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Flux-map-based optimal current reference generation for copper-loss minimization and fault-tolerant control of a six-phase electrically excited synchronous motor

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Electrically excited synchronous motors (EESMs) provide an additional degree of freedom through independent rotor-field current, allowing same torque production by multiple combinations of stator d-q, and rotor field currents. However, magnetic saturation complicates the selection of the optimal currents for minimum-copper-loss operation. This paper proposes a variable-field look-up-table (VF-LUT) current-reference generation strategy for six-phase EESM. The LUT is generated offline over the full torque-speed range by optimizing the stator d-q, and rotor field currents subject to torque, current, and voltage constraints based on an experimentally-obtained three-dimensional nonlinear d-q flux-linkage maps to minimize the combined stator and rotor copper losses. The proposed VF-LUT control is experimentally evaluated under healthy and single open phase fault (1OPF) conditions and compared with the conventional FOC and a similar control approach to VF-LUT with constant field current. Over a wide range of healthy operating points, the VF-LUT reduces the total copper loss by an average of 21.9 W relative to the CF-LUT and 8.57 W relative to FOC, with a maximum reduction of 27 W (37%) relative to FOC. 1OPF results further demonstrate continued operation with stable speed and torque regulation, confirming the effectiveness of the proposed VF-LUT control for copper-loss reduction and fault-tolerant six-phase EESM operation.

Keywords Electrically excited synchronous motor (EESM), electric vehicles (EVs), field-oriented control (FOC), look-up table (LUT), flux weakening (FW), maximum torque per ampere (MTPA), minimum total copper loss (MTCL).

Introduction

Permanent-magnet synchronous motors (PMSMs) are widely employed in high-performance electric-drive applications, particularly in electric-vehicle traction, owing to their high torque density, efficiency, and favorable dynamic performance [1-3]. However, the dependence of high-performance permanent magnets (PMs) on rare-earth materials raises concerns regarding supply-chain concentration, market volatility, and the environmental impacts associated with rare-earth extraction and processing [4]. Consequently, increasing attention has been directed toward the development of magnet-free electrical machine topologies. In this context, electrically excited synchronous motors (EESMs) have emerged as a promising alternative. Unlike PMSMs, EESMs employ rotor field windings instead of PMs, thereby eliminating rare-earth dependency and avoiding irreversible demagnetization. In addition, the direct controllability of the rotor field current provides superior operational flexibility and improved field-weakening capability, making EESMs highly suitable for next-generation traction and industrial drive applications [5, 6].

In addition, multiphase machine topologies, particularly six-phase drive systems, have attracted considerable research interest due to their enhanced fault-tolerant capability, reduced torque ripple, improved reliability, and superior power distribution compared with conventional three-phase machines. These advantages make six-phase EESM an attractive candidate for safety-critical and high-performance applications such as electric transportation and aerospace systems.

A defining characteristic of EESMs is the ability to independently regulate the rotor magnetic field strength through the field current. Consequently, the machine control problem involves three independent control variables: stator d-axis current (i_d), stator q-axis current (i_q), and rotor field current (i_f). This additional degree of freedom offers significantly greater control flexibility compared with conventional PMSMs [7, 8]. However, the existence of numerous current combinations capable of producing the same electromagnetic torque considerably complicates the realization of optimal operating conditions [9].

In conventional PMSM drives, Maximum Torque Per Ampere (MTPA) strategies are widely adopted to provide maximum torque with minimum stator current magnitude, thereby reducing stator copper losses, improving efficiency, and mitigating thermal stress [10, 11]. Conventional MTPA, strategies applied to EESMs, primarily minimize armature-current-related losses and may therefore neglect the rotor field-winding copper loss [12, 13]. Consequently, recent research has shifted toward Minimum Total Copper Loss (MTCL) strategies, in which both stator and rotor currents are optimized simultaneously. Analytical and hybrid optimization methods have been proposed to determine copper-loss-minimizing operating points [14]. However, their implementation can involve nonlinear equation solving and iterative calculations, particularly when current-dependent machine

parameters are considered. Analytical loss-minimization strategies have also been developed for EESMs. In[15], an extended MTPA strategy is combined with closed-loop flux-weakening control to minimize the stator and rotor Joule losses over wide speed range.

Recently, a single lookup table (LUT) approach for copper-loss minimization in wound-field synchronous motors (WFSMs) was presented in [16]. The proposed method utilized experimentally obtained flux-torque maps to construct a single LUT that generates the optimal current references (i_d^* , i_q^* , i_f^*) corresponding to minimum copper losses while considering the nonlinear variation of machine inductances. In addition, the method reduced memory requirements compared with conventional multi-LUT approaches and demonstrated effective operation in both constant-torque and field-weakening regions. However, the consideration of the stator voltage limit within the optimization process was not explicitly reported. Furthermore, the study was limited to a conventional three-phase WFSM drive operating under healthy conditions, and fault-tolerant operation was not investigated.

Recent studies have addressed magnetic nonlinearity and excitation coupling in synchronous-machine control. For IPMSM drives, magnetic saturation was incorporated into maximum-torque-to-current control in [17], whereas a field-current control strategy accounting explicitly for the coupling between the stator d-axis and rotor field windings was developed for WRSMs in [18]. These studies highlight the importance of considering magnetic saturation and coupling effects, but they do not address the joint stator-and-field copper-loss minimization problem. More recently, copper-loss-minimizing control has been extended to WRSMs considering the nonlinear magnetic characteristics. In[19], an analytically derived maximum-torque-per-Joule-loss strategy minimizes both stator and rotor winding losses, while measured flux maps are used to account for nonlinear machine parameters and the resulting control strategy is experimentally verified. Offline approaches have also been applied to nonlinear WRSM control; for example, [20] generated lookup-table-based maximum-torque references from offline calculations while accounting for nonlinear machine parameters, which was experimentally validated. In [21], a single-LUT strategy was developed for WFSMs by identifying minimum-copper-loss current combinations over the available field-current range while accounting for nonlinear inductance variation. The resulting LUT was experimentally evaluated in both constant-torque and field-weakening regions.

Fault-tolerant control of multiphase synchronous drives has also received considerable attention. In [22], pre- and post-fault current-control structures were developed for dual three-phase reluctance synchronous drives and experimentally validated under open-phase operation. More recently, [23] investigated fault-tolerant optimization of dual three-phase PMSM drives over the full operating range, including minimum-copper-loss post-fault operation. However, these studies focus on reluctance or PM machines and do not address integration of flux-map-based variable-field copper-loss-optimized current references with a multiphase EESM. In contrast to the three-phase healthy-operation framework reported in [16], this paper proposes a flux-map-based copper-loss-optimized current-reference generation to control a six-phase EESM using the resultant variable-field look-up-table (VF-LUT). The references of the stator d-q and rotor field currents are generated as functions of the operating torque and speed using an offline optimization performed under healthy-operation constraints. The optimization establishes the proper current combinations to attain the operating torque and speed, minimize the combined stator and rotor copper loss, and satisfy the voltage and current constraints. To account for the magnetic saturation while generating the VF-LUT without relying on constant inductance approximations, three-dimensional d-q flux-linkage maps are experimentally obtained. The performance of the proposed VF-LUT control strategy is experimentally evaluated under both healthy and single open phase fault (IOPF) conditions and compared with the conventional field-oriented-control (FOC) and a similar approach to the VF-LUT, which keeps the field current constant at the rated and named constant-field look-up-table (CF-LUT). The key factors used in comparison are combined stator and rotor field copper-loss energy, matched healthy operating-point comparisons, dynamic tests, and single-open-phase fault experiments.

Therefore, the main contributions of this paper can be summarized as follows:

- Generation of a VF-LUT based on flux-map-based copper-loss-optimized current references for a six-phase EESM, in which i_d , i_q , and i_f are optimized offline under healthy-operation constraints to minimize the combined stator and rotor copper loss.
- Incorporation of experimentally-obtained three-dimensional d-q flux-linkage maps into the VF-LUT generation process to account for magnetic saturation over the full torque-speed range.
- Evaluation of the healthy-optimized VF-LUT under IOPF operation, where the secondary subspace currents (i_x , i_y) are generated based on the fundamental subspace currents (i_α , i_β) according to the MTPA criteria.
- Experimental evaluation of the proposed VF-LUT under healthy and IOPF conditions, and comparison against conventional FOC and a CF-LUT control, dynamic current-reference tracking, and post-fault copper-loss evaluation including the secondary-subspace current contribution.

Mathematical modeling of the six-phase EESM

Six-Phase EESM Drive Topology

Fig. 1 illustrates the investigated six-phase EESM drive topology. The stator comprises two isolated three-phase winding sets $a_1b_1c_1$ $a_2b_2c_2$ displaced electrically by 60° , forming a symmetrical six-phase stator winding that are fed through a six-phase VSI. The investigated machine employs double-layer distributed windings with 30-slot stator. The rotor field winding is powered by a

DC/DC chopper to control field current, which plays a vital role in copper-loss minimization and field-weakening control. The EESM specifications and parameters are summarized in Table. 1.

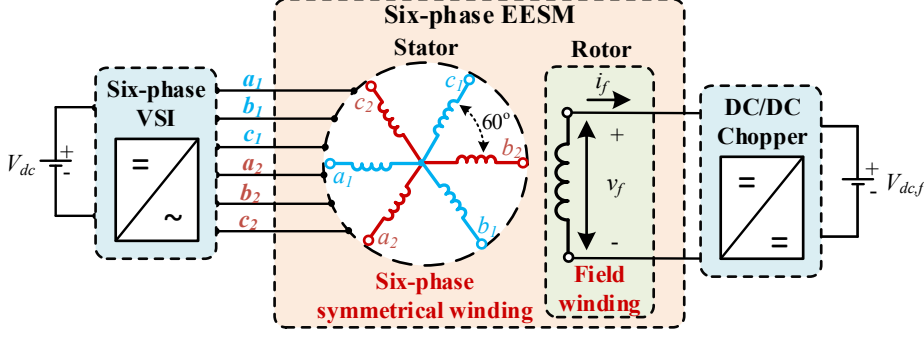


Fig. 1 Proposed six-phase EESM drive topology.

Parameter	Value	Parameter	Value
Rated power	1.1 kW	Rated stator phase voltage	80 V (peak)
Rated speed	1500 rpm	Rated stator phase current	7 A (peak)
Rated torque	7 N·m	Rated rotor field voltage	50 V
Pole pairs	1	Rated rotor field current	1 A
Switching frequency	13.33 kHz	Rotor field resistance (R_f)	50 Ω
		Stator phase resistance (R_s)	1.1 Ω

Table 1. The EESM Specifications and Parameters.

EESM Modeling

For the symmetrical six-phase EESM, vector space decomposition (VSD) projects the machine variables into orthogonal decoupled subspaces using the amplitude-invariant VSD transformation matrix (T), given by (1).

$$T = \frac{2}{6} \begin{bmatrix} 1 & -1/2 & -1/2 & 1/2 & -1 & 1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 & -\sqrt{3}/2 \\ 1 & -1/2 & -1/2 & -1/2 & 1 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 & \sqrt{3}/2 & 0 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 & 1/2 & 1/2 & 1/2 \\ 1/2 & 1/2 & 1/2 & -1/2 & -1/2 & -1/2 \end{bmatrix} \quad (1)$$

After applying the VSD transformation, the stator variables are decomposed into three orthogonal subspaces: the fundamental $\alpha\beta$ subspace, the secondary xy subspace, and the zero-sequence subspace. The fundamental $\alpha\beta$ subspace is the torque-producing component, while the secondary xy subspace does not contribute directly to torque production but it is useful for harmonic and fault analysis. The zero-sequence subspace is ideally absent in the six-phase EESM with isolated neutral points, which is neglected in this work. Since the secondary xy subspace exhibits nearly linear magnetic characteristics and does not contribute to the torque production according to [22, 24], the secondary xy subspace can be modeled using constant inductance parameters and represented by an equivalent RL circuit.

$$v_{xy} = R_s i_{xy} + L_{xy} \frac{di_{xy}}{dt} \quad (2)$$

where, v_{xy} is the stator xy subspace voltage, i_{xy} is the stator xy subspace current, L_{xy} is the xy subspace inductances, and R_s is the stator resistance. In contrast, the nonlinear flux-linkage maps are only required for the torque-producing fundamental subspace. Therefore, the fundamental $\alpha\beta$ subspace is represented in the synchronous reference frame, as shown:

$$v_{dq} = R_s i_{dq} + \frac{d\varphi_{dq}}{dt} + j\omega_e \varphi_{dq} \quad (3)$$

$$v_f = R_f i_f + \frac{d\varphi_f}{dt} \quad (4)$$

where, v_{dq} is the stator d-q voltage, and v_f is the rotor field voltage. Similarly, i_{dq} is the stator d-q current, and i_f is the rotor field current. R_f denotes the rotor field-winding resistance, and ω_e is the electrical angular speed. The quantities φ_{dq} and φ_f denote the stator d-q and rotor field flux linkages, respectively.

$$\varphi_{dq} = f_{dq}(i_d, i_q, i_f) \quad (5)$$

$$\varphi_f = f_f(i_d, i_f) \quad (6)$$

where, f_{dq} denotes the experimentally obtained nonlinear d-q flux-linkage map function, which account for magnetic saturation effect. f_f denotes the nonlinear field flux-linkage function.

$$T_e = \frac{6}{2}p (\varphi_d i_q - \varphi_q i_d) \quad (7)$$

where, p denotes the number of pole pairs. Since d-q flux linkages (φ_{dq}) are functions of i_{dq} and i_f , the electromagnetic torque inherently accounts for the effects of magnetic saturation and the rotor field excitation. Consequently, multiple combinations of i_{dq} and i_f can produce the same electromagnetic torque, providing the additional degree of freedom required for copper-loss minimization.

The proposed flux-map-based LUT control system

Overall Control Architecture

The proposed six-phase EESM control architecture is shown on Fig. 2. Concerning the fundamental $\alpha\beta$ subspace, it comprises two control loops: outer speed controller loop and inner current controller loop. The outer loop comprises a PI speed controller that provides torque reference (T^*). The inner loop employs the proposed VF-LUT control, which feeds the reference torque (T^*) and speed (ω_m^*) to three LUTs that share same torque-speed breakpoints and provide the current references (i_{dq}^* , i_f^*). These LUTs are generated via offline optimization process implemented for healthy case. Therefore, there is no need for an online nonlinear optimizer during real-time operation. After that, the stator d-q current references (i_{dq}^*) are fed to PI current controllers that give the stator d-q voltage references (v_{dq}^*). These voltage references (v_{dq}^*) are transformed back to the stationary reference frame and give the stator $\alpha\beta$ voltage references ($v_{\alpha\beta}^*$). The field current reference (i_f^*) is fed to another PI current controller, which gives the field voltage reference (v_f^*) that is used to generate the PWM signal of the field chopper circuit.

Concerning the secondary xy subspace, the secondary xy subspace current references (i_{xy}^*) depend on the operating condition (healthy or 1OPF). Under healthy operation, the secondary xy subspace current references are set to zero ($i_{xy}^* = 0$). Under 1OPF operation, the secondary xy subspace current references (i_{xy}^*) are chosen based on the MTPA criteria, shown in (8), to redistribute the remaining phase currents and produce the torque demand [25].

$$i_{xy}^* = \begin{bmatrix} -1 & 0 \\ 0 & -0.3334 \end{bmatrix} i_{\alpha\beta}^* \quad (8)$$

Under the 1OPF condition, equation (8) directly determines the secondary xy current references (i_{xy}^*) from the fundamental $\alpha\beta$ current references ($i_{\alpha\beta}^*$). Therefore, i_{xy}^* are dependent variables rather than additional independent control variables. Once the optimized stator d-q current references (i_{dq}^*) are obtained and transformed to the $\alpha\beta$ reference frame ($i_{\alpha\beta}^*$), the corresponding post-fault xy current references (i_{xy}^*) are determined algebraically from (8). Accordingly, i_{xy}^* are not included as additional decision variables in the offline optimization.

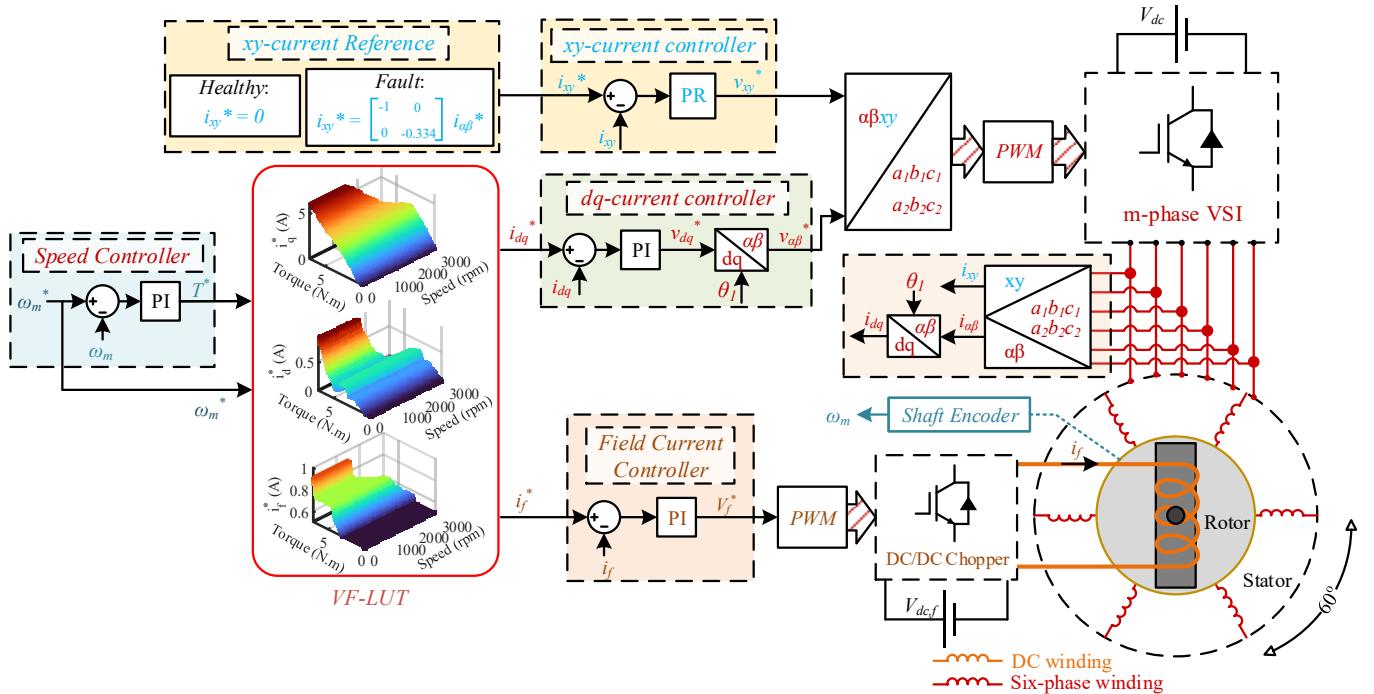


Fig. 2 The proposed flux-map-based VF-LUT control of the six-phase EESM drive system.

For both conditions, these secondary xy subspace current references (i_{xy}^*) are controlled via PR controllers, which gives the stator xy voltage references (v_{xy}^*). Since the six-phase EESM has isolated neutral points, the zero-sequence current components are

neglected. Finally, the stationary reference frame voltages ($v_{\alpha\beta}^*, v_{xy}^*$) are transformed back to the six-phase voltages via the inverse VSD transformation matrix (T^{-1}) and then, generate the PWM signal of the six-phase inverter.

The nonlinear d-q flux-linkage maps were experimentally obtained by operating the machine in torque-control mode and performing a systematic current sweep. The rotor field current i_f was successively set to 0.5, 0.75, and 1 A, while i_d and i_q were swept from -5 to 6 A and from -6 to 6 A, respectively. At each operating point, the d-q voltages (v_{dq}^*), currents (i_{dq}, i_f), and rotor speed (ω_m) are measured. Using (3), and neglecting flux-linkage derivative terms under steady-state operation, the corresponding φ_{dq} are determined from the measured quantities and the known stator resistance R_s . The resulting data are assembled to construct the three-dimensional $\varphi_{dq}(i_d, i_q, i_f)$ maps used in the offline optimization. Figure 3 confirms that rotor excitation significantly modifies the nonlinear d-q flux-linkage characteristics; therefore, the measured three-dimensional flux maps are directly used during optimization to retain saturation effect.

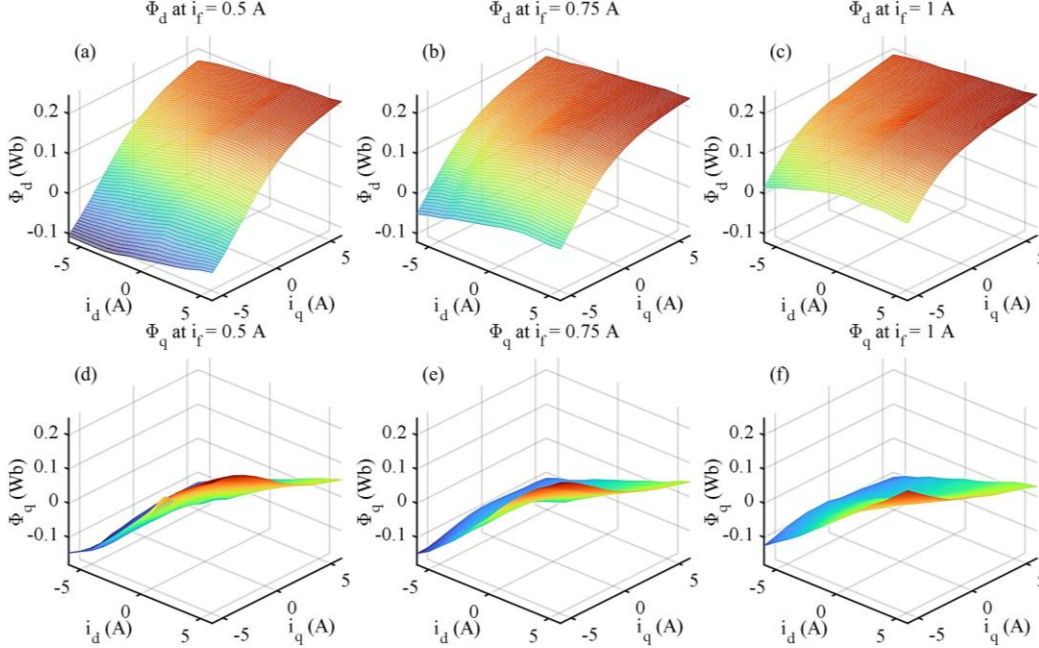


Fig. 3 The nonlinear d-q flux linkage maps (Φ_d, Φ_q) of the six-phase EESM at field current levels of 0.5A, 0.75A, 1A.

Flux-Map-Based MTCL Optimization

Due to the controllable field current, multiple feasible combinations of i_d , i_q , and i_f can produce the same torque; therefore, these currents are optimized to minimize the MTCL objective function that is defined under healthy condition as follows:

$$P_{cu,healthy} = 3R_s(i_d^2 + i_q^2) + R_f i_f^2 \quad (9)$$

The optimization problem is solved subject to the imposed maximum torque constraints (T_{max}) over the full torque-speed range, shown in Fig. 4. The torque-speed range is defined according to the rated machine requirements. The rated torque of 7 N·m is maintained up to the base speed of 1500 rpm. While above the base speed, the operating torque envelope follows the rated output power of 1.1 kW, corresponding to approximately 3.5 N·m at 3000 rpm. The field current (i_f) search is restricted to the experimentally characterized range of 0.5-1 A. Consequently, operating points, for which the optimized field current (i_f) reaches the lower bound of 0.5 A should be interpreted as boundary-constrained solutions within the measured three-dimensional d-q flux maps domain; lower field-current values are not evaluated in the present study.

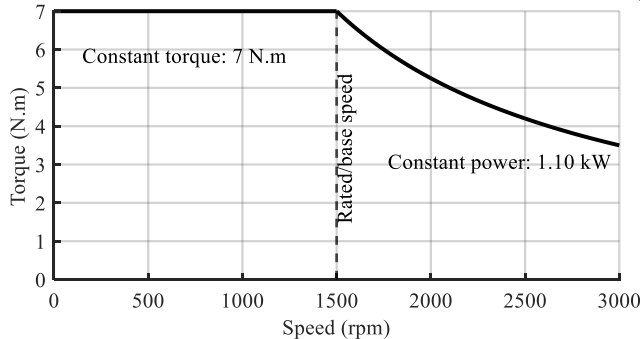


Fig. 4 The torque-speed operating envelope.

The electromagnetic torque is evaluated using the nonlinear d-q flux maps and the stator d-q currents (i_{dq}^*) using (7), such that the stator current magnitude (I_s) is constrained by (10).

$$I_s = \sqrt{i_d^2 + i_q^2} \leq i_s^{\max} \quad (10)$$

where, $i_s^{\max}$ is the rated stator phase current magnitude (7A). In addition, the derivative terms in (3) become zero ($\frac{d\phi_d}{dt} = \frac{d\phi_q}{dt} = 0$) due to steady state operation. Hence, the stator d-q voltage magnitude (V_{dq}) can be obtained by (11) and constrained by 90% of the rated stator phase voltage magnitude ($V_s^{\max}$) that is 80V.

$$V_{dq} = \sqrt{(R_s i_d - \omega_e \phi_q)^2 + (R_s i_q + \omega_e \phi_d)^2} \leq 0.9 V_s^{\max} \quad (11)$$

Although the VF-LUT is generated using the healthy-case d-q flux maps and the decision variables i_{dq} and i_f , the available stator d-q voltage (v_{dq}) is intentionally derated to provide voltage headroom for post-fault secondary xy current (i_{xy}^*) regulation. The secondary xy subspace of the investigated six-phase EESM is characterized by a relatively low impedance; therefore, the xy voltage (v_{xy}^*) required to regulate the post-fault xy currents (i_{xy}^*) is considerably smaller than the fundamental $\alpha\beta$ voltage ($v_{\alpha\beta}^*$). Accordingly, a 10% safety margin is reserved during offline optimization, such that the stator d-q voltage magnitude (V_{dq}) constraint is limited to 90% of the rated stator voltage capability ($V_s^{\max}$). The remaining voltage headroom is retained for the secondary xy voltage (v_{xy}) required to enforce the post-fault current references defined by (8).

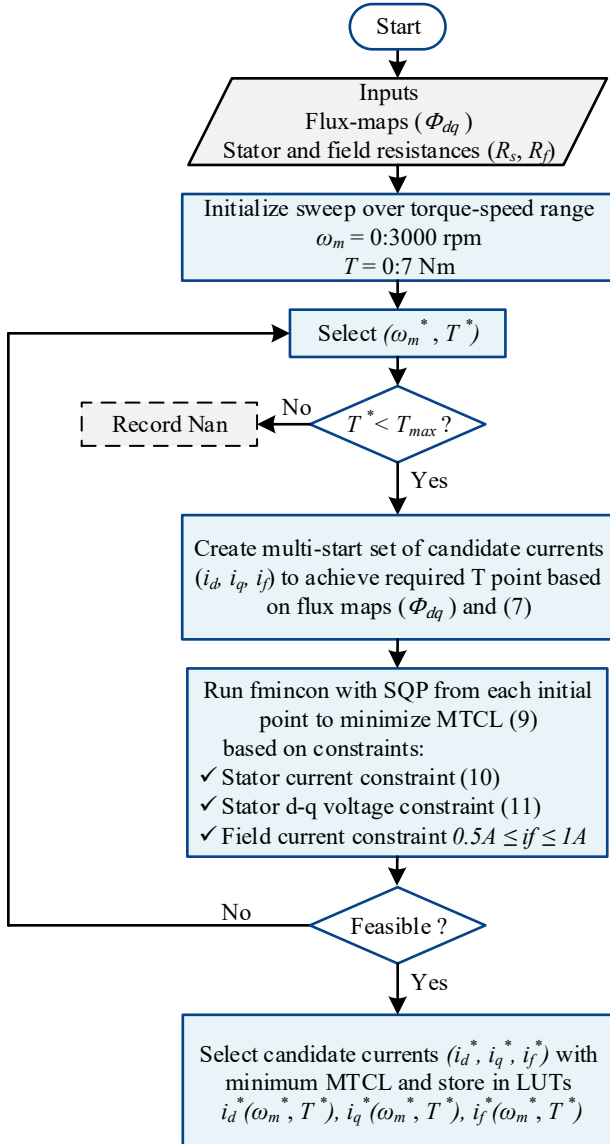


Fig. 5 The proposed VF-LUT creation process for MTCL optimization.

For higher speed operation, flux-weakening becomes mandatory to avoid exceeding the rated stator voltage ($V_s^{\max}$). Accordingly, flux-weakening can be achieved by coordinating the stator d-axis current (i_d) with the rotor field current (i_f). Based on the torque-

speed range and the mention voltage and current constraints, two LUTs are generated: the constant-field LUT (CF-LUT) and the variable-field LUT (VF-LUT). In the CF-LUT, the field current (i_f) is fixed at its rated value of 1 A, while the stator d-q currents references (i_{dq}^*) are optimized. In the proposed VF-LUT, the stator d-q currents (i_{dq}^*) and the rotor field current (i_f) are optimized. At each torque-speed operating point, i_d , i_q , and i_f are optimized as continuous variables using trilinear interpolation of the measured three-dimensional d-q flux maps. The offline constrained optimization is solved using MATLAB fmincon with multi-start Sequential Quadratic Programming (SQP) algorithm. Figure 5 summarizes the proposed offline MTCL optimization, and the resulting optimal current references are stored in the torque-speed LUT for real-time implementation.

The resulting current reference trajectories of the proposed VF-LUT are compared with that of the conventional FOC over the operating torque-speed range under healthy condition. In the conventional FOC, the stator d-axis current (i_d^*) is maintained at zero, while the current reference distributions for i_q^* and i_f^* are shown in Fig. 6. The stator q-axis current (i_q^*) increases with torque demand, while the field current reference (i_f^*) remains at its rated value (1A) below the base speed and decreases progressively in the field-weakening region.

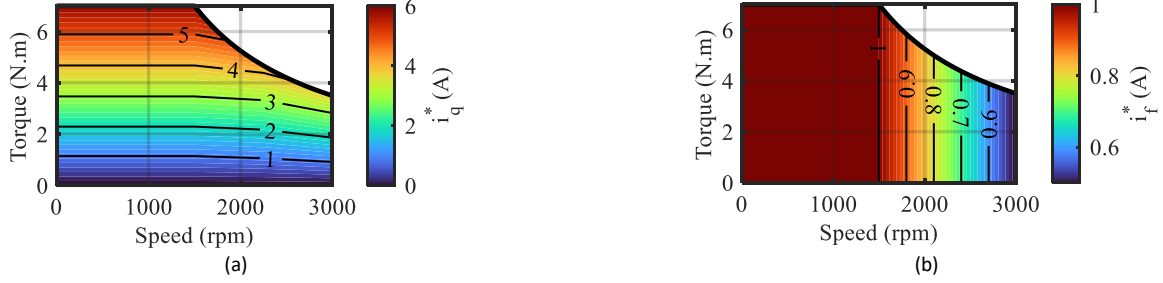


Fig. 6 The conventional FOC current reference distributions: (a) q-axis current reference (i_q^*), (b) field-current reference (i_f^*).

While the current reference maps of i_d^* , i_q^* and i_f^* generated by the proposed VF-LUT are shown in Fig. 7. The field current (i_f^*) remains close to its lower bound over a significant portion of the low-load region and increases with torque demand, while the stator d-q current references (i_{dq}^*) vary across the torque-speed range based on the operating point.

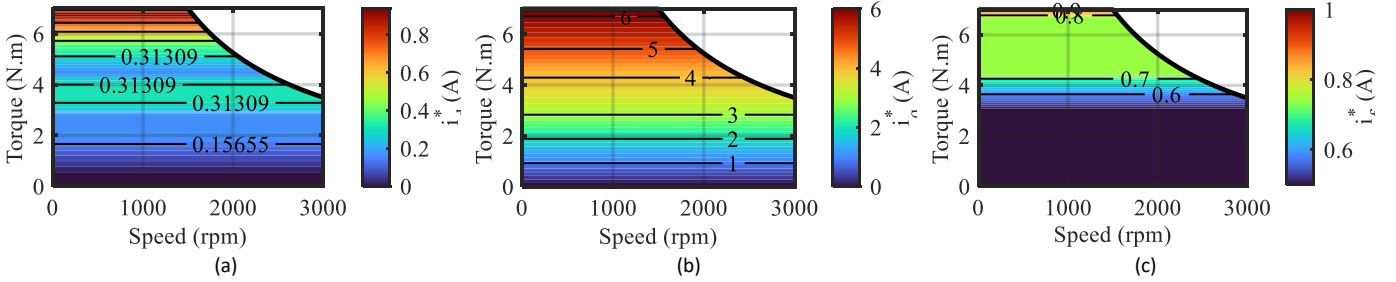


Fig. 7 The proposed VF-LUT current reference maps: (a) d-axis current reference (i_d^*), (b) q-axis current reference (i_q^*), and (c) field-current reference (i_f^*).

Figure 8 shows the combined stator and rotor field copper loss distributions for the two control strategies. The VF-LUT exhibits lower copper loss over most of the torque-speed range, with the largest differences occurring at low and medium torque points. At higher torque values, there is a smaller difference between the two strategies as the required stator and field current levels increase.

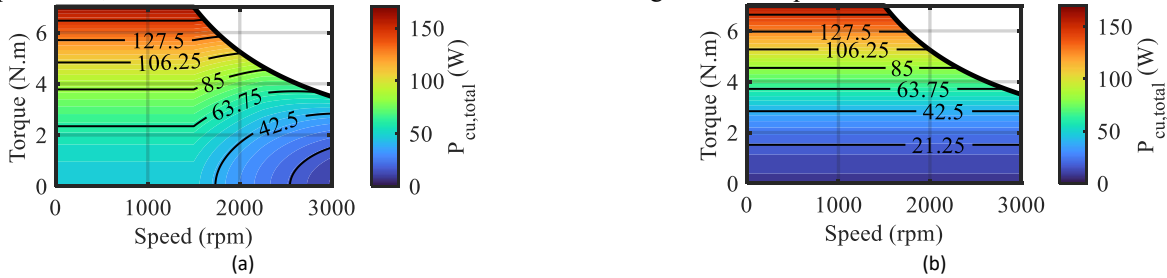


Fig. 8 Comparison of the combined stator and rotor field copper loss under healthy operation: (a) conventional FOC and (b) proposed VF-LUT.

Experimental validation

The dynamic and steady-state performance of the investigated EESM drive is experimentally evaluated using the proposed VF-LUT control (shown in Fig. 2) and the conventional FOC under healthy and IOPF conditions. The experimental setup is shown in Fig. 9. It comprises an EESM that features a six-phase symmetrical winding on stator and a DC field winding on rotor. The stator six-phase winding is fed by two three-phase voltage source inverters (VSIs) supplied from a 160V DC source. While the rotor field winding is fed through a DC/DC chopper supplied from a 60V DC source. Both converters are controlled using dSPACE-MicroLabBox-DS1202 platform with sampling frequency of 13.33 kHz. Currents are measured using LA-55-PLEM current sensor

boards, while the mechanical speed is measured using an E6B2-CWZ1X incremental encoder. The motor torque is estimated based on (7) using the measured stator d-q currents and the obtained d-q flux maps. The EESM shaft is mechanically coupled with a DC generator serving as a mechanical load. For healthy condition, steady-state performance has been investigated for the VF-LUT, the CF-LUT and the FOC control strategies. In addition, dynamic performance has been investigated using synchronized torque-speed profiles for both the VF-LUT and the FOC control strategies. For the 1OPF condition, the dynamic performance has been investigated for the VF-LUT and the FOC control strategies.

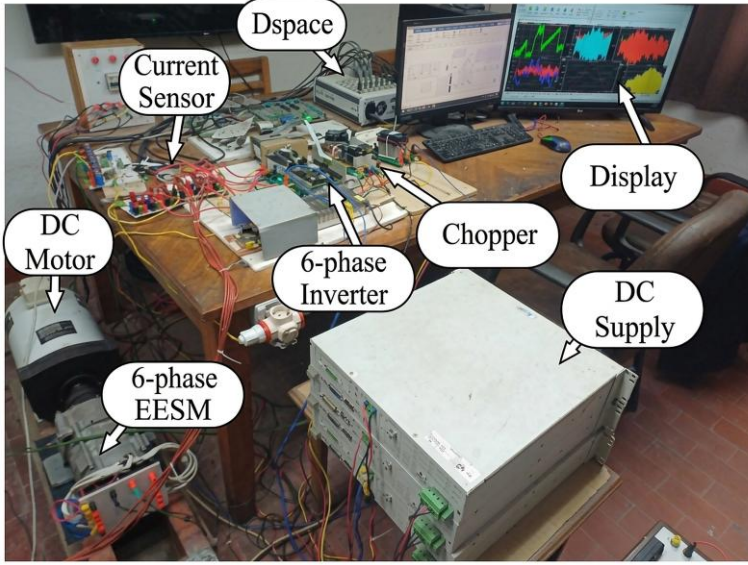


Fig. 9 Experimental test bench of the six-phase EESM drive system.

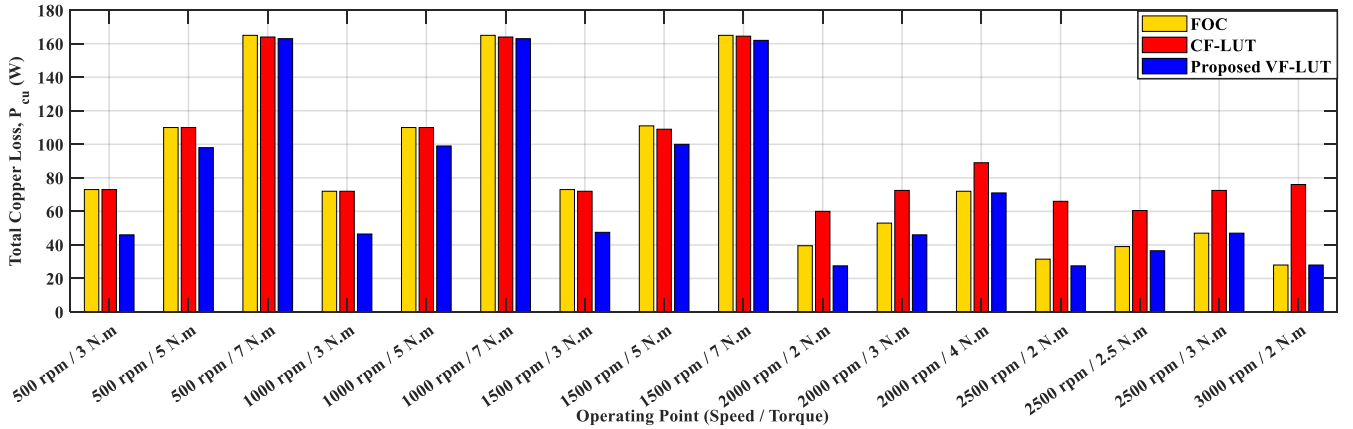


Fig. 10 Experimental steady-state comparison of the total copper-loss for VF-LUT, CF-LUT, and FOC under healthy-condition.

Steady-State Performance Comparison of VF-LUT, CF-LUT, and FOC under Healthy-Condition

In steady-state comparison, the proposed VF-LUT, the CF-LUT, and the FOC are experimentally investigated at same 17 speed-torque points. The CF-LUT uses fixed rated field current to study the performance without using variable-field optimization. The total copper loss has been calculated using (9) for the three control techniques and represented as shown in Fig.10. It can be noticed that the proposed VF-LUT yields lower total copper-loss when compared to CF-LUT and FOC with an average reduction of approximately 21.9 W and 8.57 W, respectively. Additionally, for operating points with rated torque (7 N.m) and below rated speed (1500 rpm), the reduction in total copper loss can be neglected for the three control methods. While the largest benefit occurs at low and medium load conditions, where field-current optimization reduces the rotor field copper-loss component.

Dynamic Performance Comparison of VF-LUT and FOC under Healthy-Condition

The healthy-condition dynamic performance of the proposed VF-LUT and the conventional FOC is experimentally evaluated using a predefined torque-speed profile to assess speed and current-reference tracking, voltage-limit compliance, and the total copper loss calculated using (9). Figure 11 shows the dynamic response results of the conventional FOC and the proposed VF-LUT, which validates stable tracking of speed and current references under healthy operation. It can also be noticed that the proposed VF-LUT exhibits lower accumulated total copper-loss energy over the experimental test interval, decreasing from 5.5782 kJ with conventional FOC to 3.8127 kJ with the proposed VF-LUT strategy, corresponding to a reduction of approximately 31.65%.

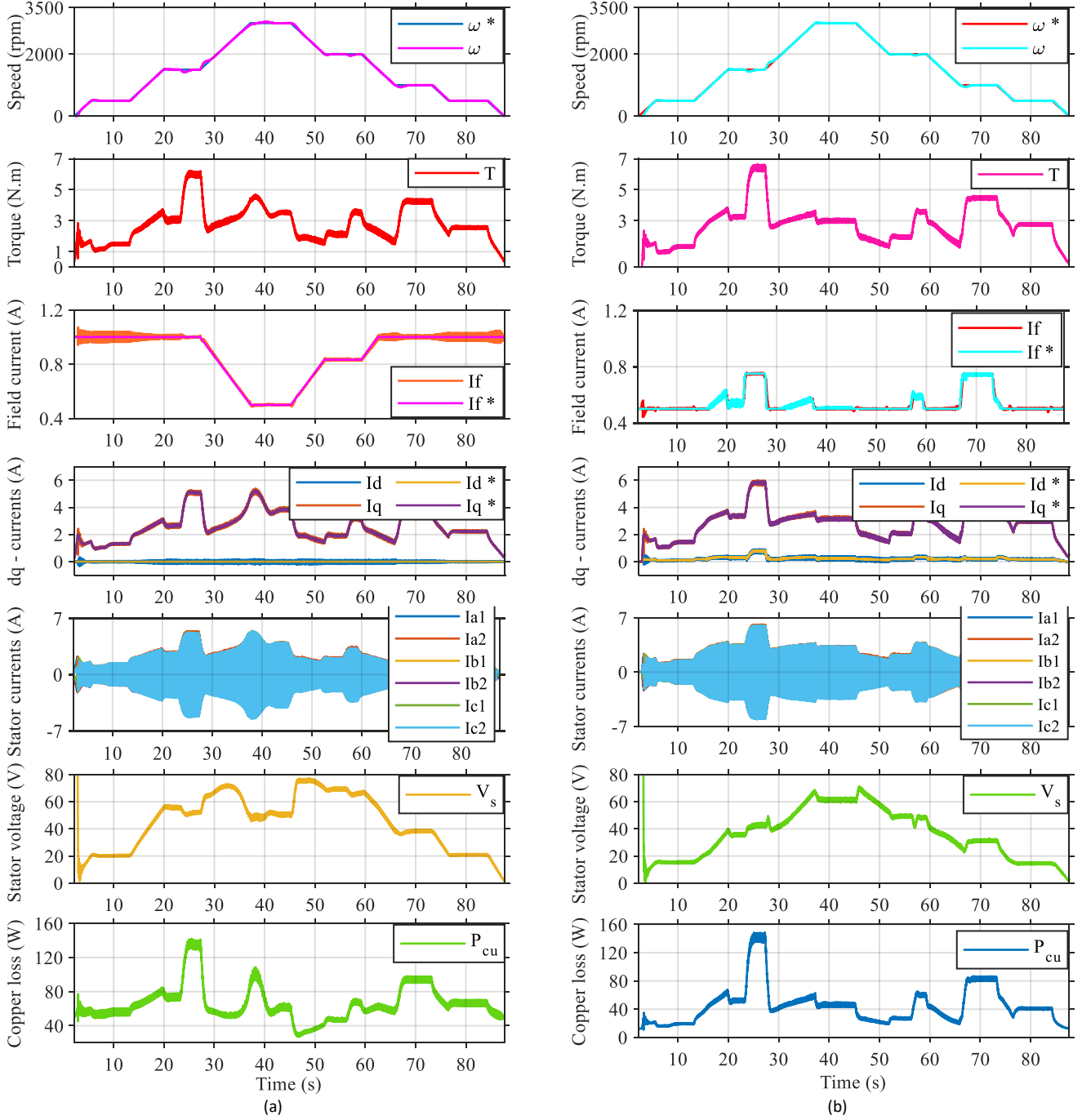


Fig. 11 Experimental results of the dynamic response under Healthy-condition for (a) FOC (b) VF-LUT.

Dynamic Performance Comparison of VF-LUT and FOC under 1OPF-Condition

The fault-tolerant capability of the conventional FOC and the proposed VF-LUT strategies is further evaluated experimentally under a 1OPF condition using a predefined torque-speed profile with lower load torque due to fault. In this test, the post-fault operation is studied using the criterion in (8), where phase-a1 is open, and assessed based on the speed and currents reference-tracking, voltage limitations, and the calculated total copper-loss. Under 1OPF condition, the secondary-subspace currents contribute to the stator copper loss and are therefore included in the post-fault loss evaluation. Since the zero-sequence components are absent due to the isolated neutral points, the calculated total copper loss under the 1OPF is expressed as:

$$P_{cu,fault} = 3R_s(i_d^2 + i_q^2 + i_x^2 + i_y^2) + R_f i_f^2 \quad (12)$$

Figure 12 shows the dynamic response results of the conventional FOC and the proposed VF-LUT under 1OPF-condition, demonstrating continued operation through redistribution of the remaining phase currents while maintaining stable speed regulation. Under 1OPF-condition, the accumulated total copper-loss energy decreases from 4.2658 kJ with conventional FOC to

2.0037 kJ with the proposed VF-LUT strategy, corresponding to a reduction of approximately 53.03%. The post-fault loss calculation includes the secondary-subspace current contribution according to the formulation in (12).

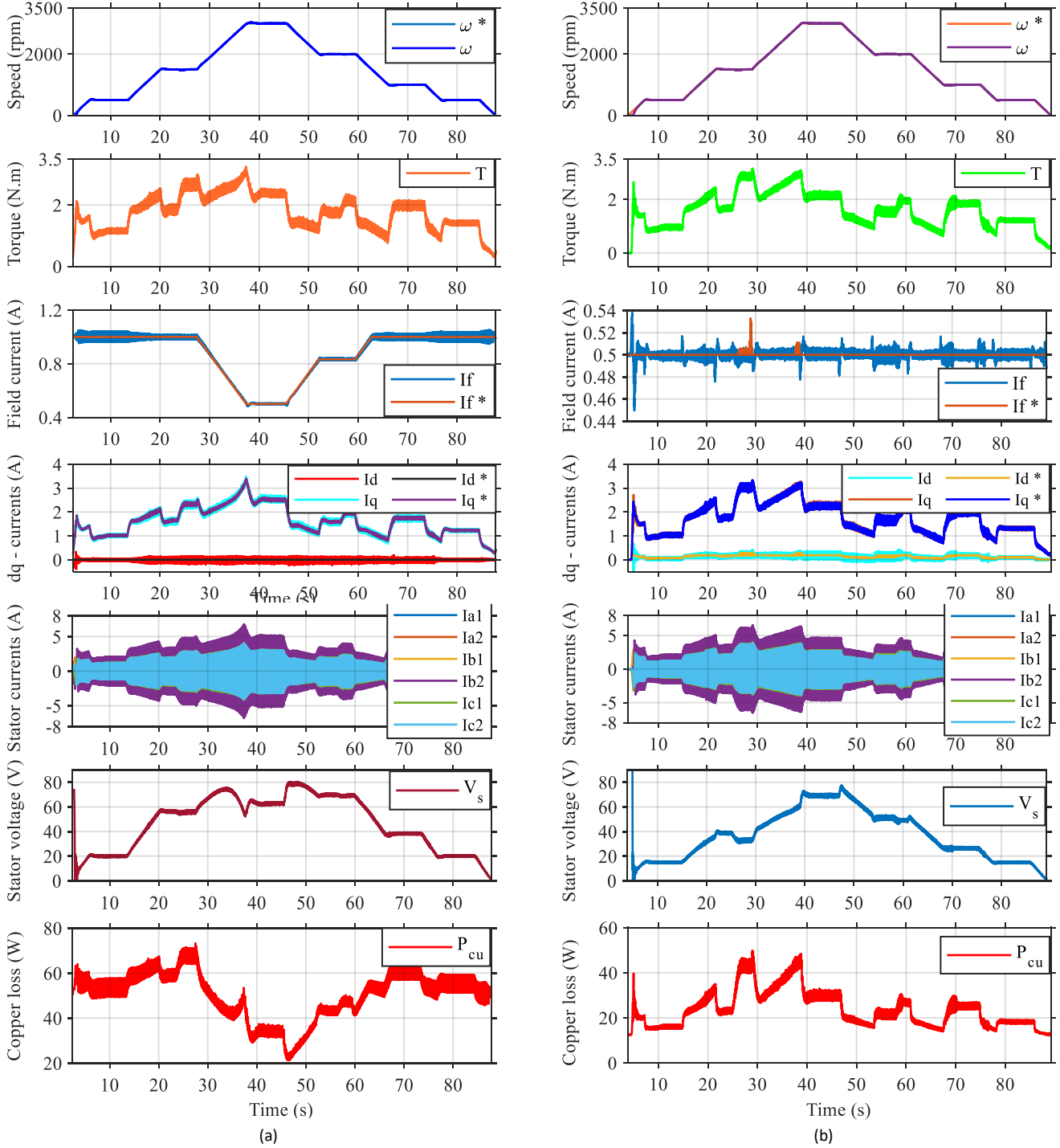


Fig. 12 Experimental results of the dynamic response under 10PF-condition for (a) FOC (b) VF-LUT.

Conclusion

This paper presented a flux-map-based VF-LUT control strategy for copper-loss-minimization current-reference generation and fault-tolerant control of a six-phase EESM. Experimentally obtained nonlinear d-q flux-linkage maps were used to optimize the stator d-q and rotor field currents while accounting for magnetic saturation. At 17 matched healthy operating points, the proposed VF-LUT reduced the combined stator and rotor field copper loss by an average of 8.57 W relative to conventional FOC. Dynamic performance has confirmed stable speed and currents regulation. Under a 10PF-condition, continued operation was maintained through secondary-subspace current compensation, while the accumulated total copper-loss energy decreased from 4.2658 kJ to 2.0037 kJ, corresponding to a 53.03% reduction. The experimental results confirm the copper-loss-reduction and fault-tolerant capabilities of the proposed six-phase EESM control strategy.

References

1. Monadi, M., Nabipour, M., Akbari-Behbahani, F. & Pouresmaeil, E. Speed control techniques for permanent magnet synchronous motors in electric vehicle applications toward sustainable energy mobility: a review. *IEEE Access* **12**, 119615–119632 (2024).
2. Chen, H. et al. Investigation of a 3D-magnetic flux PMSM with high torque density for electric vehicles. *IEEE Trans. Energy Convers.* **37**(2), 1442–1454 (2022).
3. Shen, J. et al. Online switching strategy between dual three-phase PMSM and open-winding PMSM. *IEEE Trans. Transp. Electrification* **10**(1), 1519–1529 (2024).
4. Ghorbani, Y., Ilankoon, I. M. S. K., Dushyantha, N. & Nwaila, G. T. Rare earth permanent magnets for the green energy transition: Bottlenecks, current developments and cleaner production solutions. *Resour. Conserv. Recycl.* **212**, 107966 (2025).
5. Kim, H.-V., Kim, D.-H. & Lee, J.-S. Comparison of flux-weakening control methods for wound field synchronous motor. In *2024 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2403–2408 (IEEE, 2024).
6. Stancu, C., Ward, T., Rahman, K. M., Dawsey, R. & Savagian, P. Separately excited synchronous motor with rotary transformer for hybrid vehicle application. *IEEE Trans. Ind. Appl.* **54**(1), 223–232 (2018).
7. Chai, W., Zhao, W. & Kwon, B.-I. Optimal design of the wound field synchronous reluctance machines to improve torque by increasing saliency ratio. *IEEE Trans. Mag.* **53**(11), 1–4 (2018).
8. Abdel-Moneim, M. G., Ismail, A., Abdel-Wahed, A. T., Abdel-Khalik, A. S. & Ahmed, S. Experimental assessment and mathematical modeling of a self-excited wound rotor synchronous motor with multiphase stator design. *IEEE Trans. Energy Convers.* **41**(3), 2053–2065 (2026).
9. Deriszadeh, A., Calasan, M. P., Alaei, A. & Gieras, J. F. A novel field current estimation method for brushless wound-field synchronous machine. *IEEE Trans. Transp. Electrification* **8**(3), 3524–3533 (2022).
10. Sun, T., Wang, J. & Chen, X. Maximum torque per ampere (MTPA) control for interior permanent magnet synchronous machine drives based on virtual signal injection. *IEEE Trans. Power Electron.* **30**(9), 5036–5045 (2015).
11. Gallegos-Lopez, G., Gunawan, F. S. & Walters, J. E. Optimum torque control of permanent-magnet AC machines in the field-weakened region. *IEEE Trans. Ind. Appl.* **41**(4), 1020–1028 (2005).
12. Ionta, A. et al. Direct flux vector control of electrically excited synchronous machines for electrical vehicles. In *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, 6431–6438 (IEEE, 2024).
13. Guldan, M. M., Akgul, K., Tap, A. & Ergene, L. T. Variable speed control of wound rotor synchronous motor with MTPA technique. In *2023 International Aegean Conference on Electrical Machines and Power Electronics & 2023 International Conference on Optimization of Electrical and Electronic Equipment (ACEMP-OPTIM)*, 1–6 (IEEE, 2023).
14. Kim, Y. & Nam, K. Copper-loss-minimizing field current control scheme for wound synchronous machines. *IEEE Trans. Power Electron.* **32**(2), 1335–1345 (2017).
15. Breda, R., Andrioli, G., Calligaro, S. & Petrella, R. Extended MTPA and flux-weakening control with total copper loss minimisation and transient torque compensation for wound-rotor synchronous machines. In *2023 IEEE Energy Conversion Congress and Exposition (ECCE)*, 4829–4836 (IEEE, 2023).
16. Kim, J.-S., Ryu, J.-H., Kim, D.-H. & Lee, J.-S. Single look-up table creation method for copper-loss minimization in a wound-field synchronous motor. *IEEE Trans. Transp. Electrification* **11**(6), 13404–13415 (2025).
17. Mademlis, C. & Agelidis, V. G. On considering magnetic saturation with maximum torque to current control in interior permanent magnet synchronous motor drives. *IEEE Trans. Energy Convers.* **16**(3), 246–252 (2001).
18. Hwang, D. & Gu, B.-G. Field current control strategy for wound-rotor synchronous motors considering coupled stator flux linkage. *IEEE Access* **8**, 111811–111821 (2020).
19. Hruska, K., Glac, A. & Suchy, O. Verification of maximum torque per Joule loss control of a wound-rotor synchronous machine with strongly non-linear parameters. *Electronics* **14**(24), 4924 (2025).
20. Wang, Q., Lee, H.-H., Park, H.-J., Kim, S.-I. & Lee, G.-H. An off-line maximum torque control strategy of wound rotor synchronous machine with nonlinear parameters. *J. Electr. Eng. Technol.* **11**(3), 609–617 (2016).
21. Kim, J.-S., Kim, D.-H., Lee, J.-H. & Lee, J.-S. Copper-loss minimizing strategy based on single look-up table for wound field synchronous machine. In *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, 6425–6430 (IEEE, 2024).
22. Eldeeb, H. M., Abdel-Khalik, A. S., Kullick, J. & Hackl, C. M. Pre- and postfault current control of dual three-phase reluctance synchronous drives. *IEEE Trans. Ind. Electron.* **67**(5), 3361–3373 (2020).
23. Lu, L. et al. Fault-tolerant optimization control of open-winding dual three-phase PMSM drives in full operation range. *IEEE Trans. Power Electron.* **40**(2), 3385–3394 (2025).
24. Eldeeb, H. M., Abdel-Khalik, A. S. & Hackl, C. M. Dynamic modeling of dual three-phase IPMSM drives with different neutral configurations. *IEEE Trans. Ind. Electron.* **66**(1), 141–151 (2019).
25. Munim, W. N. W. A. et al. A unified analysis of the fault tolerance capability in six-phase induction motor drives. *IEEE Trans. Power Electron.* **32**(10), 7824–7836 (2017).

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