Frequency analysis in fault detection of dual-channel BLDC motors with combined star–delta winding

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Abstract
This study compares the properties of dual-channel brushless DC motors with permanent magnets (DCBLDCMs) in three configurations of the stator windings of both channels. An analysis was performed of star-connected (Y), delta-connected (Δ), and combined star–delta (YΔ) channel windings. A proprietary mathematical model of a DCBLDCM machine with combined star–delta windings is presented. Each type of winding configuration was evaluated in terms of tolerance to the occurrence of a discontinuity in the channel. An Fast Fourier Transform (FFT) analysis of the selected voltage signal was used to diagnose the operating status of the DCBLDCM. It was demonstrated that it provides unambiguous information about the operating status of individual channels of the motor. In the case of 24/10 DCBLDCM design, the harmonic spectra of a selected voltage signal in relation to the artificial neutral point, are presented. The results of simulation tests were compared with the results of laboratory measurements. It was demonstrated that an FFT analysis of a voltage signal in relation to the artificial neutral point identifies a fault in a channel of the motor. When evaluating the characteristics of individual winding configurations, the value of electromagnetic torque, torque ripple, system efficiency, and emitted noise were taken into account. In the conclusions, the advantages of the combined star–delta winding compared to the traditional star and delta winding configurations are presented.

1 | INTRODUCTION

The use of a dual-channel power supply in an electric motor is aimed at increasing the reliability and certainty of operation of the drive system. This also applies to safety-critical applications. For such applications, popular induction motors [1–3], brushless motors with permanent magnets [4–9], synchronous motors [10–11], and switched reluctance motors [12–14] are suitable. Each of these motors meets, to a greater or lesser extent, the criteria for increased reliability. The criteria include fault tolerance and the ability to operate continuously after the occurrence of various types of faults, for example, open-winding fault [13]. The consequences of this fault depend on the type of winding used. This issue has not been analysed as widely. Publication [18] analyses cases of open winding faults and their effects on motor operation. The Fast Fourier Transform (FFT) analysis is quite often used to detect consequences of faults [19]. This type of analysis can be successfully used to detect various types of faults including breaks in motor windings.

A comparison is performed of a dual-channel brushless DC motor with permanent magnets (DCBLDCM) in three different winding configurations. Star (Y), delta (Δ), and combined star–delta (YΔ) winding configurations are analysed. Each configuration is evaluated for tolerance to the occurrence of an open winding in one of the channel windings. An FFT analysis of the voltage signal was used to diagnose the operating status of the system [4]. Based on the FFT analysis, information about the operating status of both channels was obtained. An FFT analysis of the voltage across two channels (Figure 1(a)) can also be applied for system monitoring.
It provides information concerning incipient faults. Nevertheless, it is not sufficient to determine which channel is damaged. Therefore, an analysis of signals of each channel is required. The results of the simulation tests were verified in a laboratory. The resistance of the different configurations was also evaluated as to the tolerance of the consequences of the occurrence of the fault state analysed. The FFT analysis has shown to provide unambiguous information about the operating status of the channels.

2 | ANALYSIS OF THE WINDING TOPOLOGY OF A DUAL-CHANNEL BRUSHLESS DC MOTOR

The winding configuration possibilities depend on the design of the motor. Tests on the influence of the configuration of dual-channel power supply windings were conducted on a design with 24 slots and 10 pairs of permanent magnets (Table 1). As a consequence of the design of the motor, there are 12 slots per channel. Each phase of one channel occupies four slots. In the design analysed, three configurations of windings for each channel are used, that is, Y/Y, Δ/Δ, and YΔ/YΔ. To achieve the smallest possible discrepancy between the back electromotive forces (BEMF) in different configurations, a parallel connection of groups in each phase was used in the Y/Y configuration. Figure 1 shows the analysed concept of a dual-channel power supply of a BLDC motor (Figure 1(a)) and the winding connection options considered (as an example, only for channel A—Figure 1(b)–(d)).

| Parameter                  | Value  |
|----------------------------|--------|
| Maximum DC current         | 100 A  |
| Phase current              | 20 A   |
| Continuous torque          | 2 Nm   |
| No. of phases              | 3      |
| No. of stator slots        | 24     |
| No. of rotor pole-pairs    | 10     |
| Type of rotor              | Outrunner |
| Diameter of rotor          | 102 mm |
| Diameter of stator         | 93.1 mm |
| Length of core             | 25 mm  |
| Air-gap                    | 0.45 mm |
| Rotor magnet               | N48H   |
| Stator core                | M130-23S |
| Pole winding resistance    | 0.035 Ω |
| Type of winding            | Concentrated |
| Winding configuration      | Y, Δ, YΔ |
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as line the design show in base relation to the the different configurations: Y/Y - Iref Δ/Δ - \( \sqrt{2/3} \) Iref YΔ/YΔ - \( \sqrt{3/8} \) Iref. Proceeding from this assumption, the static torque characteristics (Figure 2(a)) were determined for the dual-channel power supply. The reference value of the current was assumed to be \( I_{\text{ref}} = 20 \text{A} \) for each channel (10A per branch of star configuration). The induced voltage (determined at the speed of 1000 r/min) for the winding configurations analysed is shown in Figure 2(b).

| Constant/configuration | Y/Y | Δ/Δ | YΔ/YΔ |
|------------------------|-----|-----|-------|
| Torque constant \( K_T \) (N·m/A) | 0.0927 | 0.107 | 0.1418 |
| Voltage constant \( K_E \) (V/1000 r/min) | 7.26 | 8.39 | 11.1 |

Table 2 specifies the torque and voltage constants of the configurations tested and obtained in the numerical calculations [20].

3 | MATHEMATICAL MODEL OF A DCBLDC MOTOR WITH A STAR–DELTA WINDING

The mathematical model of a DCBLDC with a combined star–delta (YΔ) winding configuration is presented. The following simplifying assumptions were adopted in the model of a three-phase DCBLDC motor proposed:

- a linear magnetic circuit, a symmetrical cylindrical stator,
- and a permanent magnet-type rotor omission of phenomena relating to cogging torque, eddy currents, and magnetic hysteresis; in particular, assumption of zero losses in stator and rotor cores.

The general structure of the mathematical model of a three-phase DCBLDC motor with a combined star–delta (YΔ) winding configuration for dual-channel operation (DCO) mode can be described as follows:

**FIGURE 2** Selected results of numerical calculations: (a) electromagnetic torque vs. rotor positions and (b) waveforms of line-to-line BEMF
\[
\begin{bmatrix}
    \mathbf{u}^k_Y \\
    \mathbf{u}^k_{\Delta}
\end{bmatrix} =
\begin{bmatrix}
    \mathbf{R}^k_Y & 0 & 0 \\
    0 & \mathbf{R}^k_{\Delta} & 0 \\
    0 & 0 & \mathbf{R}^k_Y
\end{bmatrix}
\begin{bmatrix}
    \mathbf{i}^k_Y \\
    \mathbf{i}^k_{\Delta}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    \mathbf{L}^{AA}_{YY} & \mathbf{L}^{AA}_{Y\Delta} & \mathbf{L}^{AB}_{YY} & \mathbf{L}^{AB}_{Y\Delta} \\
    \mathbf{L}^{AA}_{\Delta Y} & \mathbf{L}^{AA}_{\Delta \Delta} & \mathbf{L}^{AB}_{\Delta Y} & \mathbf{L}^{AB}_{\Delta \Delta} \\
    \mathbf{L}^{BA}_{YY} & \mathbf{L}^{BA}_{Y\Delta} & \mathbf{L}^{BB}_{YY} & \mathbf{L}^{BB}_{Y\Delta} \\
    \mathbf{L}^{BA}_{\Delta Y} & \mathbf{L}^{BA}_{\Delta \Delta} & \mathbf{L}^{BB}_{\Delta Y} & \mathbf{L}^{BB}_{\Delta \Delta}
\end{bmatrix}
\begin{bmatrix}
    \mathbf{i}^k_Y \\
    \mathbf{i}^k_{\Delta}
\end{bmatrix}
\]

\[
\begin{aligned}
\frac{d}{dt} \begin{bmatrix}
    \mathbf{i}^k_Y \\
    \mathbf{i}^k_{\Delta}
\end{bmatrix} + \frac{d\theta}{dt} + \mathbf{T}_L = \mathbf{T}_e
\end{aligned}
\]

where total electromagnetic torque \( \mathbf{T}_e \):

\[
\mathbf{T}_e = \frac{1}{\omega_m} \left( (i^k_Y)^T \mathbf{e}^k_Y + (i^k_{\Delta})^T \mathbf{e}^k_{\Delta} \right)
\]

In Equations (1)–(3) for channels \( k \in \{A, B\} \), vectors representing phase voltages \( \mathbf{u}^k \), phase currents \( \mathbf{i}^k \), phase BEMF voltages \( \mathbf{e}^k \), as well as matrices of stator resistances \( \mathbf{R}^k \), and coefficients of self- and mutual inductances \( \mathbf{L}^k \), are defined as follows:

\[
\begin{aligned}
\mathbf{u}^k &= [u^k_{1Y}, u^k_{2Y}, u^k_{3Y}]^T, \quad \mathbf{i}^k = [i^k_{1Y}, i^k_{2Y}, i^k_{3Y}]^T \\
\mathbf{e}^k &= [e^k_{1Y}, e^k_{2Y}, e^k_{3Y}]^T \\
\mathbf{R}^k &= [R^k_Y, R^k_Y, R^k_Y] \\
\mathbf{L}^k &= [L^k_Y, L^k_{Y\Delta}] = \text{diag}(R^k_Y, R^k_Y, R^k_Y)
\end{aligned}
\]

The following symbols are used in Equations (2) and (3): \( J \) —rotor (and load) moment of inertia, \( \omega_m \) —mechanical speed of rotor, \( D \) —rotor damping of viscous friction coefficient, and \( T_L \) —load torque.

The phase BEMF voltage vectors \( \mathbf{e}^k_Y \), \( \mathbf{e}^k_{\Delta} \) in Equations (1) and (3) for channels \( k \in \{A, B\} \) have the same structure and are defined as follows:

\[
\frac{d\theta}{dt} = \omega + \mathbf{K}^k_{Y\Delta}
\]

\[
\begin{bmatrix}
    f^k_{Y\Delta}(	heta) \\
    f^k_{\Delta Y}(	heta)
\end{bmatrix}
\]

**FIGURE 3** YY—Symmetry—FFT: (a) FFT of \( \mathbf{u}_{1\Delta} \)—numerical calculations and (b) FFT of \( \mathbf{u}_{1\Delta} \)—measurement
where $\theta$ — electrical rotor angle, $\omega = \frac{d\theta}{dt} = \frac{p}{\rho^{\text{m}}}$ — electrical speed, $p$ — rotor pole-pairs, $\psi_{\text{PM}}(\theta), \psi_{\Delta}(\theta)$ for $i \in (1, 2, 3)$ are the stator windings linkage fluxes produced by permanent magnets, $K_{\text{EY}}^k, K_{\text{EA}}^k$ — BEMF constant of one phase, $f_{\text{Y}}^k(\theta), f_{\Delta}^k(\theta)$ — phase functions, profile BEMF. The permanent magnet flux linkage of each stator winding of the DCBLDC motor follows the trapezoidal profile back-EMF.

The real phase BEMF is not a flat and ideal trapezoidal waveform and functions $f_{\text{Y}}^k(\theta), f_{\Delta}^k(\theta)$ can be expressed for $k \in (A, B)$ and $i \in (1, 2, 3)$ as Fourier series.

The total electromagnetic torque (3) in Equation (2) is produced by the interaction between the rotor’s permanent magnets and the stator's channel A and B energized windings, and can be expressed as:

$$T_e = \frac{1}{\rho^{\text{m}}} \sum_{k=A}^{B} \sum_{i=1}^{3} \left( e_{k,i}^Y i_{k,i}^Y + e_{k,i}^\Delta i_{k,i}^\Delta \right)$$

The electromagnetic torque (5), including (4), can be described as:

FIGURE 4 YY—OC—waveforms:
(a) electromagnetic torque—numerical calculations
(b) line currents—numerical calculations, and (c) line currents—measurement
\[ T_e = \sum_{k=A}^{B} \sum_{i=1}^{3} \left( i_{kY}^Y K_{kY}^Y f_{kY}^Y \left( \theta - (i - 1) \frac{2\pi}{3} \right) \right) \]
\[ + \sum_{k=A}^{B} \sum_{i=1}^{3} \left( i_{k\Delta}^\Delta K_{k\Delta}^\Delta f_{k\Delta}^\Delta \left( \theta - (i - 1) \frac{2\pi}{3} \right) \right) \]

where \( K_{kY}^Y, K_{k\Delta}^\Delta \)—torque constants, \( f_{kY}^Y(\theta), f_{k\Delta}^\Delta(\theta)\)—phase functions, profile back-EMF of Y\(\Delta\) windings for channel \(k \in (A, B)\).

Additional constraints on voltages and currents are imposed by the arrangement of motor phase windings in a star (\(Y\)), delta (\(\Delta\)) or combined star-delta (\(Y\Delta\)) configuration. The relationship of line and phase voltages and currents in a star-delta (\(Y\Delta\)) connection, for example, can be written as \(k \in (A, B)\):

\[
\begin{bmatrix}
\mu_{12}^A \\
\mu_{23}^A \\
\mu_{31}^A \\
\end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1 \\
\end{bmatrix} \begin{bmatrix}
\mu_{1Y}^Y \\
\mu_{2Y}^Y \\
\mu_{3Y}^Y \\
\end{bmatrix} + \begin{bmatrix}
\mu_{1\Delta}^\Delta \\
\mu_{2\Delta}^\Delta \\
\mu_{3\Delta}^\Delta \\
\end{bmatrix} : \sum_{i=1}^{3} \mu_{i\Delta}^\Delta = 0
\]

\[
\begin{bmatrix}
\delta_{1Y}^k \\
\delta_{2Y}^k \\
\delta_{3Y}^k \\
\end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 \\
-1 & 1 & 0 \\
0 & -1 & 1 \\
\end{bmatrix} \begin{bmatrix}
\delta_{1\Delta}^k \\
\delta_{2\Delta}^k \\
\delta_{3\Delta}^k \\
\end{bmatrix} : \sum_{i=1}^{3} \delta_{iY}^k = 0
\]

For example, the line-to-line voltage model of a three-phase DCBLDC motor with combined star-delta (\(Y\Delta\)) windings in single-channel operation (SCO) mode, only for channel \(A\), can be described as:

\[
\begin{bmatrix}
\mu_{12}^A \\
\mu_{23}^A \\
\mu_{31}^A \\
\end{bmatrix} = \begin{bmatrix} R & -R_N & -R_N \\
-R_N & R & -R_N \\
-R_N & -R_N & R \\
\end{bmatrix} \begin{bmatrix}
\tilde{i}_{1\Delta}^A \\
\tilde{i}_{2\Delta}^A \\
\tilde{i}_{3\Delta}^A \\
\end{bmatrix}
\]

\[
+ \begin{bmatrix} L & M & M \\
M & L & M \\
M & M & L \\
\end{bmatrix} \frac{d}{dt} \begin{bmatrix}
\tilde{i}_{1\Delta}^A \\
\tilde{i}_{2\Delta}^A \\
\tilde{i}_{3\Delta}^A \\
\end{bmatrix} + \begin{bmatrix}
e_{1Y}^A - e_{2Y}^A + e_{3Y}^A \\
e_{2Y}^A - e_{1Y}^A + e_{3Y}^A \\
e_{3Y}^A - e_{1Y}^A + e_{2Y}^A \\
\end{bmatrix}
\]

\[
T_e = \sum_{i=1}^{3} \left( i_{iY}^Y K_{iY}^Y f_{iY}^Y \left( \theta - (i - 1) \frac{2\pi}{3} \right) \right)
\]
\[+ \sum_{i=1}^{3} \left( i_{i\Delta}^\Delta K_{i\Delta}^\Delta f_{i\Delta}^\Delta \left( \theta - (i - 1) \frac{2\pi}{3} \right) \right)\]

The equivalent motor parameters in Equation (9) are determined by the following relationships:

(FIGURE 5) YY—OC—FFT: (a) FFT of \(u_{iY}^A\)—numerical calculations and (b) FFT of \(u_{iY}^A\)—measurement

(FIGURE 6) \(\Delta/\Delta\)—Symmetry—FFT: (a) FFT of \(u_{i\Delta}^A\)—numerical calculations and (b) FFT of \(u_{i\Delta}^A\)—measurement
\[ R = 2R_Y + R_\Delta, \quad L = 2(L_Y - M_Y) + L_\Delta + 2(L_Y - M_Y), \]
\[ M = -L_Y + M_Y + M_\Delta - L_Y + M_Y. \]

The BEMF voltages in Equation (9) \( e^A_1, e^\Delta_1 (i=1,2,3) \) are defined in Equation (4) for \( k = A \).

Equations (9)–(10) and (2) with Equation (11) constitute, in general, a mathematical model of the DCBLDC motor with combined star–delta (YΔ) windings in SCO mode. Equations for DCO mode can be formulated similarly.

4 | RESULTS OF SIMULATION AND EXPERIMENTAL TESTS

All tests were conducted for a fixed operating point at a speed of \( n = 1500 \text{ r/min} \). In laboratory conditions, two independent power supply systems (two DC power supplies, two converters), a Yokogawa WT 1600 6-channel power analyser, a Yokogawa DL850 scopeorder, and a Magtrol PB43 dynamometer were used. The systems used the built-in algorithm.

*FIGURE 7 Δ/Δ—OC—waveforms:*
(a) Electromagnetic torque—numerical calculations, (b) line currents—numerical calculations, and (c) line currents—measurement
for determination of the position using the sensorless method to detect the rotor position. The supply voltages of both channels were adjusted to obtain the same no-load operation point \( n_0 = 1750 \text{ r/min} \). This is due to different voltage constants for the configurations analysed (Table 1).

## 4.1 YY configuration

### 4.1.1 YY symmetry

For the star configuration, the waveforms of the currents and of the electromagnetic torque were determined \( T_{\text{av}} = 1.92 \text{ N-m at 35\% ripple} \). Additionally, the voltage waveforms of the diagnostic signals were determined. Figure 3 shows the FFT analysis of the \( u_{0A} \) voltage for channel A for the numerical calculations (Figure 3(a)) and laboratory tests (Figure 3(b)). For the structure under consideration, the basic frequency is \( f_1 = n^p/60 = 250 \text{ Hz} \). It is dependent on the speed \( n \) and the number of pole pairs of the rotor \( p \). The spectrum of the diagnostic signal is dominated by multiplications of the basic frequency, which are multipliers of 3, that is, 3rd, 9th, 15th etc. The measurement spectrum also includes other frequencies, e.g. 6, 12, and 18. This is due to, among other things, the electrical and magnetic asymmetries of the actual motor.

### 4.1.2 YY open circuit

In the case of a fault state caused by opening of the open circuit (OC) switch (Figure 1(b)), one of the branches of channel A is lost. For a given star configuration (parallel connection of branches), this is not critical. However, this affects the operation of the system and causes a decrease in the value of the electromagnetic torque (Figure 4(a)). The line current waveforms are shown in Figure 4(b) and (c). Figure 5(a) shows the distribution of the harmonics of the \( u_{0A} \) diagnostic voltage signals. The distribution of the \( u_{0A} \) voltage harmonics obtained in laboratory conditions is shown in Figure 5(b).

A fault state caused by a break in the channel winding configuration analysed allows the system to continue to operate. The line currents of the defective channel change their shape. In the \( u_{0A} \) voltage signal of the defective channel, the basic frequency should appear (250 Hz and its odd multiplication factors that are not multiples of 3, i.e. 5th, 7th, 11th, and so on). However, it should be noted that the increase in the amplitudes of these harmonics in laboratory conditions is relatively small (Figure 5b).

## 4.2 \( \Delta/\Delta \) configuration

### 4.2.1 \( \Delta/\Delta \) symmetry

In the case of a delta connection for the symmetrical operation condition, the average electromagnetic torque was \( T_{\text{av}} = 2.02 \text{ N-m at 30\% ripple} \). The distribution of the harmonics of the \( u_{0A} \) voltage signal is shown in Figure 6.

As in the case of a star connection, frequencies which are multipliers of 3, that is, 3rd, 9th, 15th etc., appear in the distribution of harmonics. At the same time, other harmonics appear in laboratory conditions because the \( u_{0A} \) voltage signal is highly sensitive to various motor asymmetries but also to asymmetries of the motor control.

**Figure 8** \( \Delta/\Delta - \text{OC — FFT} 
: (a) FFT of \( u_{0A} \) — numerical calculations and (b) FFT of \( u_{0A} \) — measurement

**Figure 9** \( Y\Delta — \text{symmetry — FFT} 
: (a) FFT of \( u_{0A} \) — numerical calculations and (b) FFT of \( u_{0A} \) — measurement
4.2.2 | Δ/Δ Open circuit

After a break in one phase of channel A (open OC switch—Figure 1(b)), the defective channel can continue to operate. However, the generated electromagnetic torque is reduced (Figure 7(a)). The line current waveforms obtained are shown in Figure 7(b) and (c). The distribution of the harmonics of the $u_{0A}$ voltage signal is shown in Figure 8.

Opening of the OC switch (Figure 1(b)) causes a break in one of the phases of channel A. This has a significant impact on the distribution of line currents. In the case of a delta configuration, after a break in one of the phases of channel A, all the predicted harmonics appear both in the results of numerical calculations (Figure 8(a)) and in the laboratory results (Figure 8(b)). In this case, the fault is unambiguously indicated by the appearance of the 1st, 5th, 7th, harmonics, and so on.

**FIGURE 10** YΔ—OC1—waveforms of line currents: (a) electromagnetic torque—numerical calculations, (b) line currents—numerical calculations, and (c) line currents—measurement
whose values increase significantly. This applies especially to the first harmonic.

4.3 | YΔ/YΔ configuration

4.3.1 | YΔ/YΔ symmetry

In the YΔ configuration, part of the winding of each channel is connected in a delta configuration (Figure 1(d)). In this configuration, similarly to a typical delta configuration, there are line and phase currents. For this connection, the average value of electromagnetic torque was $T_{\text{av}} = 1.98\ \text{N} \cdot \text{m}$ at 27% ripple. The spectrum of the harmonics of the $u_{0\Delta}$ voltage signal is shown in Figure 9.

4.3.2 | YΔ/YΔ open circuit—OC1

Opening of the OC1 switch (Figure 1(c)) interrupts the power supply to one phase of channel A. This is a serious defect because virtually the entire load has to be taken over by channel B. Two line currents with a characteristic shape flow in the defective channel (Figure 10(b) and (e)). This results in a practically twofold reduction of electromagnetic torque (Figure 10(a)). The distribution of higher harmonics of the $u_{0\Delta}$ voltage signal is shown in Figure 11.

In the $u_{0\Delta}$ voltage signal, practically all the expected harmonics are present. In laboratory conditions, the 5th harmonic was not observed (Figure 11(b)).

4.3.3 | YΔ/YΔ Open circuit—OC2

Opening of the OC2 switch causes a break in the delta part of the YΔ configuration. This results in a slight decrease in the value of electromagnetic torque (Figure 12(a)). The currents in the damaged channel are slightly reduced (Figure 12(b) and (e)). The higher harmonics of the $u_{0\Delta}$ voltage signal are shown in Figure 13.

In the spectrum of the harmonics of the $u_{0\Delta}$ voltage signal, all the expected harmonics are present. However, their amplitudes are at a lower level than in the case of the OC1 fault.

4.4 | Comparison of results

Selected results of simulation and laboratory tests are presented in Tables 3–5.

The best-tolerated fault state is a break in the delta part of the star–delta configuration (OC2). Regardless of the configuration type, none of the states analysed is critical. The defective channel can continue to work to a greater or lesser extent, relieving the load on the other channel. However, this leads to an increase in the electromagnetic torque ripple. The defective channel can be switched off and the system goes into single-channel operation. This reduces the electromagnetic torque ripple and motor efficiency (Table 6). The fault states analysed do not lead to a significant increase in the noise emitted. The best result was obtained for the YΔ configuration (Table 5).

5 | CONCLUSIONS

The consequences of a fault depend on the configuration analysed. The worst case is an open winding in the star part of a combined star–delta configuration. Such a fault virtually eliminates the defective channel. It should be noted that in the case of a classic star configuration, the consequences of this defect are practically identical to those in the star part of a combined star–delta configuration. The best-tolerated fault state is an open winding in the delta part of the star-delta configuration. Regardless of the configuration type, none of the states analysed is critical. The defective channel can continue to operate or be switched off and the system goes into a single-channel operation. However, this leads to an increase in the electromagnetic torque ripple and a decrease in the efficiency of the drive system.

An FFT analysis of the voltage signal shows that, in the case of symmetry, the only basic frequency harmonics that are present are multipliers of 3. As a result of the occurrence of the fault state analysed, all the odd harmonics of the basic frequency are present. The presence of the first harmonic, which indicates asymmetry in the channel windings, is crucial. A simultaneous analysis of the signals from both channels is also important. A possible additional criterion is an analysis of the inter-channel voltage signal. This will be the subject of further research work.
by the authors. In addition, other fault operation states will be analysed, such as short circuits in windings and defects in the power supply system.

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FIGURE 13  YΔ—OC2—FFT: (a) FFT of $\mu_{\text{OA}}$—numerical calculations and (b) FFT of $\mu_{\text{OA}}$—measurement

### TABLE 3  Selected results of numerical and laboratory tests—Y configuration

| Parameter          | YΔ/Δ | Symmetry | OC1 | OC2 |
|--------------------|------|----------|-----|-----|
|                    | Num  | Lab      | Num | Lab | Num  | Lab  |
| Avg. torque (N·m)  | 1.92 | 1.57     | 1.64| 1.45|      |      |
| Torque ripple (%)  | 35   | -        | 52  | -   |      |      |
| Efficiency (%)     | 88.4 | 87.1     | 87.7| 86.8|      |      |
| Acoustic noise (dB)| -    | 61.1     | -   | 63.6|      |      |
| Amp. $I_1$ (mV)    | -    | 121      | 250 | 145 |      |      |
| Amp. $I_3$ (mV)    | 1056 | 714      | 1033| 740 |      |      |

### TABLE 4  Selected results of numerical and laboratory tests—Δ configuration

| Parameter          | Δ/Δ  | Symmetry | OC1 | OC2 |
|--------------------|------|----------|-----|-----|
|                    | Num  | Lab      | Num | Lab | Num  | Lab  |
| Avg. torque (N·m)  | 2.02 | 1.84     | 1.46| 1.45|      |      |
| Torque ripple (%)  | 30   | -        | 72  | -   |      |      |
| Efficiency (%)     | 88.8 | 87.9     | 87.2| 86.9|      |      |
| Acoustic noise (dB)| -    | 60.1     | -   | 60.4|      |      |
| Amp. $I_1$ (mV)    | -    | 183      | 580 | 693 |      |      |
| Amp. $I_3$ (mV)    | 1408 | 1035     | 1398| 918 |      |      |

### Table 5  Selected results of numerical and laboratory tests—YΔ configuration

| Parameter          | YΔ/Δ | Symmetry | OC1 | OC2 |
|--------------------|------|----------|-----|-----|
|                    | Num  | Lab      | Num | Lab | Num  | Lab  |
| Avg. torque (N·m)  | 1.98 | 2.04     | 1.18| 1.09| 1.81 | 1.87 |
| Torque ripple (%)  | 27   | -        | 88  | -   | 33   | -    |
| Efficiency (%)     | 87.7 | 86.7     | 85.7| 84.7| 86.6 | 86.6 |
| Acoustic noise (dB)| -    | 59.2     | -   | 59.9| -    | 59.5 |
| Amp. $I_1$ (mV)    | -    | 133      | 1138| 1193| 250  | 389  |
| Amp. $I_3$ (mV)    | 1170 | 830      | 2188| 1620| 1170 | 910  |

### Table 6  Selected results of numerical and laboratory tests—SCO operation

| Parameter          | SCO | Δ/Δ  | YΔ/Δ |
|--------------------|-----|------|------|
|                    | Num | Num  | Num  |
| Avg. torque (N·m)  | 0.95| 0.84 | 1.0  |
| Torque ripple (%)  | 47  | -    | 40   |
| Efficiency (%)     | 85.8| 84.5 | 86.3 |

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