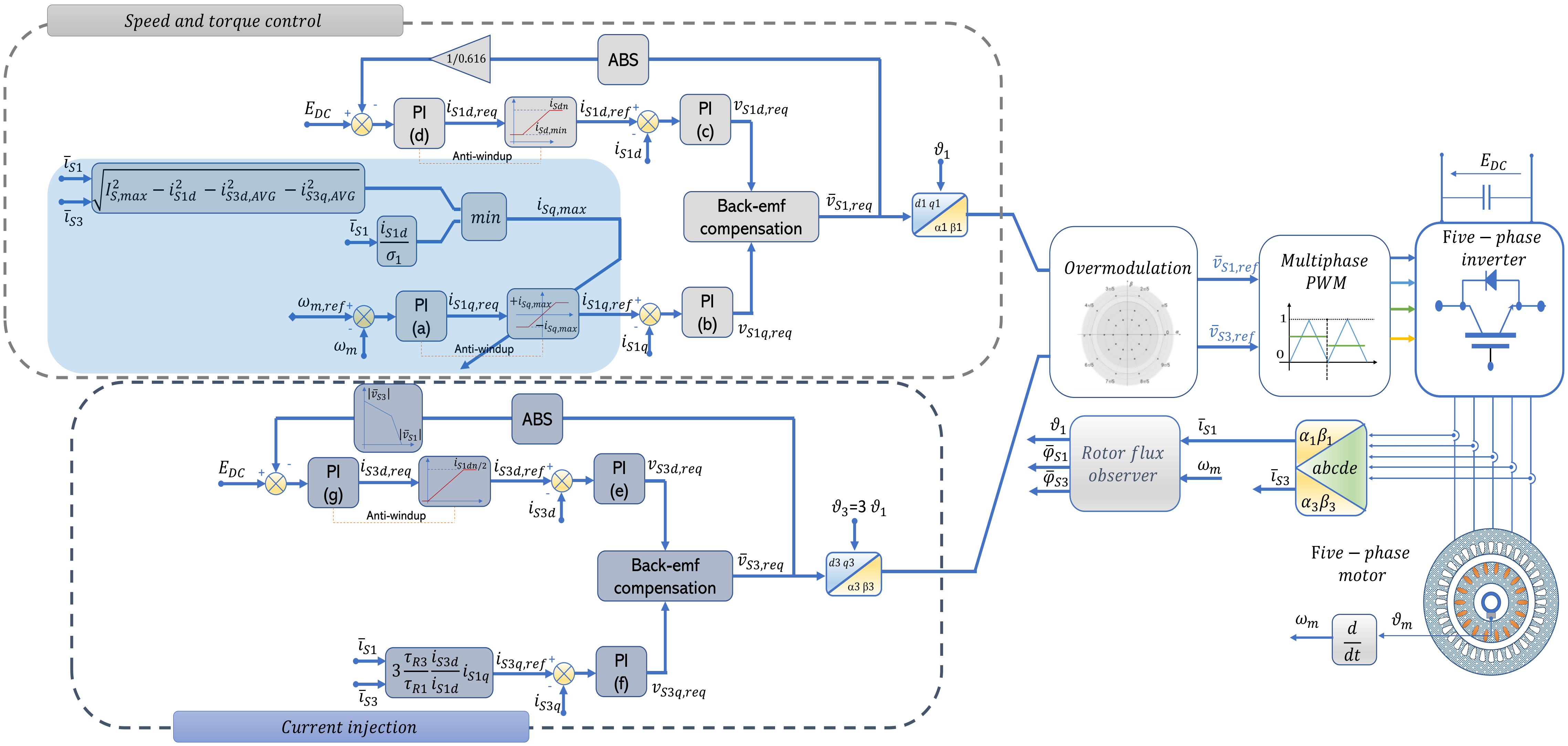

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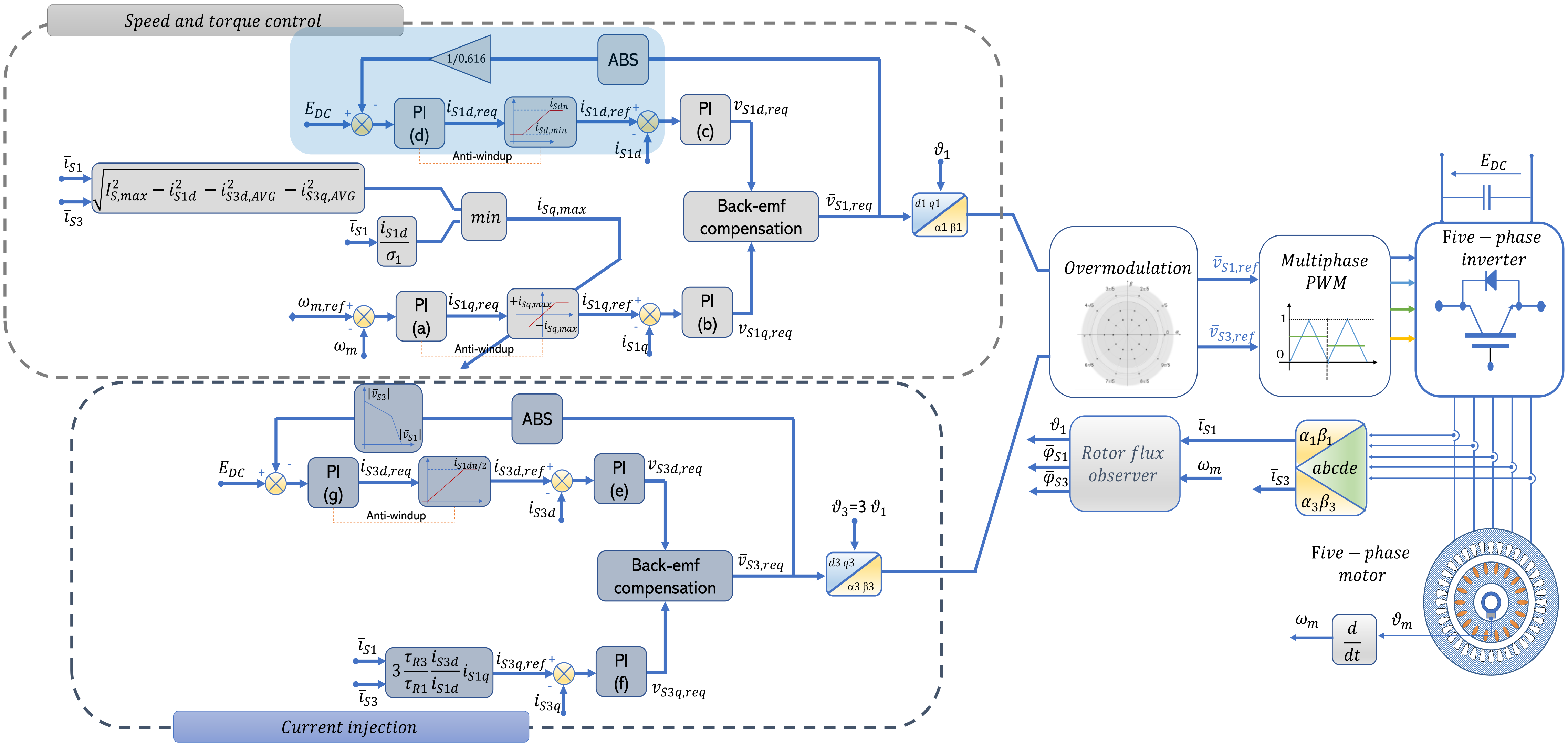

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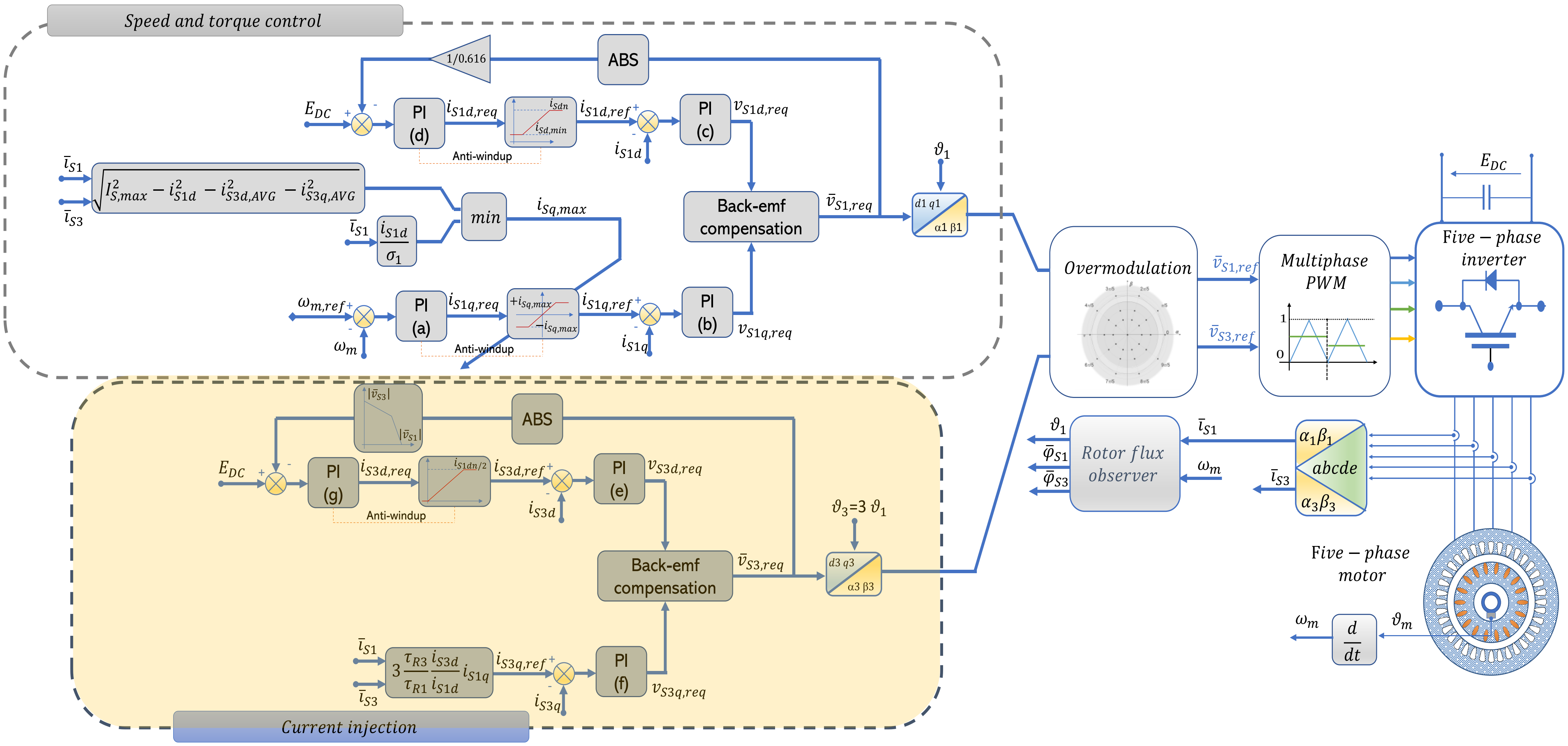

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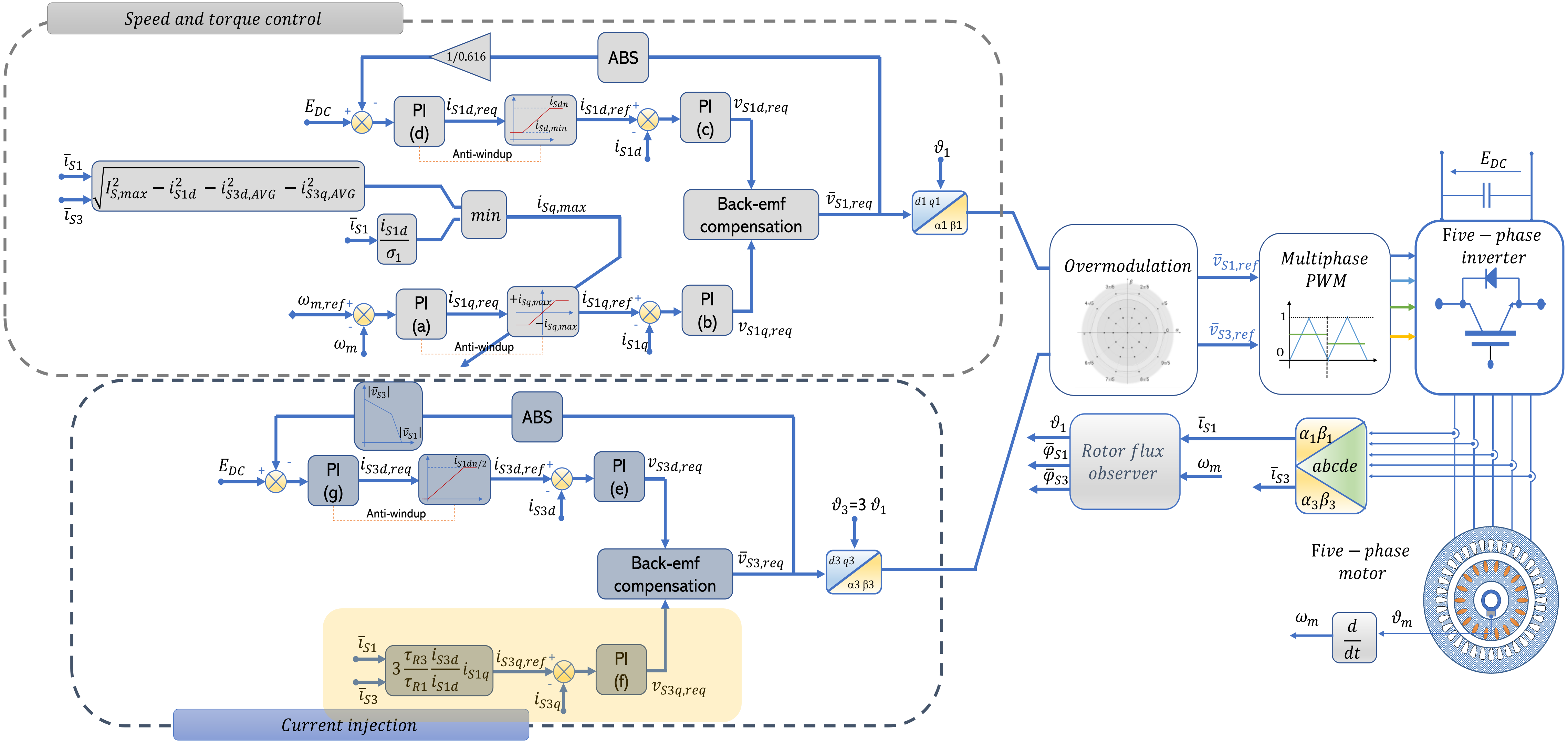

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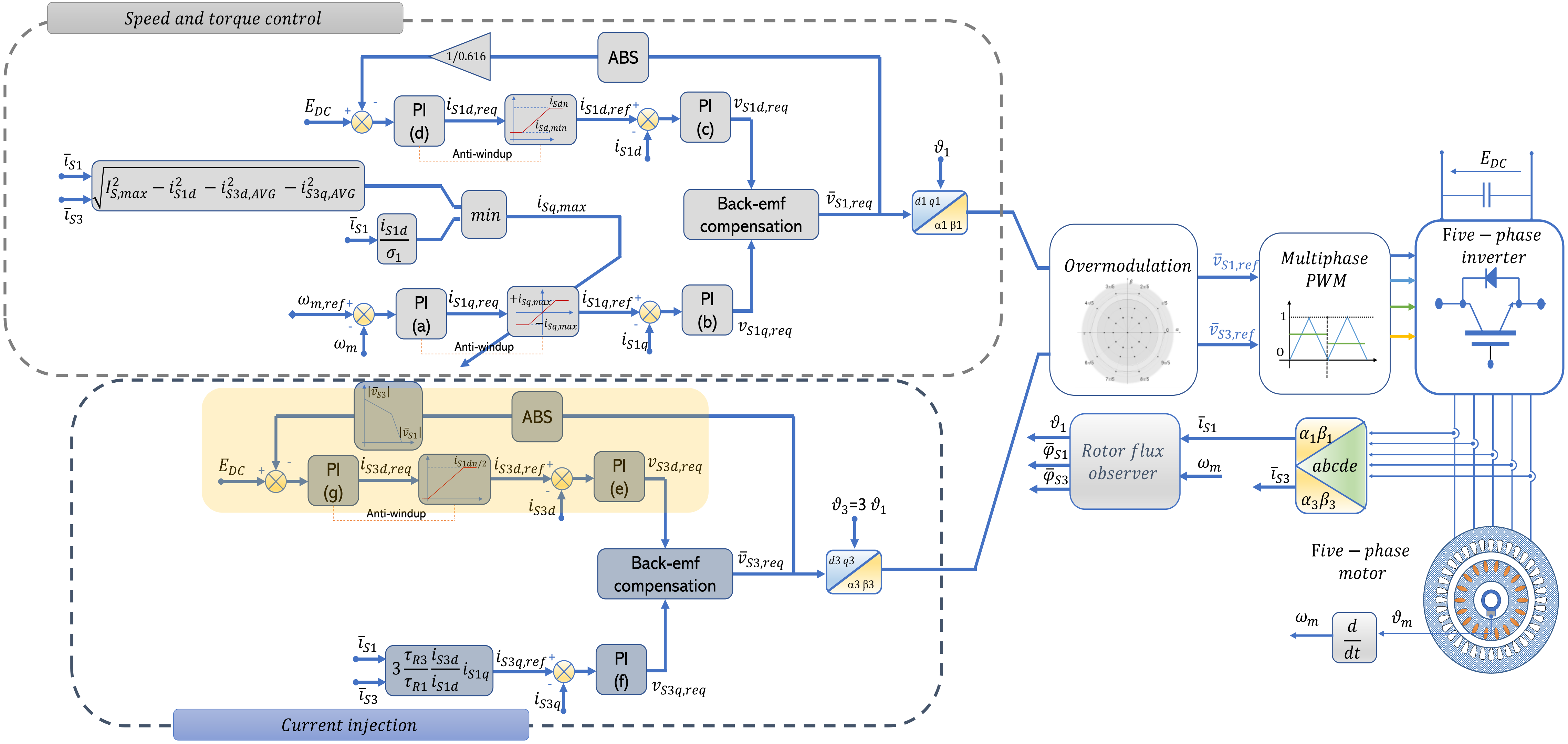

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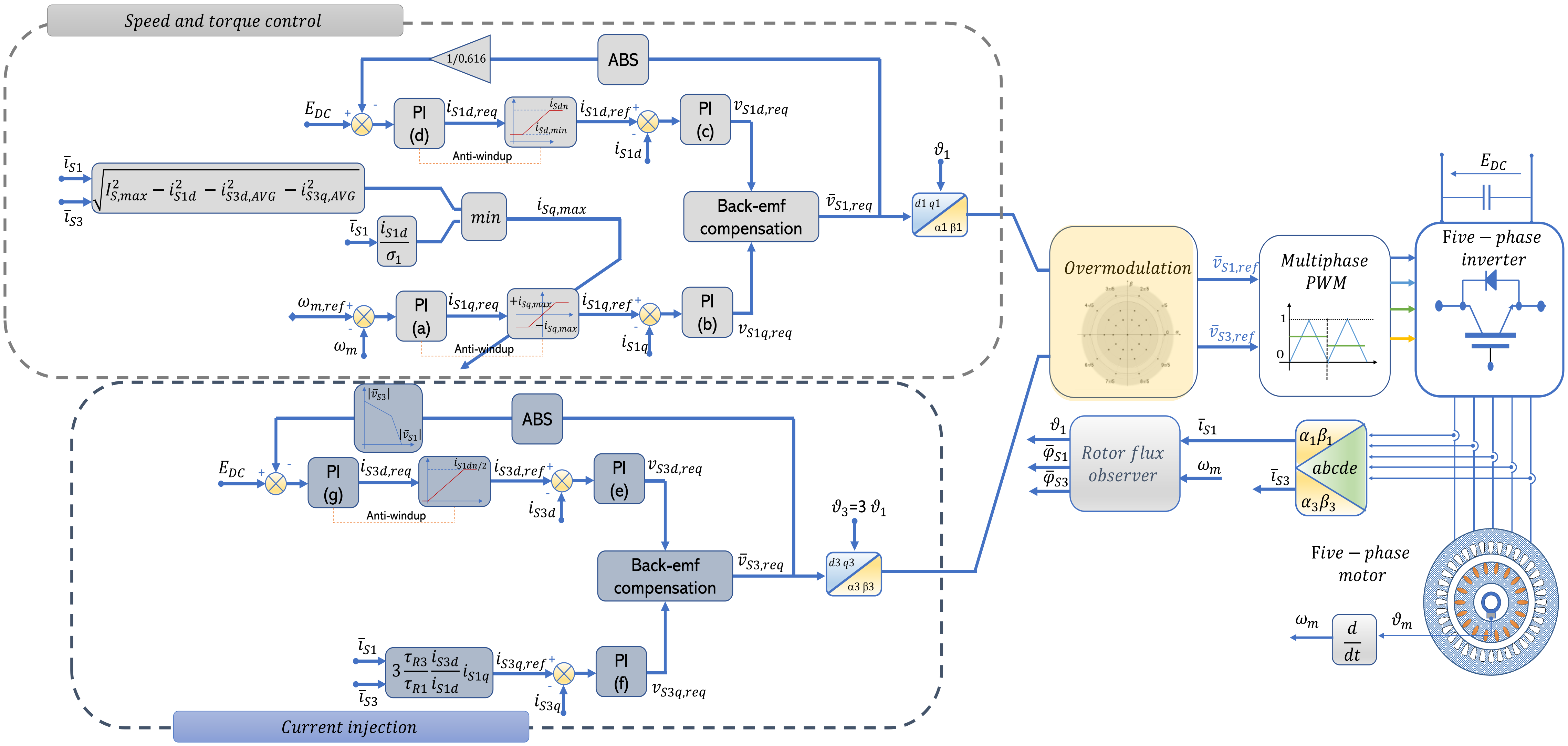
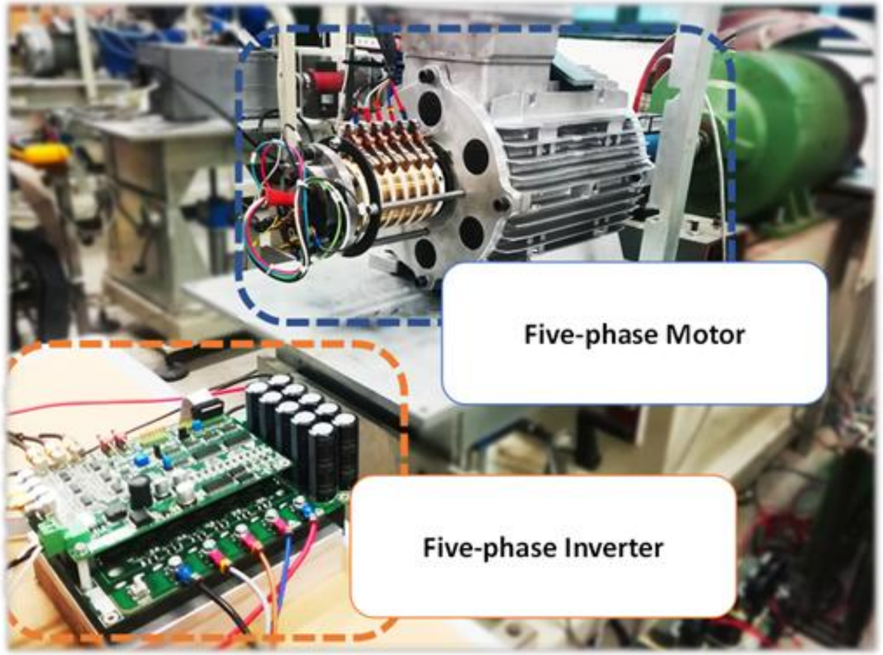


EXPERIMENTAL RESULTS



Experimental set-up of the electric drive composed by a five-phase wound-rotor induction machine and a five-phase inverter.

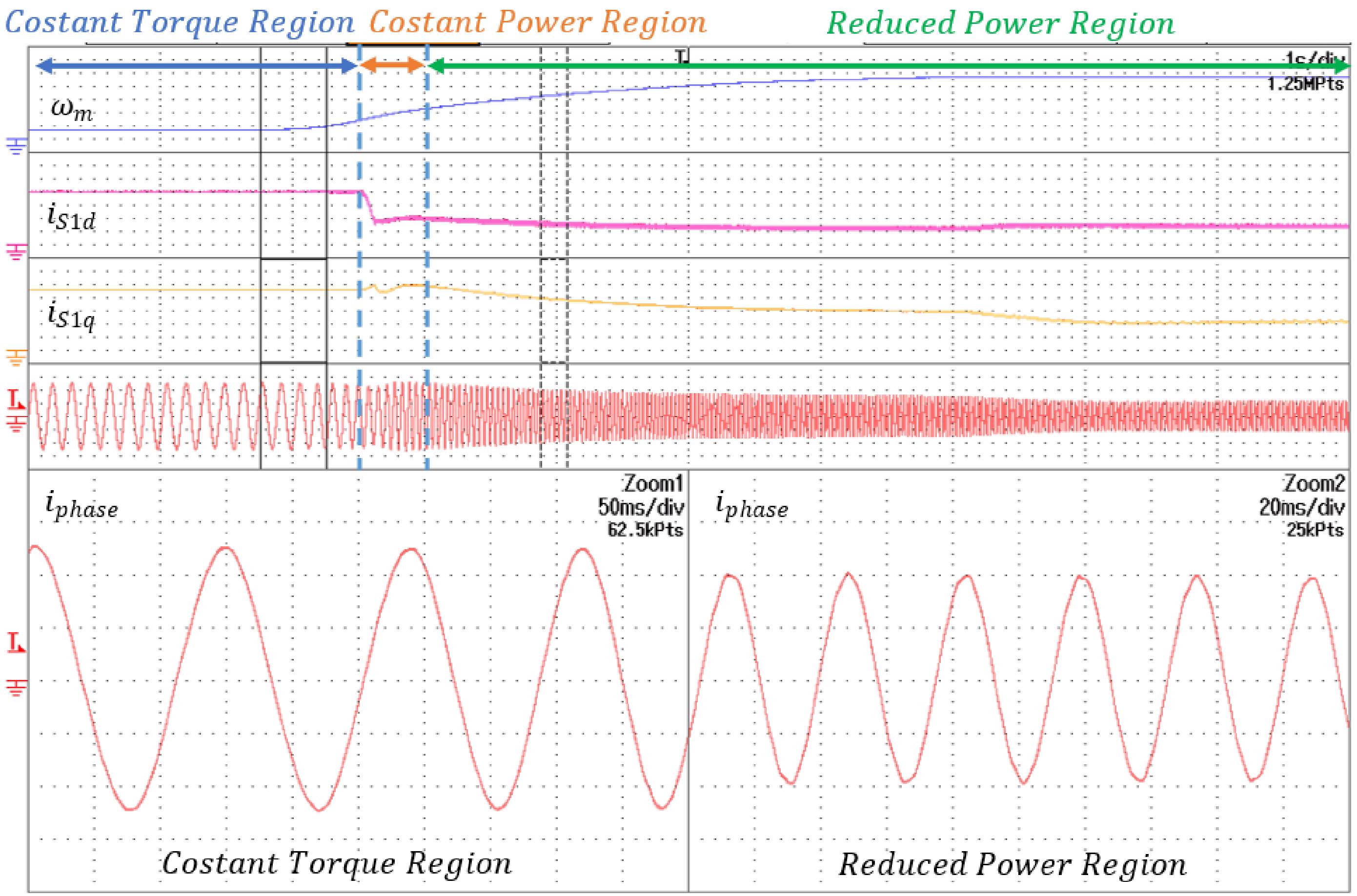
TABLE I
PARAMETERS OF THE FIVE-PHASE MACHINE

$\omega_{m,rated} = 200\ rpm$	$p = 3$
$R_S = 1.7\ \Omega$	$R_{R1} = R_{R3} = 2.03\ \Omega$
$L_{S1} = 410\ mH$	$L_{S3} = 68\ mH$
$L_{R1} = 399\ mH$	$L_{R3} = 65.8\ mH$
$M_1 = 362\ mH$	$M_3 = 35\ mH$

TABLE II
PARAMETERS OF THE FIVE-PHASE TWO-LEVEL INVERTER

$$IGBT\ Imax = 10\ A, E_{DC} = 100\ V$$
$$Switching\ frequency = 5\ kHz, dead\ time = 1.6\ \mu s$$
$$DC - link\ capacitance\ 550\ \mu F$$

EXPERIMENTAL RESULTS



Experimental result. Speed transient without third harmonic injection. ω_m (150 rpm/div), i_{S1d} (0.5 A/div), i_{S1q} (1 A/div), phase current (2 A/div).

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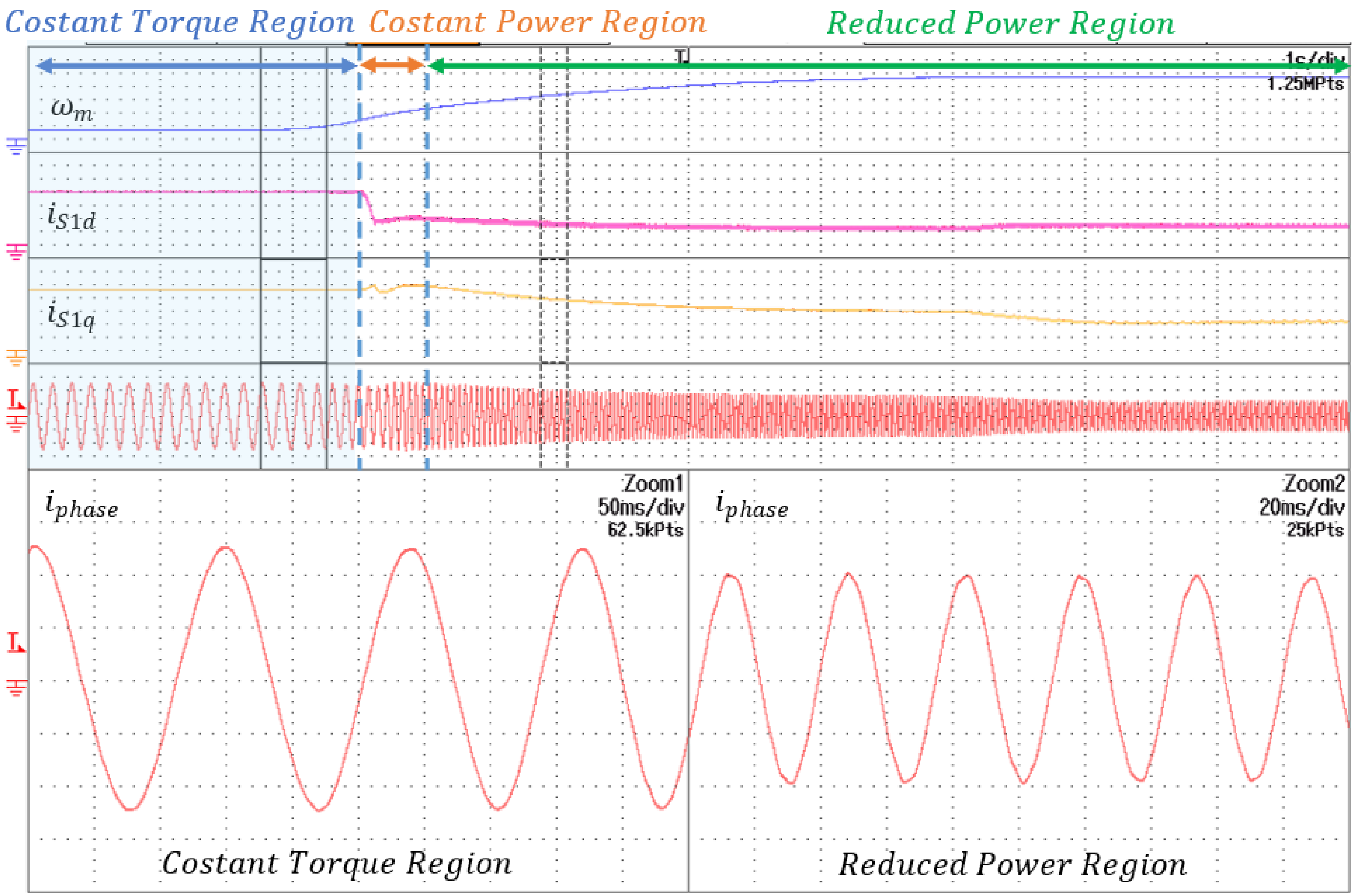

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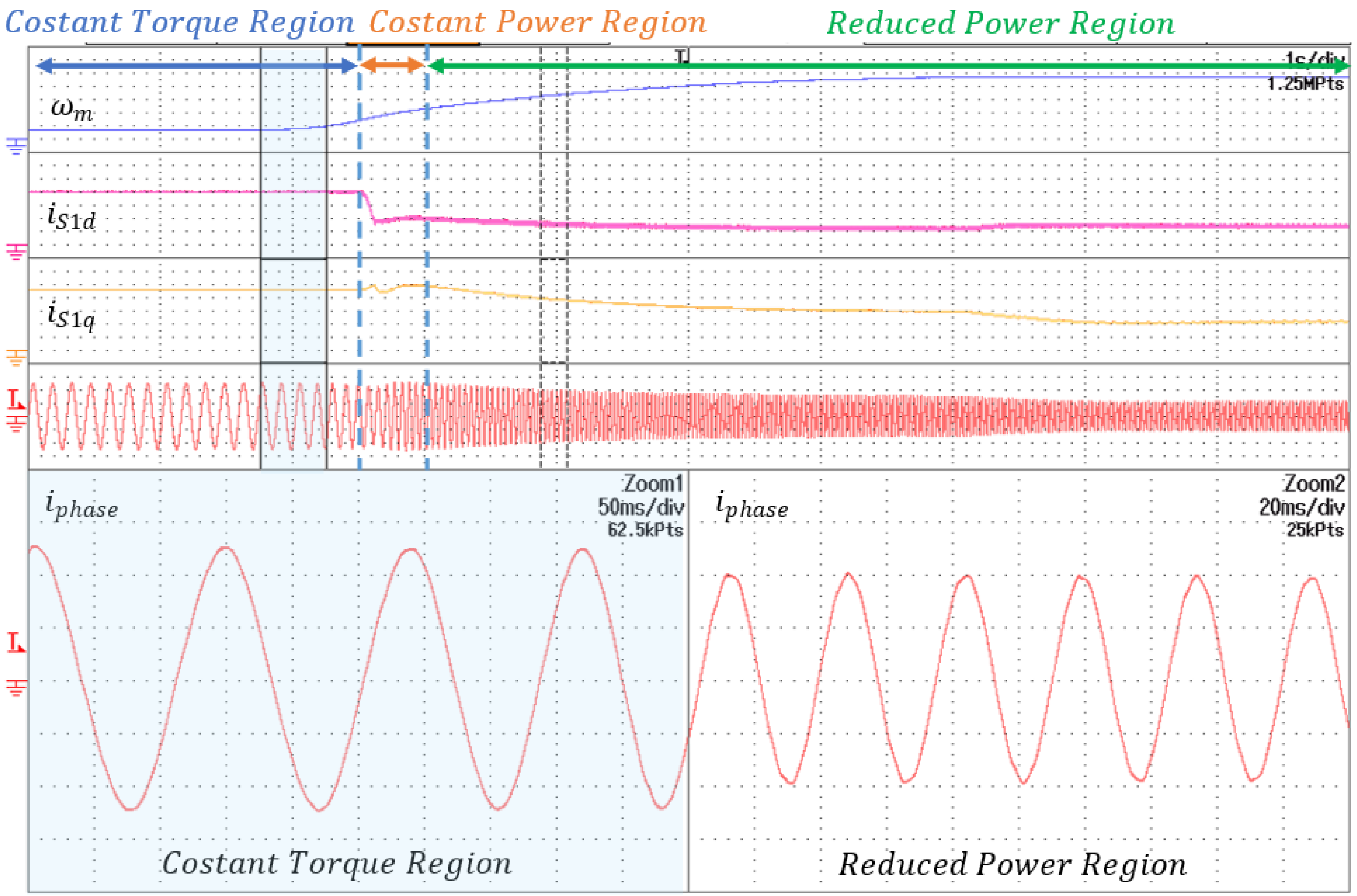

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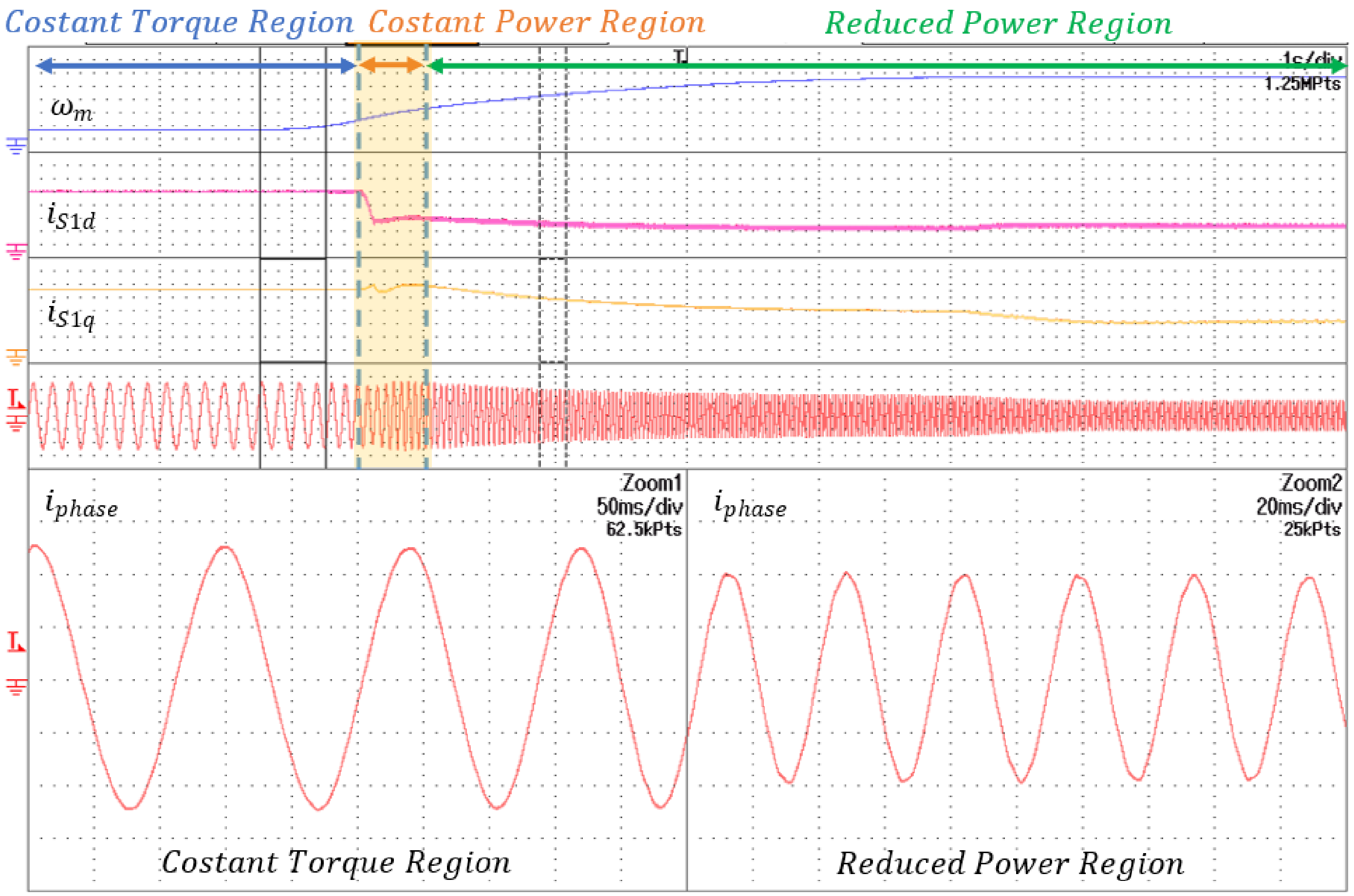

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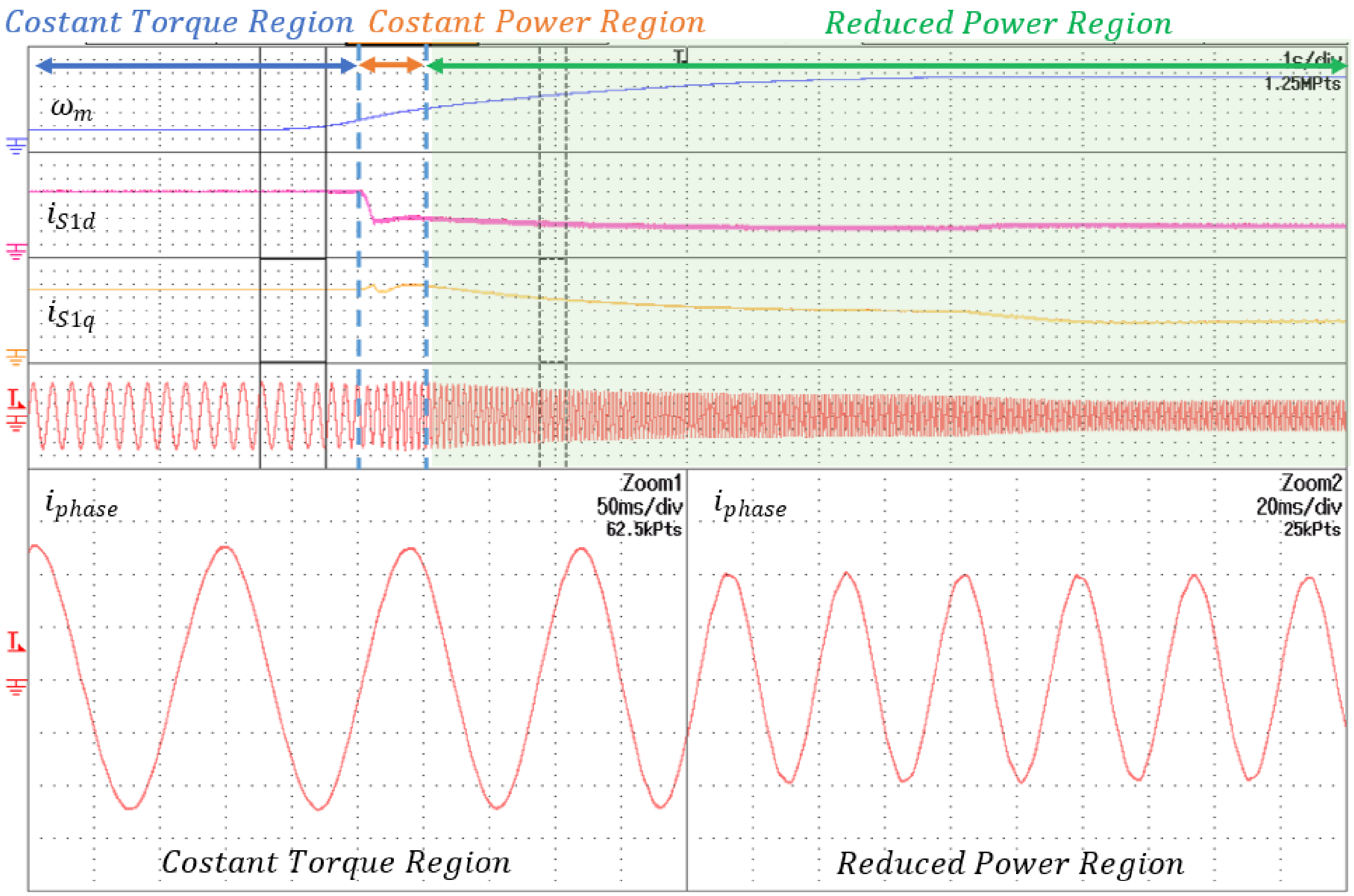

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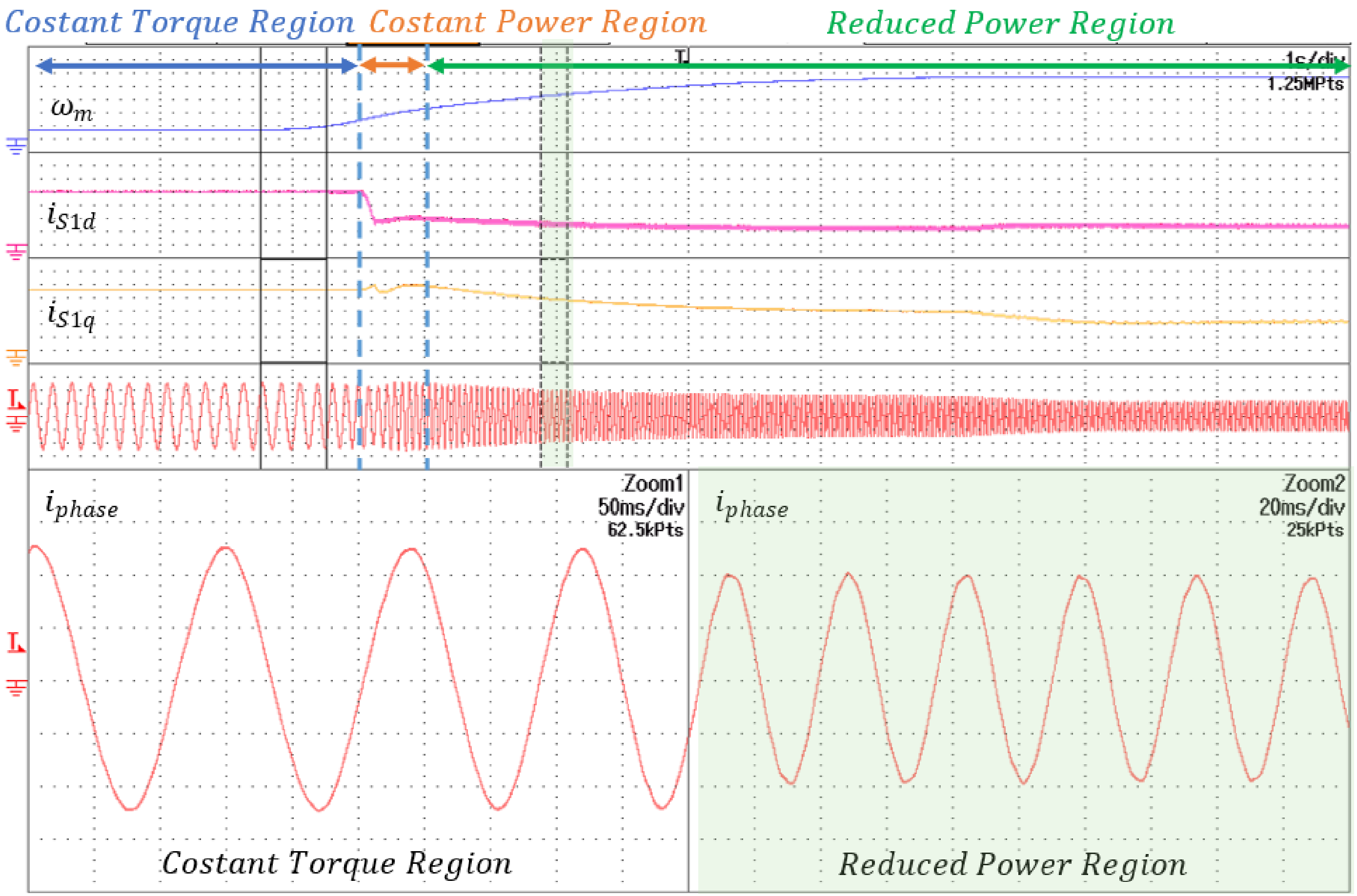
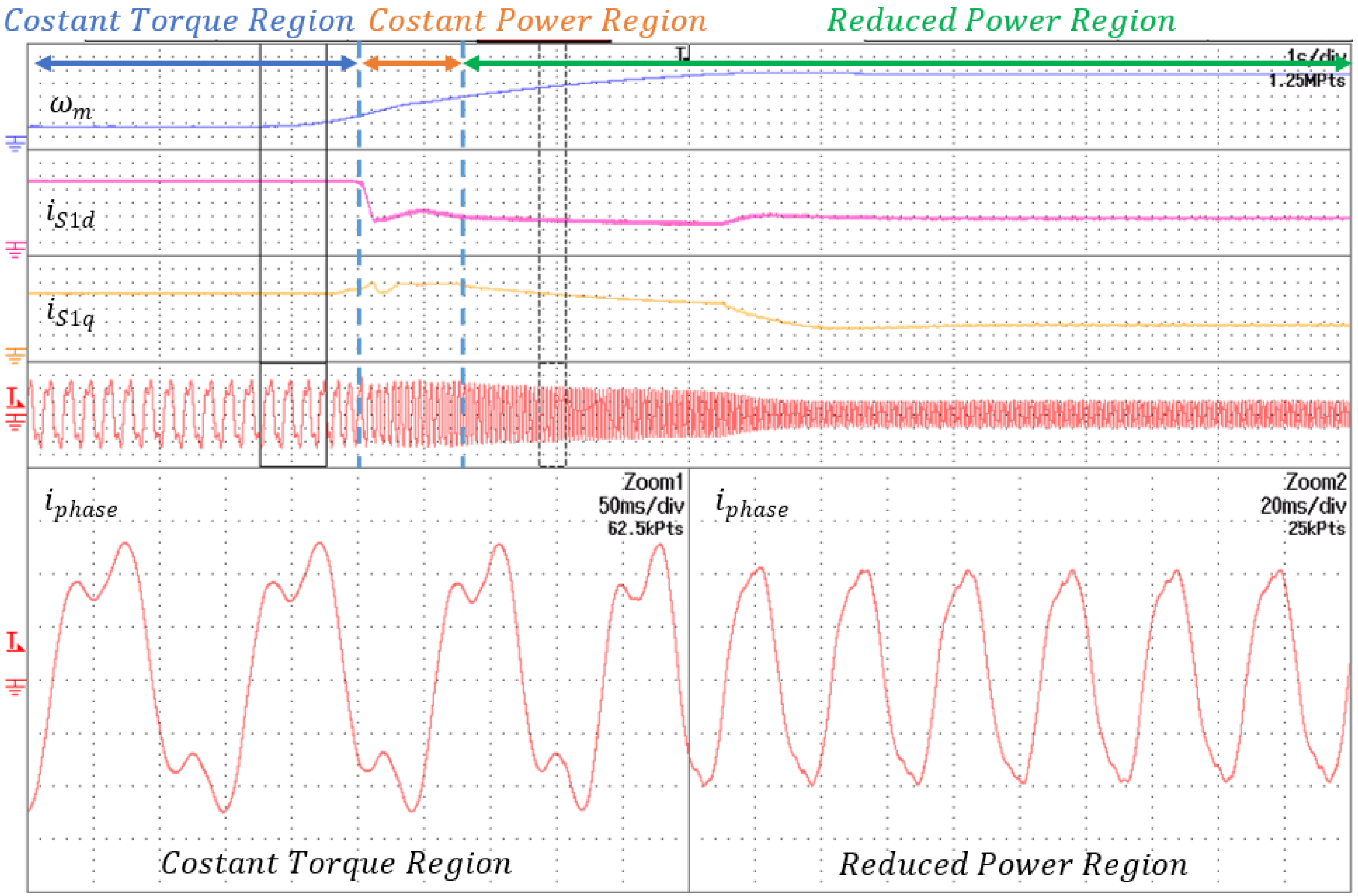


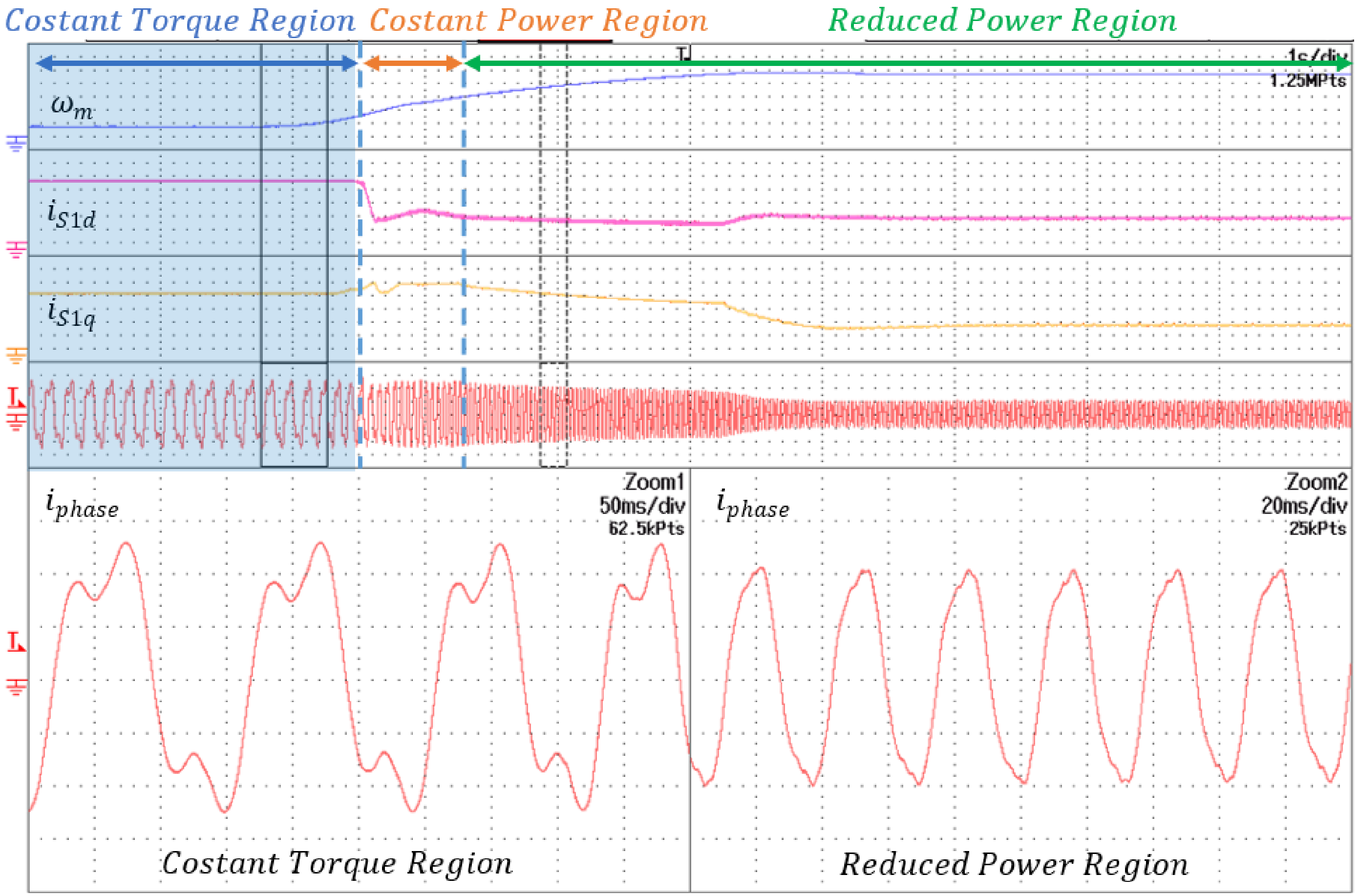
Experimental result. Speed transient without third harmonic injection. ω_m (150 rpm/div), i_{S1d} (0.5 A/div), i_{S1q} (1 A/div), phase current (2 A/div).

EXPERIMENTAL RESULTS



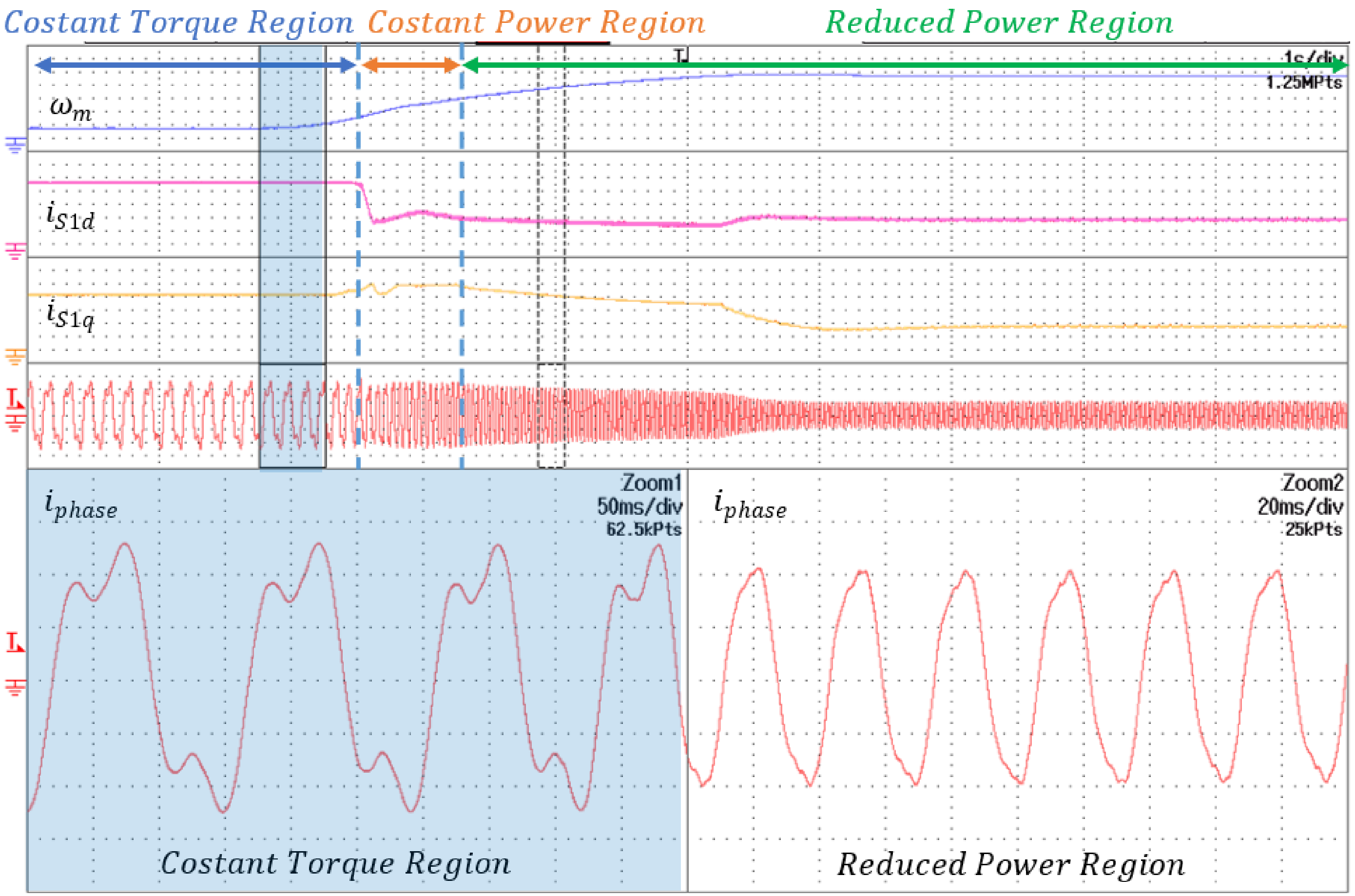
Experimental result. Speed transient with third harmonic injection. ω_m (150 rpm/div), i_{S1d} (0.5 A/div), i_{S1q} (1 A/div), phase current (2 A/div).

EXPERIMENTAL RESULTS



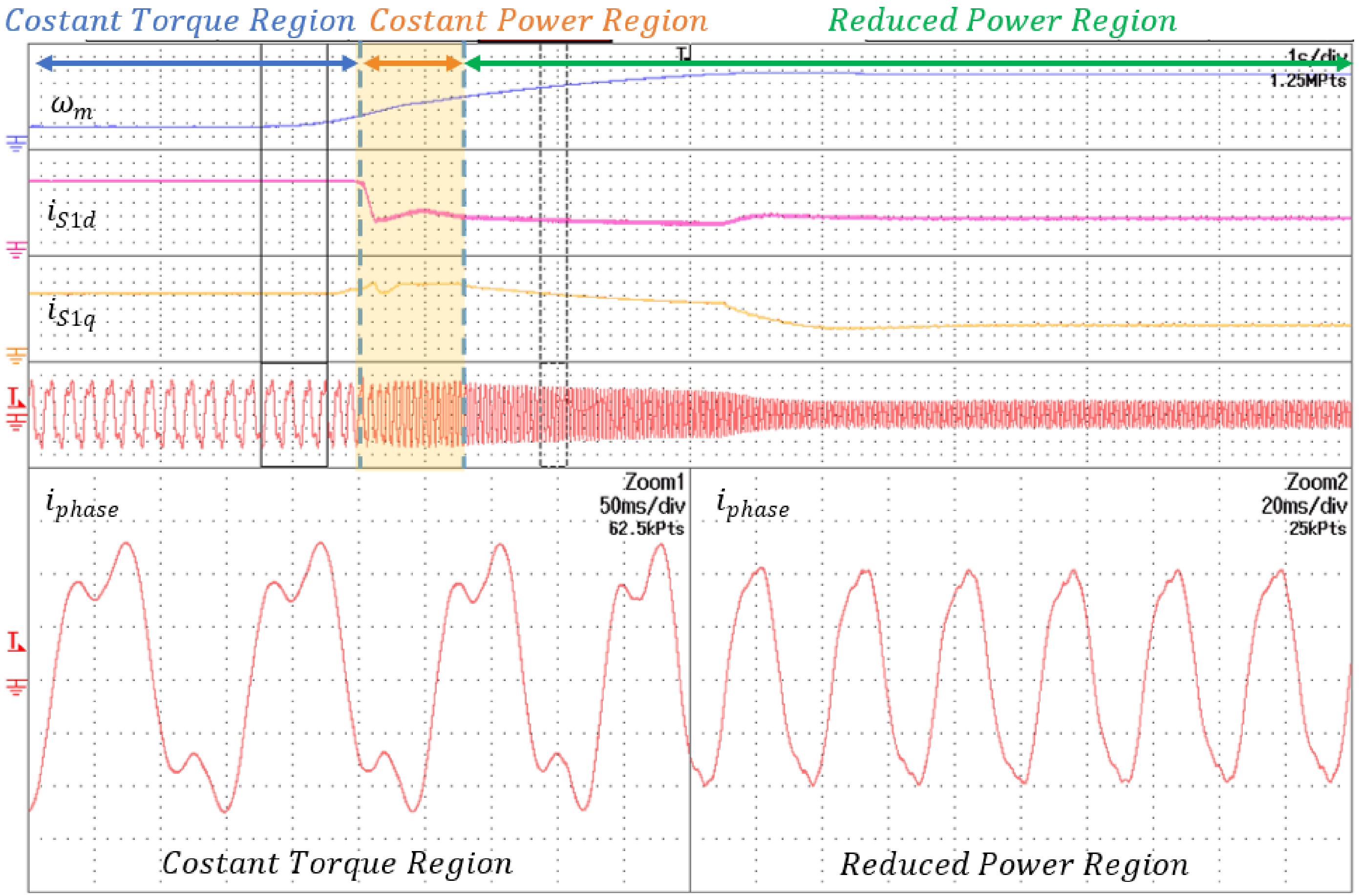
Experimental result. Speed transient with third harmonic injection. ω_m (150 rpm/div), i_{S1d} (0.5 A/div), i_{S1q} (1 A/div), phase current (2 A/div).

EXPERIMENTAL RESULTS



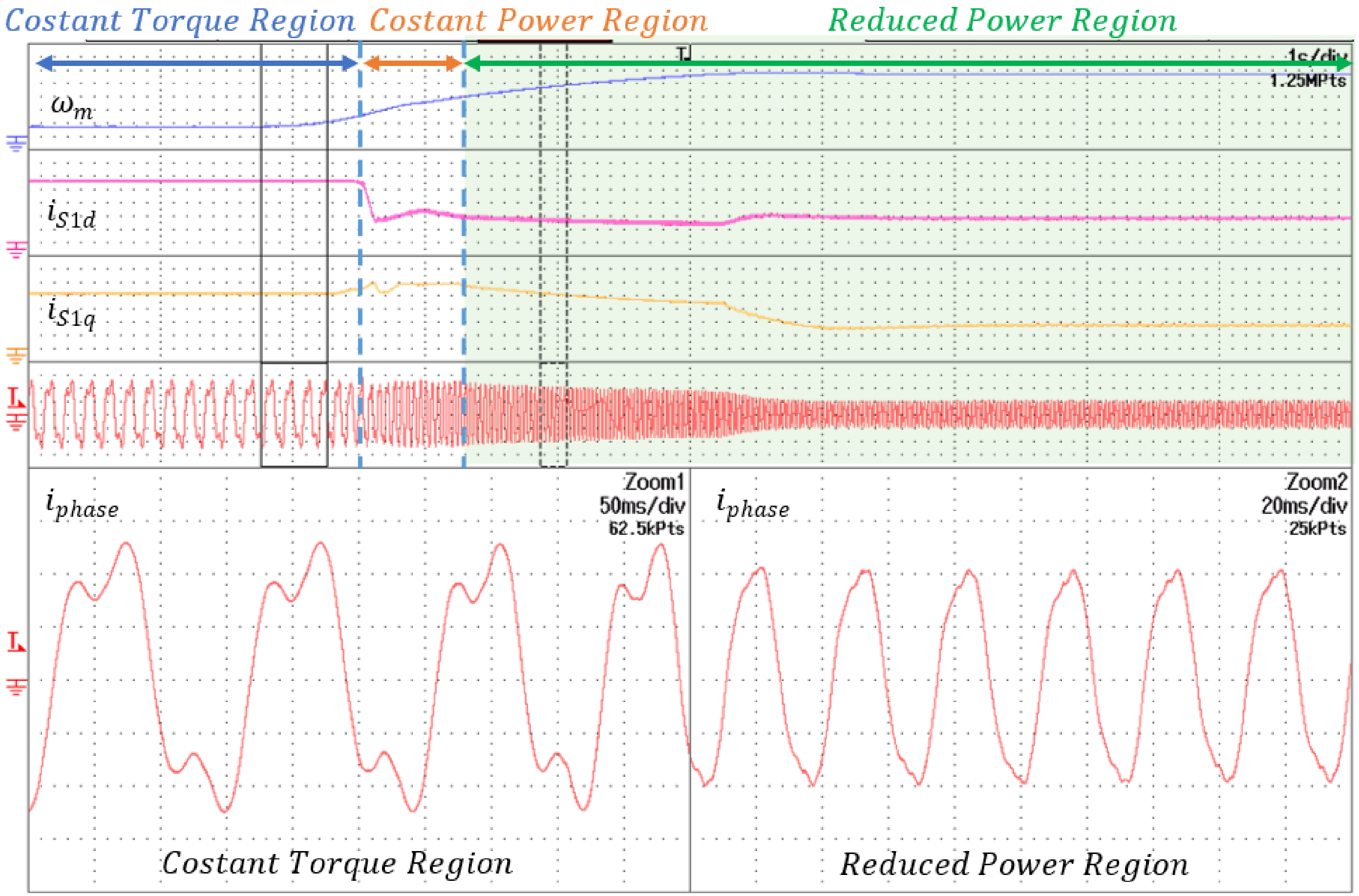
Experimental result. Speed transient with third harmonic injection. ω_m (150 rpm/div), i_{S1d} (0.5 A/div), i_{S1q} (1 A/div), phase current (2 A/div).

EXPERIMENTAL RESULTS



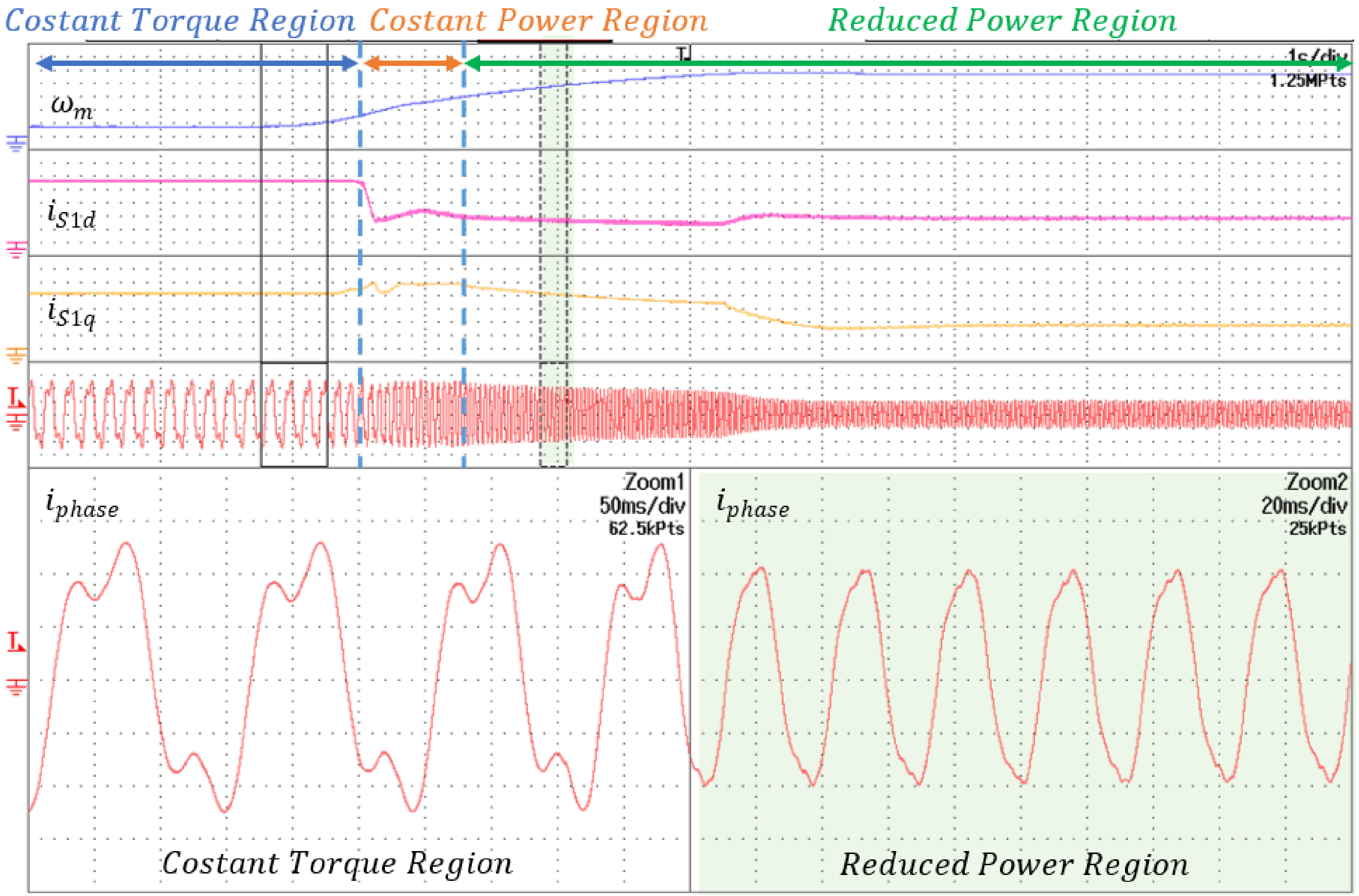
Experimental result. Speed transient with third harmonic injection. ω_m (150 rpm/div), i_{S1d} (0.5 A/div), i_{S1q} (1 A/div), phase current (2 A/div).

EXPERIMENTAL RESULTS



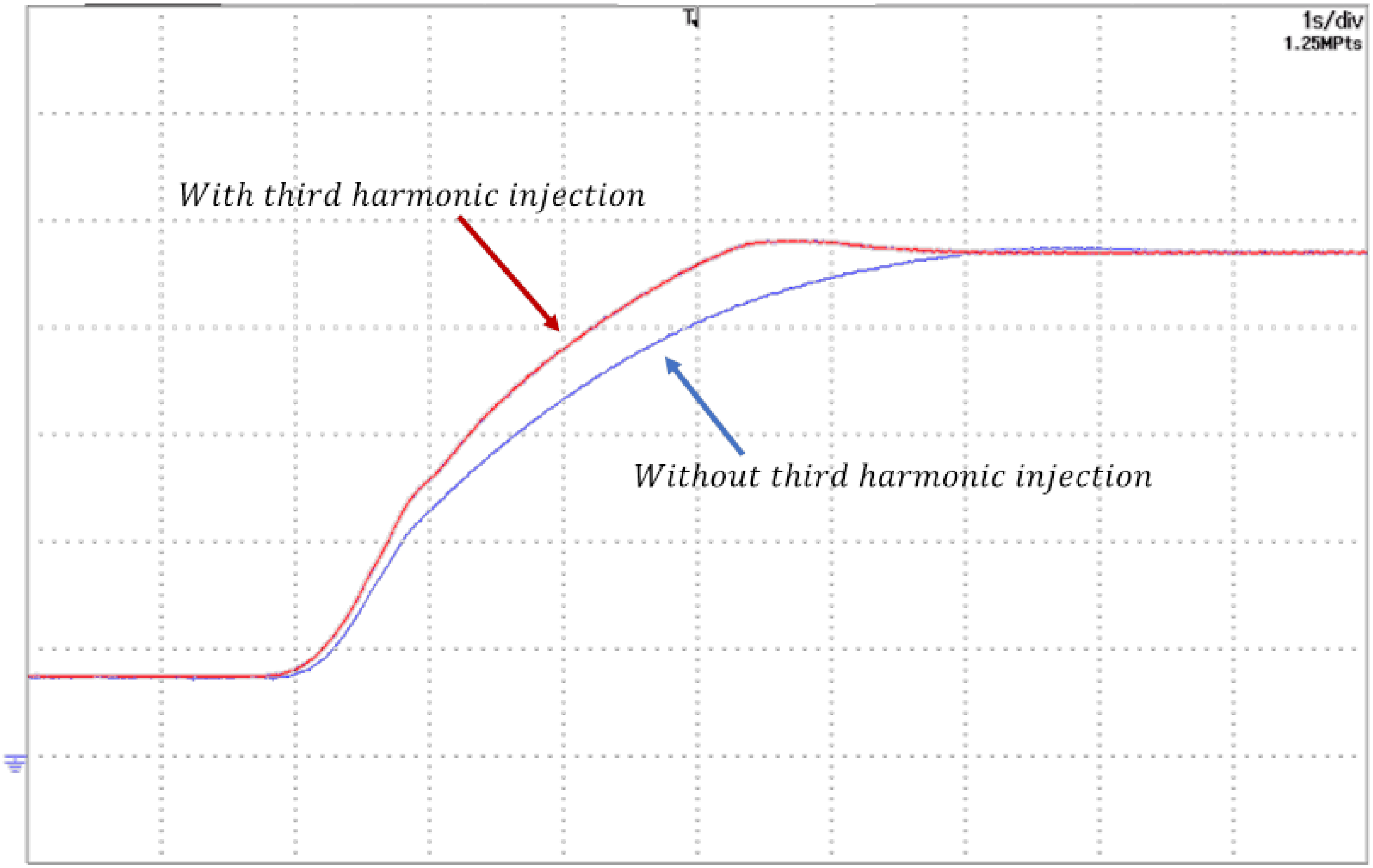
Experimental result. Speed transient with third harmonic injection. ω_m (150 rpm/div), i_{S1d} (0.5 A/div), i_{S1q} (1 A/div), phase current (2 A/div).

EXPERIMENTAL RESULTS



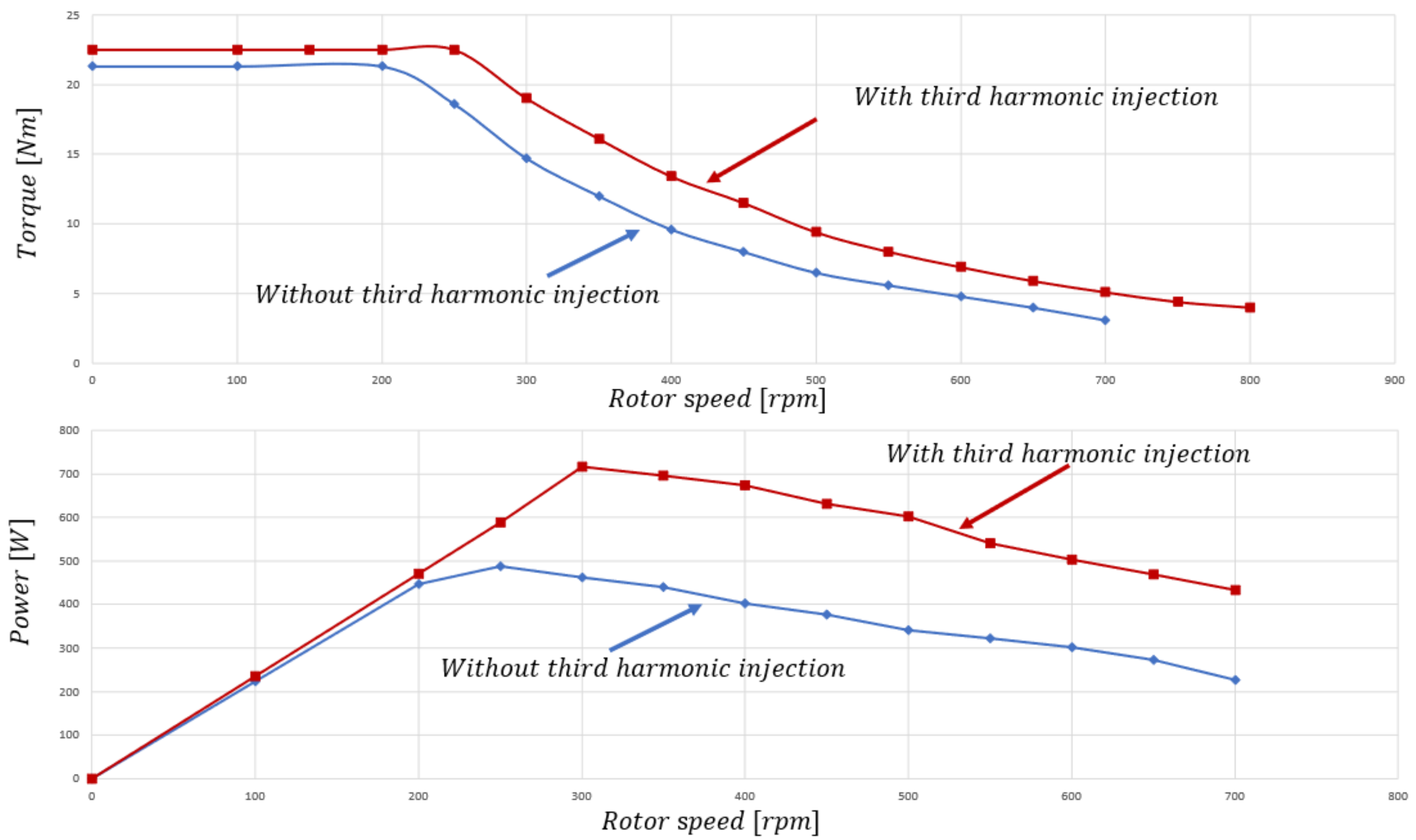
Experimental result. Speed transient with third harmonic injection. ω_m (150 rpm/div), i_{S1d} (0.5 A/div), i_{S1q} (1 A/div), phase current (2 A/div).

EXPERIMENTAL RESULTS



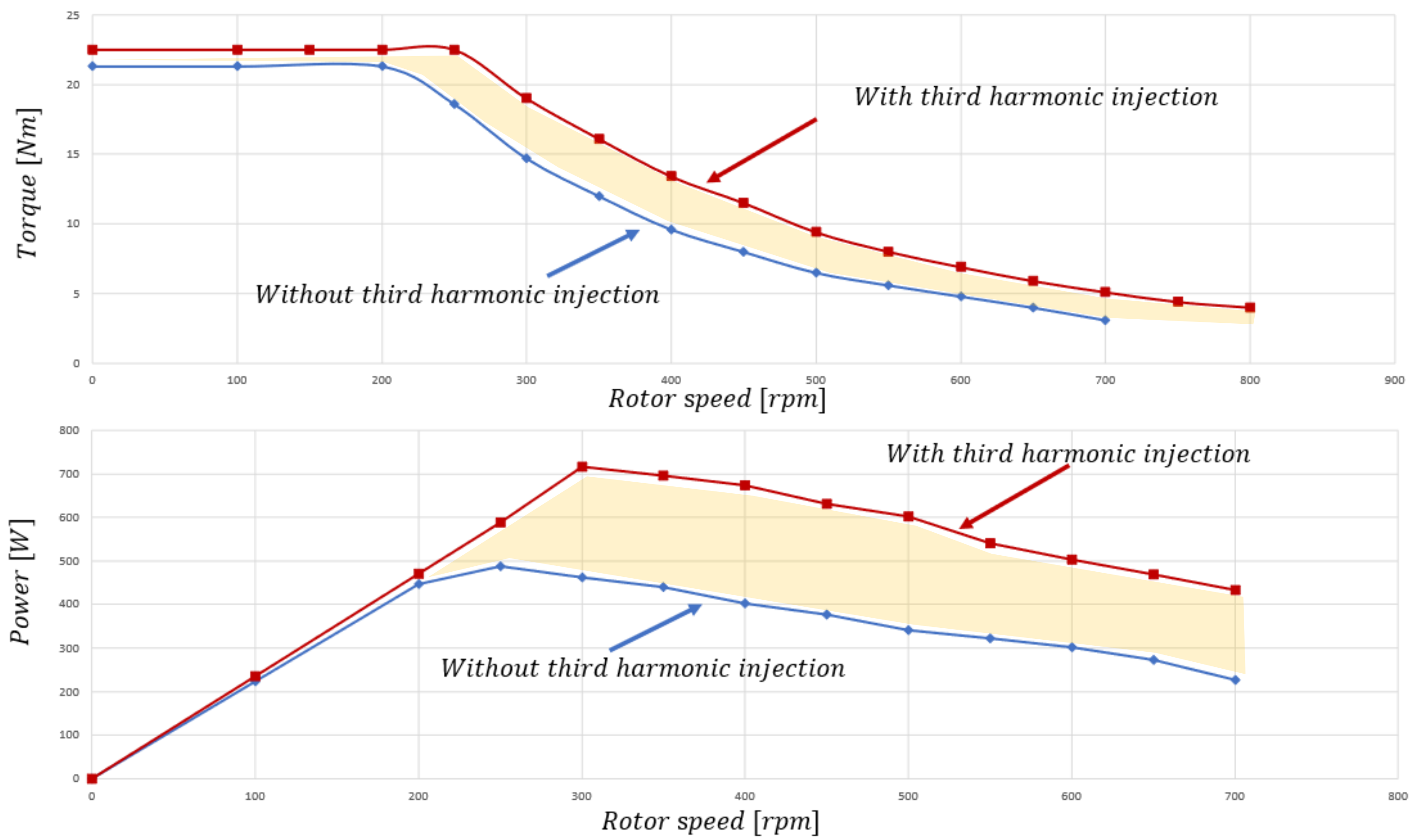
Experimental result. Speed transients with and without the third harmonic injection. Mechanical speed ω_m (150 rpm/div).

EXPERIMENTAL RESULTS



Experimental result. Torque and output power with and without third harmonic injection.

EXPERIMENTAL RESULTS



Experimental result. Torque and output power with and without third harmonic injection.

CONCLUSION

This paper investigates the use of the degrees of freedom of a five-phase induction motor to improve the drive performance over the entire speed range.

- At low speed, the developed control scheme injects a third-harmonic current component into subspace $d_3 - q_3$ that improves the distribution of the magnetic field in the air gap.
- In the field weakening region, the voltage injection into subspace $d_3 - q_3$ allows extending the linear modulation range of the fundamental voltage.
- The control scheme considers the voltage and current constraints in order to improve static and dynamic performance without exceeding the current limit.
- The theoretical analysis reveals that the main benefits of the proposed strategy are obtained at high speed, where the motor output power can increase by 40%. The experimental results have confirmed the feasibility of the proposed solution and the effectiveness of the harmonic injection.

Thank You for the Attention