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An Online Fault-Tolerant Optimization Strategy of Copper Loss for Dual Three-Phase PMSM drives

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Abstract: Dual three-phase PMSM drives have gained more and more attention by the merit of fault-tolerance ability. Thanks to the additional degrees of freedom, different system optimization targets can be achieved under post-fault condition while guaranteeing torque-ripple-free control performance. For a universal control scheme with natural fault-tolerance, the system optimization is determined by the amplitude ratio and phase shift of the positive-sequence current components between two sets of three-phase windings. On this basis, the linear interpolation of current amplitude ratio has been employed in the proposed method for the transition between minimum loss (ML) strategy and (maximum torque) MT strategy.

Minimum Loss (ML) Strategy

I: Objection function:

$$F_1 = \min_{\{K_1,K_2,K_3,K_4\}} \sum_{\gamma=A}^{F} \left\| I_\gamma \right\|^2 / (6\left\| I_{rated}^2 \right\|)$$

Subject to

$$\mathrm{C1}: (T_{VSD})_\lambda^{-1}[I_\alpha; I_\beta; I_x; I_y; 0; 0] = 0$$

Maximum Torque current (MT) Strategy

II: Objection function:

$$F_2 = \min_{\{K_1,K_2,K_3,K_4\}} \max \sum_{\gamma=A}^{F} \left\| I_\gamma \right\|$$

Subject to

$$\mathrm{C1}: (T_{VSD})_\lambda^{-1}[I_\alpha; I_\beta; I_x; I_y; 0; 0] = 0$$

Full-Range Minimum Losses (off-line)

III: Objection function:

$$F_3 = \min_{\{K_1,K_2,K_3,K_4\}} \sum_{\gamma=A}^{F} \left\| I_\gamma \right\|^2 / (6\left\| I_{rated}^2 \right\|)$$

Subject to

$$\mathrm{C1}: (T_{VSD})_\lambda^{-1}[I_\alpha; I_\beta; I_x; I_y; 0; 0] = 0$$

II. Solution:

$$K_1 = 0; K_2 = 0;$$
$$K_3 = 0; K_4 = -1$$

III. Maximum torque current of ML strategy (p.u.):

$$I_{\alpha\beta}^{ML} = 2/\sqrt{13}$$

II. Solution:

$$K_1 = -1; K_2 = 0;$$
$$K_3 = 0; K_4 = -1$$

III. Maximum torque current of MT strategy (p.u.):

$$I_{\alpha\beta}^{MT} = 2/\sqrt{12}$$

$$\mathrm{C2}: (T_{VSD})_\delta^{-1}[I_\alpha; I_\beta; I_x; I_y; 0; 0] \le I_{rated},$$
$$\delta = 1, 2, \ldots 6, \delta \ne \lambda$$

The complicated solution of FRML strategy can be calculated offline as shown in Fig. 1.

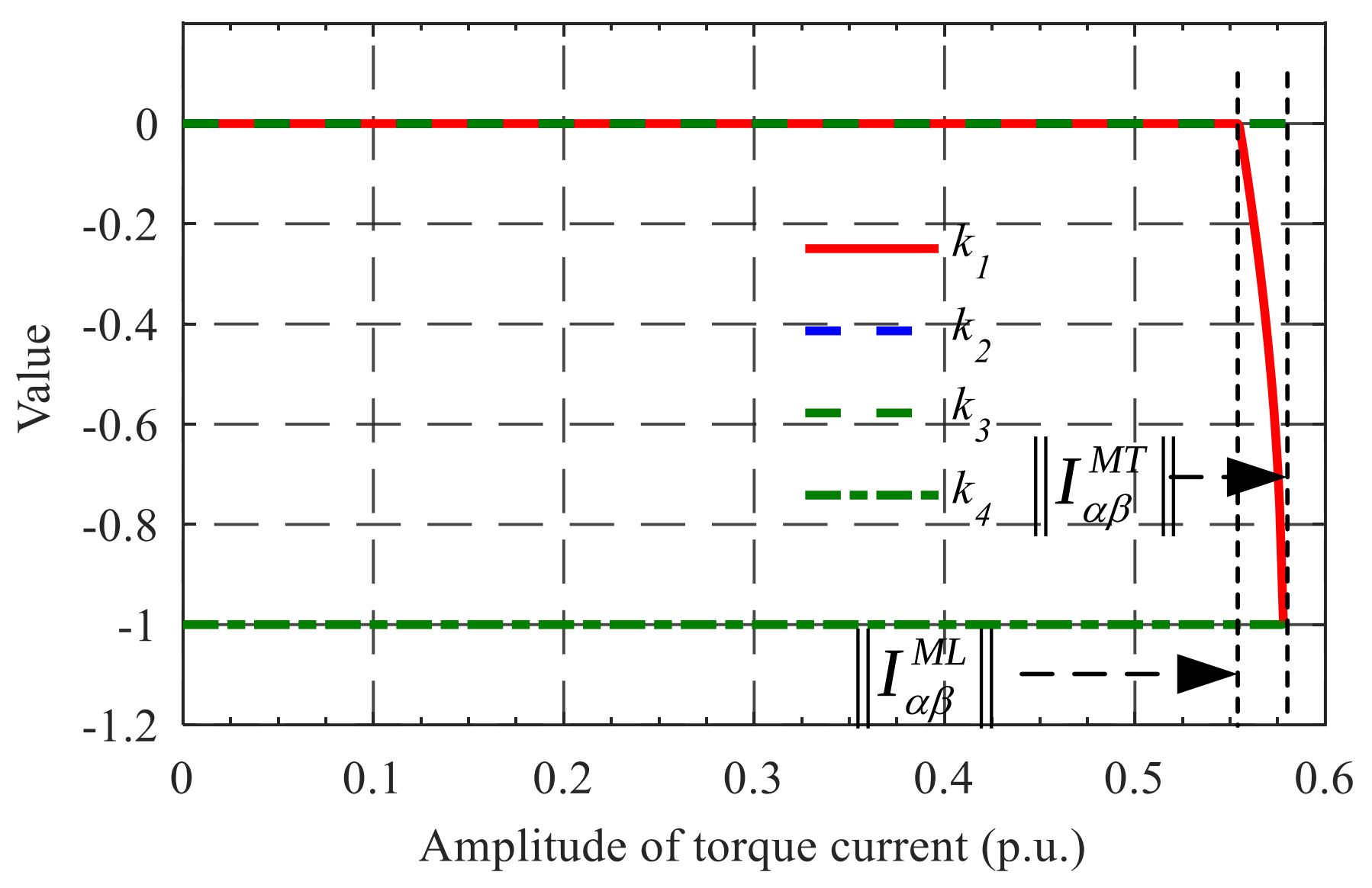

Fig. 1. The coefficients of FRML strategy with respect to the amplitude of torque current.

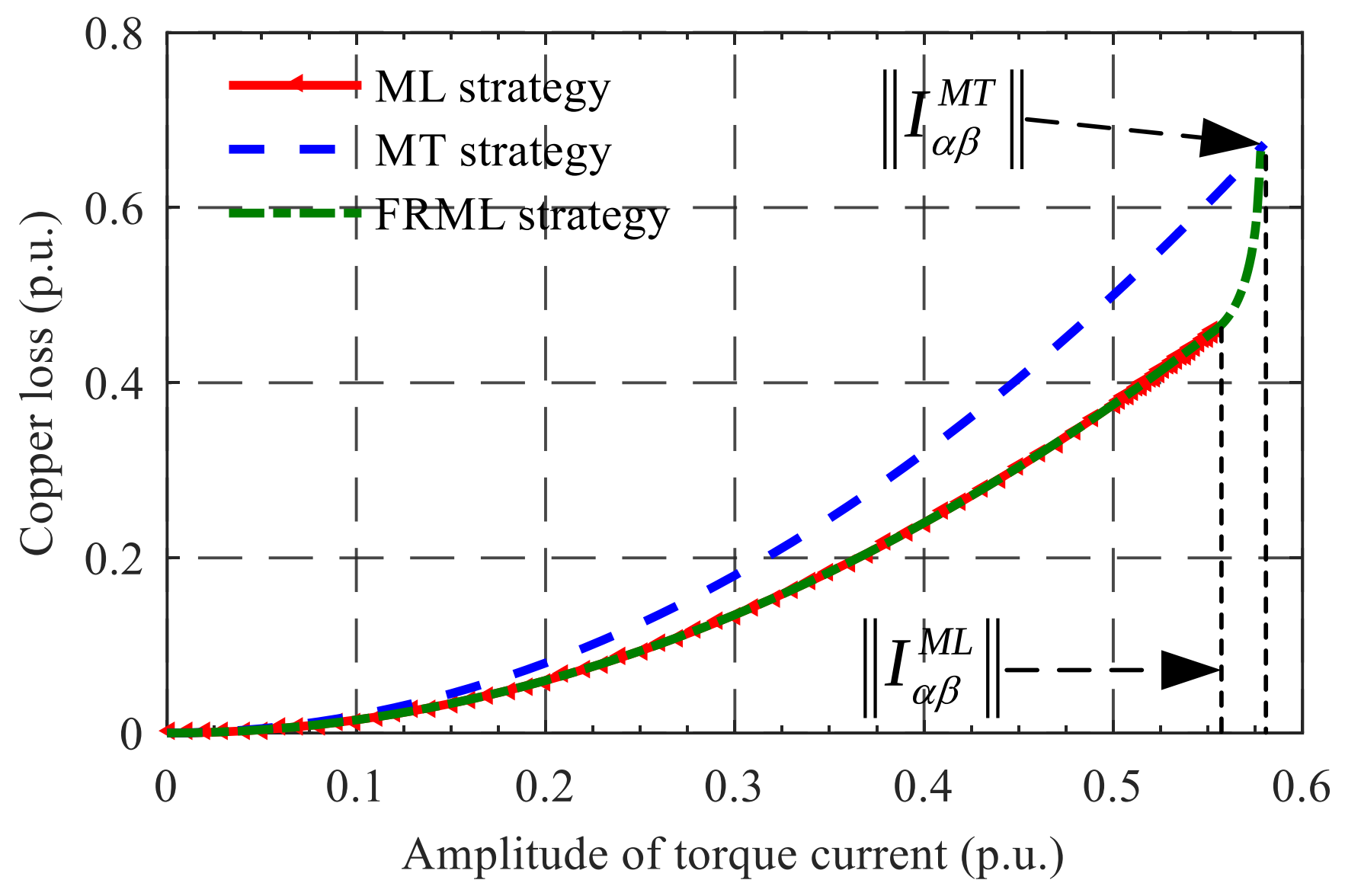

Fig. 2. Copper loss comparison of different optimization strategies with respect to the amplitude of torque current.

Current setting under Fault-tolerance in different domains:

$$I_x = K_1 I_\alpha + K_2 I_\beta$$
$$I_y = K_3 I_\alpha + K_4 I_\beta$$

Time domain

V.S

$$\boldsymbol{I}_{z1z2}^{P} = \frac{ke^{-j\theta_{shift}} - 1}{1 + ke^{-j\theta_{shift}}} \boldsymbol{I}_{dq}^{*}$$

Frequency domain

Objection function with respect to frequency variable:

$$F_1 = \min_{\{k,\theta_{shift}\}} \sum_{\gamma=A}^{F} \left\| I_\gamma \right\|^2 / (6\left\| I_{rated}^2 \right\|)$$

No constraints

Solution in frequency domain:

$$\text{ML:} \quad \{k_{ML}, \theta_{ML}\} = \begin{cases} k = 3, \theta_{shift} = 0 & \text{fault phase } \in \text{D,E,F} \\ k = 1/3, \theta_{shift} = 0 & \text{fault phase } \in \text{A,B,C} \end{cases}$$

$$\text{MT:} \quad \{k_{MT}, \theta_{MT}\} = \{k = 1, \theta_{shift} = 0\}$$

Proposed online copper loss optimization method:

$$k = k_{ML} + \frac{k_{MT} - k_{ML}}{\left\|I_{\alpha\beta}^{MT}\right\| - \left\|I_{\alpha\beta}^{ML}\right\|}(I_{torque} - \left\|I_{\alpha\beta}^{ML}\right\|); \theta_{shift} = 0$$

$$I_{torque} = \begin{cases} \left\|I_{\alpha\beta}^{ML}\right\| & \left\|I_{\alpha\beta}\right\| \le \left\|I_{\alpha\beta}^{ML}\right\| \\ \left\|I_{\alpha\beta}\right\| & \left\|I_{\alpha\beta}\right\| \ge \left\|I_{\alpha\beta}^{ML}\right\| \end{cases}$$

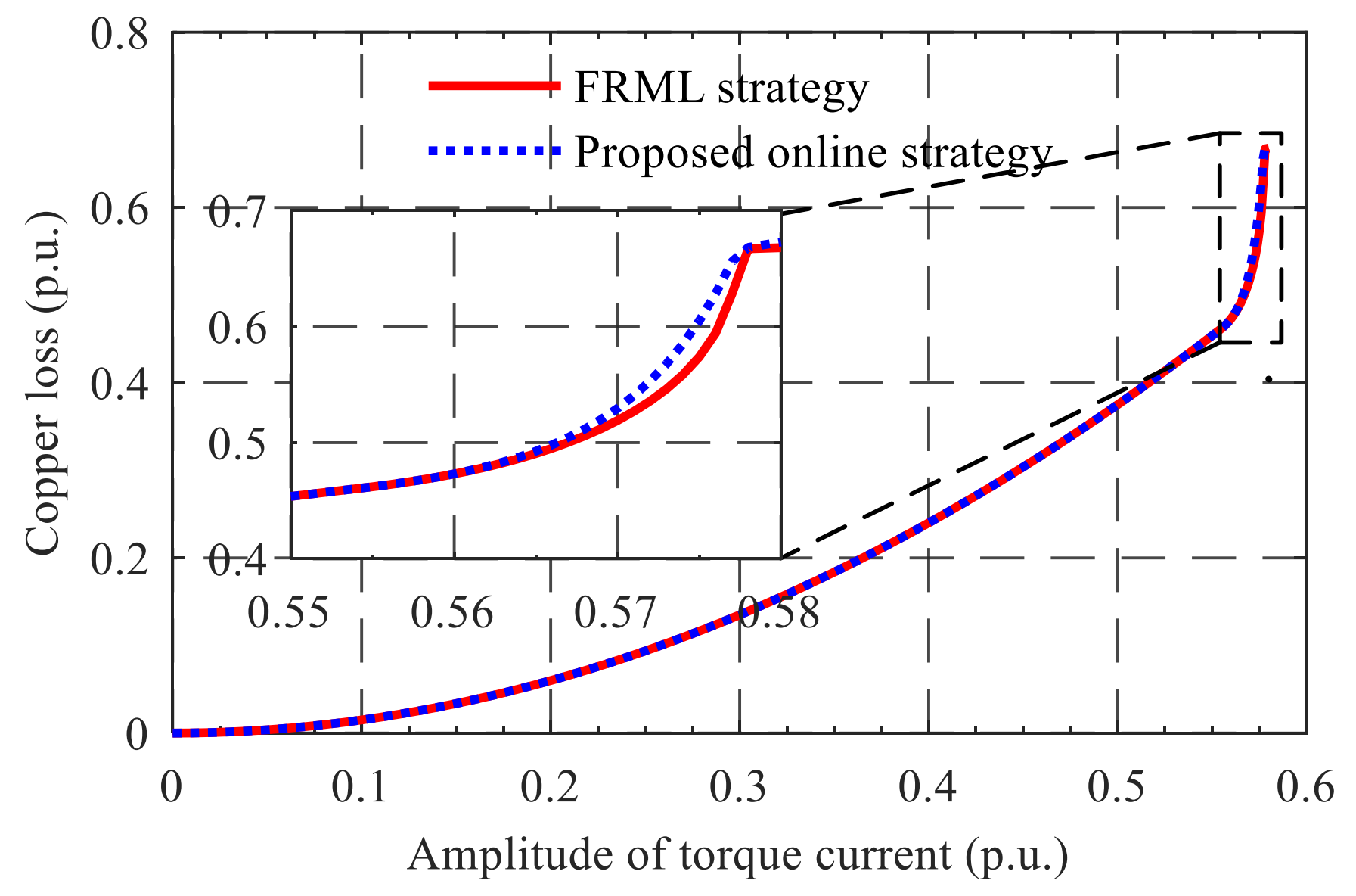

Fig. 3. Copper loss comparison of different optimization strategies (FRML and proposed online strategy) with respect to the amplitude of torque current.

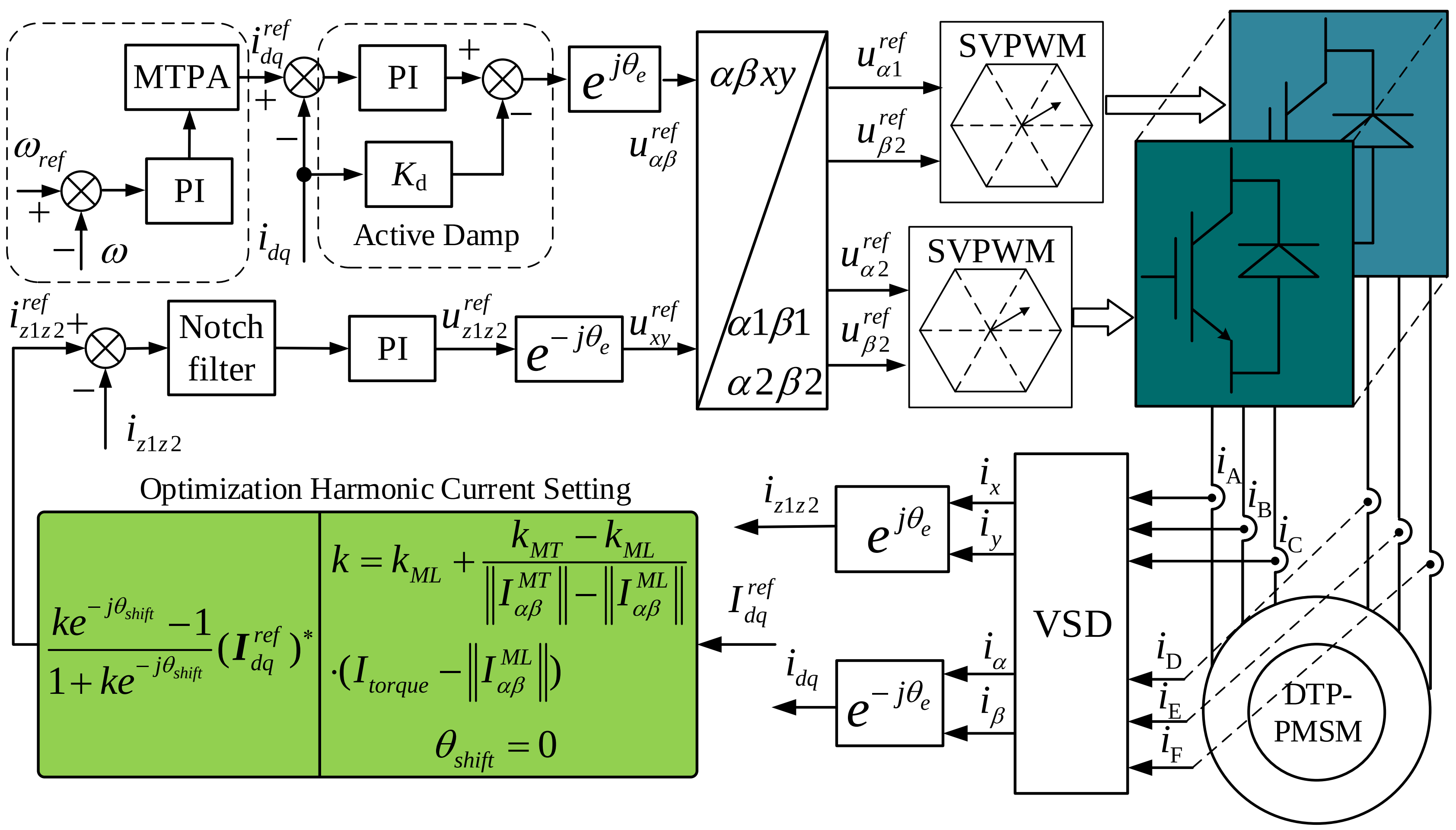

Fig. 4. Universal control scheme of dual three-phase PMSM drives with proposed online optimization strategy of minimum copper loss.

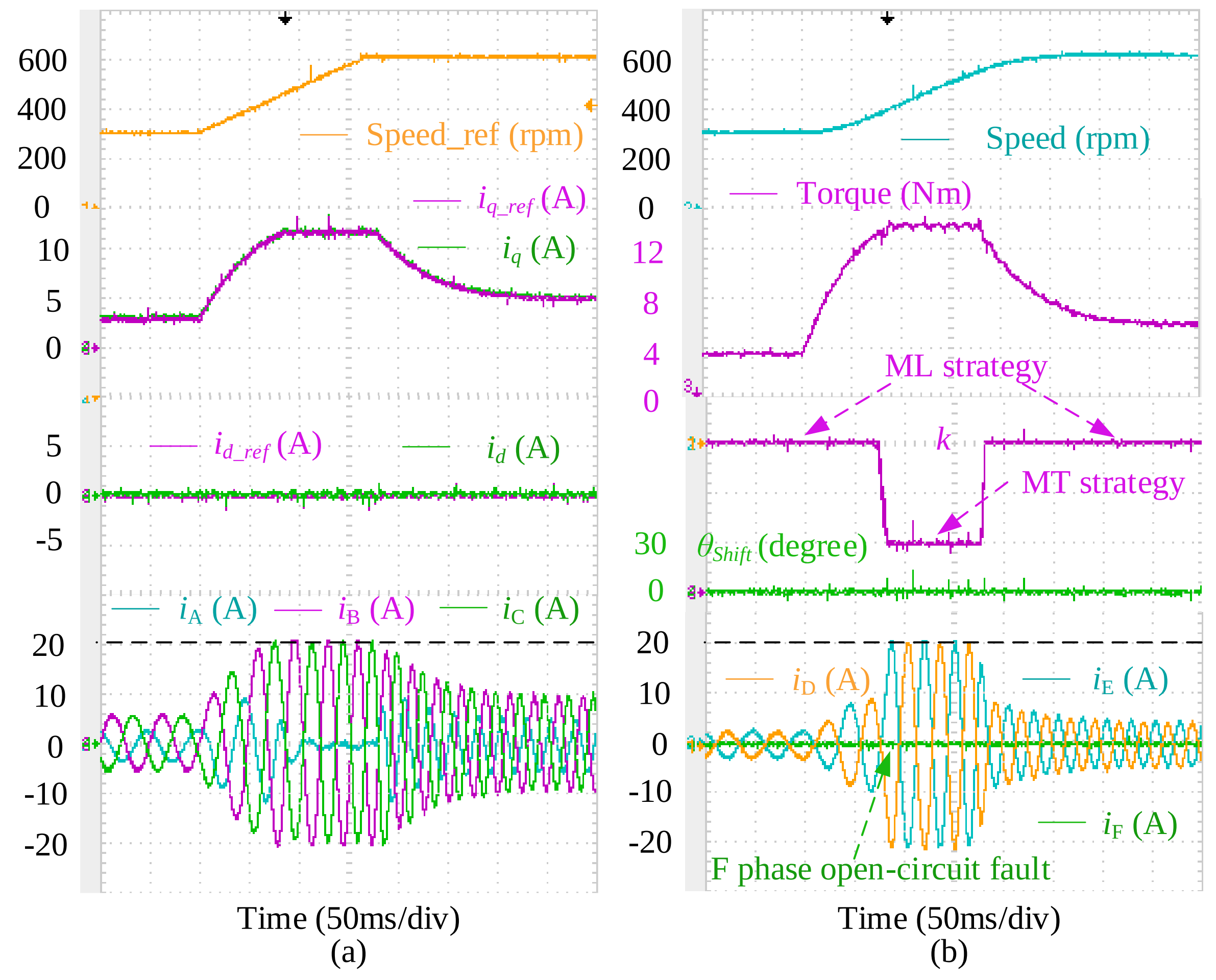

Fig. 5. Dynamic experiment of control scheme with proposed online optimization method under the fault of F phase open-circuit.

Conclusion: The proposed method can not only achieve the minimum copper loss in most torque region, but also ensure the enough torque range as wide as the MT strategy. Compared to the FRML strategy, the proposed online method is easy to be implemented in digital controller by avoiding the massive data stored with a look-up table. The simulation and experimental results have illustrated the feasibility of proposed optimization strategy on copper loss.