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Evaluation of Magnetomotive Force and Torque Ripples in Modular Type IPMSM With Multi Three-Phase Winding Configurations

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ABSTRACT Electrical machines having more than one independent three-phase unit are mostly proposed for applications that require the machine to operate continuously, even under one or more three-phase units fault. This paper discusses the concept of multi three-phase unit motor machine design in which the machine stator is divided into multiple three-phase units, with three stator slots and a rotor pole pair constituting a single independent three-phase unit motor. Firstly, an analytical method is presented to calculate the magnetomotive force (MMF), its harmonic spectrum and their impact on the machine torque ripples for the multi three-phase unit motor machine model. The proposed algorithm can be used to study the MMF and torque ripples behaviour of any multi three-phase unit motor machine operating under healthy and open-circuit fault operation. Moreover, different multi three-phase winding configurations including multi three-phase concentrated, multi three-phase distributed and multi three-phase mixed concentrated and distributed winding configuration are investigated for the modular type machine prototype. The analyzed multi three-phase winding configurations are fully studied to investigate the MMF harmonic components, the generated torque and torque ripples under healthy and open-circuit fault operations. The performance analysis of the prototype machine is investigated using detailed Finite Element Analysis (FEA) under the analyzed multi three-phase winding configurations, validating the effectiveness of the proposed multi three-phase unit motor machine windings configurations. This study presents useful conceptual hints for the multi three-phase unit motor machine design, while the analyzed three different types of winding configurations can help machine designers select the best multi three-phase winding design approach with lower generated torque ripples and lower unbalanced magnetic forces, particularly under different unit motors open-circuit fault operating conditions.

INDEX TERMS Permanent magnet synchronous motor, modular winding configurations, MMF harmonics, torque ripples, fault-tolerance.

I. INTRODUCTION

Multiphase electrical machines have widespread applications in many areas, including their mandatory use in high power industrial applications, mainly due to the technical difficulties and fault-tolerance performance issues in three-phase machines under such applications. They are also considered an attractive choice in many other application areas due to their standout advantages compared to the three-phase machines [1]. Publications [2]–[4] very well discuss the advantages of using multiphase machines in detail. Some of the mentioned advantages are reduced weight, more reliability, lower stator MMF harmonics, and reduction in torque ripples. Multiphase machines also offer the possibility to lower the phase current of the stator. In contrast, the phase voltage is maintained at the same level, resulting in a considerable reduction in current ripples [5]. Additionally, multiphase machine drives offer an additional degree of freedom, which can be used in the improvement of the torque and the converter performance under fault-tolerant working conditions of the machine [6], [7]. Among all the mentioned advantages, the advantage of torque improvement and the magnetomotive

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force harmonic compensation is investigated the most in multiphase machines. An increase in the number of phases above three results in a possible increase in the torque density and a potential reduction of torque ripples [8]. Previously, the generated torque and the harmonic components in a multiphase machine have been analytically and experimentally investigated in [9]. Similarly, [10]–[12] propose a general mathematical expression for the field harmonics and the torque ripple production in a multiphase machine having two layers of windings, while [13] discuss about the use of multi-layer windings to reduce the harmonic contents in a multiphase machine.

The fractional slot concentrated windings (FSCW) machines are generally considered to be one of the most suitable choices for harmonic compensation in an electrical machine, particularly in multiphase machines. Publication [14] suggests different slots and poles combinations, while [15] uses different FSCW for harmonic compensation and torque ripple reduction in multiphase machines. Tooth coil windings having FSCW design is proposed in [16], presenting a new technique to model harmonic compensation and torque ripple in multi three-phase star-connected machines. Similarly, the FSCW machine with tooth coil windings is also known for its simple and compact structure. A single layer winding design of the tooth coil windings method is proposed in [17], while the double layer winding design having tooth coil windings for the n-phases star-connected machine is presented in [18]. Multi three-phase machines can be considered as a suitable solution for fault-tolerant applications. Nevertheless, as opposed to the standard three-phase symmetrically wound machines, multi three-phase machines exhibit the worst behavior in the case of one inverter opening in particular, an undesired and unbalanced radial force appears due to the asymmetric distribution of magnetomotive force, which needs to be investigated properly particularly, under different multi three-phase winding configurations [19].

This paper discusses the multi three-phase unit motor machine design model. The prototype machine model used in this analysis has six sectors having separate three-phase unit motors. Each sector consists of three slots and a pole pair with an independent three-phase supply to form a basic unit motor. The main focus is on the analytical investigation of the MMF harmonic components and their effect on the torque ripples in multi three-phase unit motor machine design in case of normal and unit motors open-circuit fault operation. Similarly, the impact of different multi three-phase winding configurations on the generated torque ripples is also studied. There are VII sections in this paper. Section II presents the different modular winding topologies along with the structure of the prototype machine, while section III describes the theoretical considerations and proposed algorithm for the multi three-phase unit motors machine design with emphasis on two separate multi three-phase winding configurations. Performance analysis and validation of the machine prototype and the analyzed modular winding configurations are discussed in section IV. The generated torque and torque ripples response of the machine prototype with multi three-phase concentrated and multi three-phase distributed winding configurations under normal and fault-tolerant conditions is presented in detail in section V, while section VI presents the analysis about the third type of winding configuration which is a combination of the multi three-phase concentrated and the multi three-phase distributed winding configurations. A comprehensive conclusion is given in section VII.

II. MODULAR TYPE WINDING CONFIGURATIONS OF THE MACHINE MODEL

The stator and the rotor of the prototype IPMSM machine model with fractional slot concentrated winding (FSCW), is shown in Fig. (1a-1b). Table 1 presents the basic design parameters for the multi three-phase unit motor machine. The analyzed multi-pole pair IPMSM can be divided into multi three-phase units, which are physically isolated from each other having the same geometrical structure. The machine prototype having modular three-phase windings in separate sectors is termed as multi three-phase sector winding (MT-SW) machine, which are widely used for fault-tolerant applications.

TABLE 1. Design parameters of the prototype motor.

Design Parameters	Values
Rated power (kW)	35
Rated Speed (r/min	3600
Rated Torque (N.m)	93
Poles per Slots	12/18
Number of magnets per Pole	2
Magnets width (mm)	20
Magnets Thickness (mm)	5
Winding method	Star
Number of Three-phase units	6

Firstly, different combinations of MT-SW configurations are proposed using some basic winding design principles and then the impact of different modular winding configurations on the magnetomotive force (MMF) harmonics, radial force, generated torque and torque ripples under three-phase units normal and open-circuit fault operations is investigated for the prototype machine. The first type of MT-SW configuration investigated in this paper is the multi three-phase concentrated sector winding (MT-CSW) in which each three-phase unit motor cover a single pole pair in a concentrated sector design approach as shown in Fig.1 (c). The second type of MT-SW configuration discussed is the multi three-phase distributed sector winding (MT-DSW) configuration in which the three-phase windings for each unit motor covers more than one pole pair in a distributed sector design approach as shown in Fig.1 (d).

III. THEORETICAL ANALYSIS AND PROPOSED ALGORITHM FOR THE MT-SW MACHINE DESIGN

A. THE MT-SW MACHINE MODEL

This section presents a brief discussion about the modular type multi three-phase sector windings (MT-SW) machine

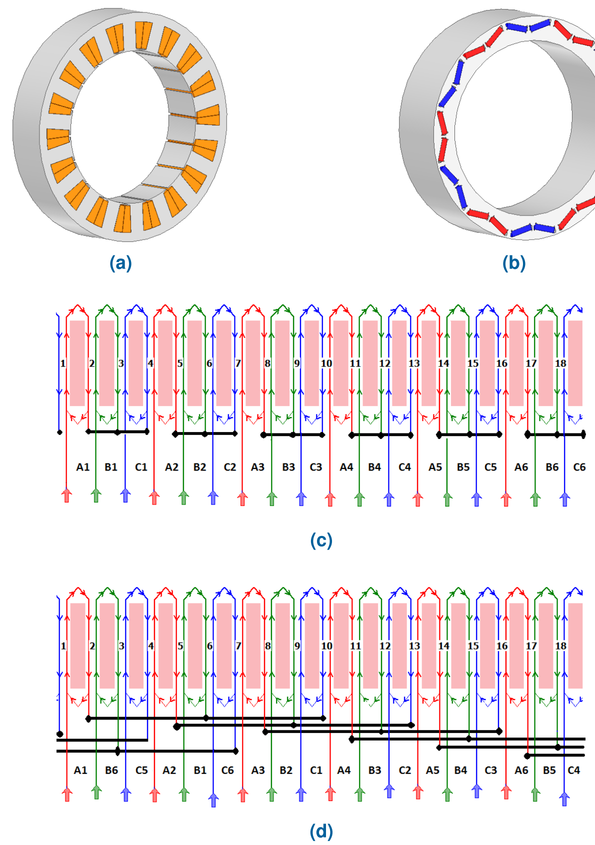


FIGURE 1. Machine prototype and winding arrangements (a) Machine stator (b) Rotor of the prototype machine (c) MT-CSW configuration (d) MT-DSW configuration.

design. The detailed guidelines about the selection of MT-SW configurations are presented, starting with the definition of the basic design parameters and rules for the selection of pole numbers, the winding configurations, and the electrical and magnetic axis principles for the modular type multi three-phase unit motor machine. [16] discuss a similar type of algorithm but is implemented on multi-n-star type designed machines. However, the developed algorithm and the analysis presented in this section discuss the MT-SW machine design with two different types of multi three-phase sector winding configurations. First, the basic design parameters like the number of coil C_N, poles number P_N, and the number of three-phase units S_N are defined for the MT-SW machine design. These three parameters specify the base unit for the MT-SW machine design. The base three-phase unit consists of a single pole-pair ($P_N = 2$) with three slots having double layer winding configuration forming a basic unit motor. The equations for the number of poles based on the specified parameters for the MT-SW unit motor machine design are presented as

$$P_N = S_N (C_N - 1) \tag{1}$$

where equation (1) set the design rules for choosing the best possible selection for the number of poles in a multi three-phase unit motor machine design based on the machine parameters. The declared machine parameters C_N, S_N, P_N defines the base unit motor, which is represented by M_N. After selecting the base unit motor, its base angle is selected considering a span angle from 0 to πP_N. The electrical angle of the stator tooth pitch is represented by ϑ_{coil}. Similarly, ϑ_{phase} represents the electrical angle between two phases of the same three-phase unit motor, while ϑ_{Sec} represents the electrical angle between two adjacent three-phase unit motors. The corresponding angle parameters for the multi three-phase concentrated sector winding (MT-CSW) configuration are given below

$$\begin{aligned} \vartheta_{coil} &= \left(\frac{P_N \pi}{C_N S_N}\right) \frac{1}{S_N} \\ \vartheta_{phase} &= \left(\pi - \frac{\pi}{C_N}\right) \frac{1}{S_N} \\ \vartheta_{Sec} &= \left(\pi - \frac{\pi}{C_N}\right) \frac{C_N}{S_N} \end{aligned} \tag{2}$$

Similarly, the corresponding angle parameters for the multi three-phase distributed sector winding (MT-DSW) configuration are given by

$$\begin{aligned} \vartheta_{coil} &= \left(\frac{P_N \pi}{C_N S_N}\right) \frac{1}{S_N} \\ \vartheta_{phase} &= \left(\pi - \frac{\pi}{C_N}\right) \frac{4}{S_N} \\ \vartheta_{Sec} &= \left(\pi - \frac{\pi}{C_N}\right) \frac{C_N}{S_N} \end{aligned} \tag{3}$$

These parametric angles help to identify the winding configurations for both the (MT-CSW) and the (MT-DSW) designs. Table 2 represents the base angles and the phasor diagrams for the multi three-phase unit motor machine design up to its six times repetition.

B. THE MT-SW MACHINE MMF HARMONIC MODEL

An analytical technique to calculate the MMF harmonics for the multi three-phase unit motors machine model is discussed in this section. The spectrum of MMF harmonics consists of the slot harmonics, which are the r_{th} harmonics contributing a non-zero rotating field to the machine air gap with an amplitude of $\frac{C_N S_N M_N}{2}$ times the amplitude of the MMF for a single phase coil winding. Similarly, the stator MMF for a single phase coil n supplied by a sinusoidal current excitation, while taking r to be the harmonic order of the winding configuration is given by

$$f_{s_h} = \sum_{r=1}^{\infty} f_{s_h}^{n,r} cos\left(\omega t + \lambda - \vartheta_e\right) * cos\left(r\left(\alpha - \alpha_n\right)\right) \tag{4}$$

$f_{s_h}^{n,r}$ represents the amplitude of the r_{th} harmonic of the stator MMF for a single coil. The electrical angle of the coil n is represented by ϑ_e, while α_n represents the axis angular position for the coil n. Considering N to be the total number of coils in a multi-phase machine. The stator MMF is then given by

$$f_{s_h} = \sum_{n=1}^{N}\sum_{r=1}^{\infty} f_{s_h}^{n,r} cos\left(\omega t + \lambda - \vartheta_e\right) * cos\left(r\left(\alpha - \alpha_n\right)\right) \quad (5)$$

Since the stator MMF comprises of the forward and reverse rotating fields henceforth, the stator MMF harmonics from equation (5) can be written as

$$f_{s_h} = \sum_{n=1}^{N}\sum_{r=1}^{\infty} f_{s_h}^{r_{F_k}} cos\left(\omega t + \lambda - \vartheta_e\right) * cos\left(r_{F_k}\left(\alpha - \alpha_n\right)\right) + \sum_{n=1}^{N}\sum_{r=1}^{\infty} f_{s_h}^{r_{R_k}} cos\left(\omega t + \lambda + \vartheta_e\right) * cos\left(r_{R_k}\left(\alpha - \alpha_n\right)\right) \quad (6)$$

The stator MMF and its harmonics for a multi three-phase concentrated sector winding machine can be calculated considering the following rules

$$N = C_N.S_N.M_N$$
$$\vartheta_e = (n-1)\frac{S_N}{C_N}\theta_{phase}$$
$$\alpha_n = \frac{(n-1)\,2\pi}{N} \quad (7)$$

The stator MMF for the forward and reverse rotating fields in a multi three-phase concentrated sector winding machine using the above rules can be calculated as

$$f_{s_{h_{F,R}}} = \sum_{n=1}^{C_N S_N M_N}\sum_{r=1}^{\infty} f_{s_h}^{r_{F_k}, r_{R_k}} cos((\omega t + \lambda - r\alpha) - (n-1)\frac{S_N}{C_N}\theta_{Sec} \pm r_{F_k,R_k}\frac{2\pi(n-1)}{C_N S_N M_N}) \quad (8)$$

$$f_{s_{h_{F,R}}} = \sum_{n=1}^{C_N S_N M_N}\sum_{r=1}^{\infty} f_{s_h}^{r_{F_k}, r_{R_k}} cos((\omega t + \lambda + r\alpha) - (n-1)(\frac{S_N(C_N\pi - \pi)}{C_N S_N}) \pm r_{F_k,R_k}\frac{2\pi(n-1)}{C_N S_N M_N}) \quad (9)$$

The amplitudes of the rotating magnetic fields ($f_{s_h}^{r_{F_k}, r_{R_k}}$) in equation (9) for a single phase coil is equal to the r_{th} amplitude of the MMF harmonics multiplied by $\frac{C_N S_N M_N}{2}$.

$$f_{s_{h_{F,R}}} = \sum_{n=1}^{C_N S_N M_N}\sum_{r=1}^{\infty} f_{s_h}^{r_{F_k}, r_{R_k}} cos((\omega t + \lambda - r\alpha) - 2\pi(n-1)(\frac{M_N S_N(C_N - 1) \pm 2 r_{F_k,R_k}}{2 C_N S_N M_N})) \quad (10)$$

In equation (10) r_{F_k} and r_{R_k} represent the forward and reverse harmonic order which must satisfy equation (11) and (12) to generate a rotating field of harmonics order r.

$$(\frac{M_N S_N(C_N - 1) - 2r_{F_k}}{2C_N S_N M_N}) = k \quad (11)$$
$$(\frac{M_N S_N(C_N - 1) + 2r_{R_k}}{2C_N S_N M_N}) = k \quad (12)$$

where k is an integer similarly, it is important to note that the harmonics r_{F_k} and r_{R_k} are actually the slots harmonics that contribute to the non-zero harmonic field. Henceforth, when these harmonic components are known, then it is possible to predict the rotating field in multi three-phase unit motor machine design. In order to satisfy equations (11) and (12), the equation for the forward and reverse sequence harmonics can be written as

$$r_{F_k,R_k} = k(C_N S_N M_N) \pm \frac{M_N S_N(C_N - 1)}{2} \quad k = 0, 1, 2, \ldots \quad (13)$$

$$r_{F_k,R_k} = k(C_N S_N M_N) \pm P \quad k = 0, 1, 2, \ldots \quad (14)$$

By applying the same algorithmic procedure for the multi three-phase distributed sector winding design of the prototype machine, the equations for the forward and reverse harmonic components can be represented as

$$r_{F_k,R_k} = k(C_N S_N M_N) \pm 2M_N S_N(C_N - 1) \quad k = 0, 1, 2, \ldots \quad (15)$$

$$r_{F_k,R_k} = k(C_N S_N M_N) \pm 4P \quad k = 0, 1, 2, \ldots \quad (16)$$

The amplitude of the forward and reverse harmonic fields can be calculated by the following equations for the multi three-phase concentrated and the multi three-phase distributed winding configurations as

$$a_{r_{F_k}, r_{r_k}} = \frac{2}{r_{F_k}, r_{R_k}} sin(r_{F_k}, r_{R_k}\frac{\pi}{C_N S_N M_N}) \quad (17)$$

$$f_{s_h}^{r_{F_k}, r_{R_k}} = \frac{C_N S_N M_N}{2} a_{r_{F_k}, r_{R_k}} NI \quad (18)$$

Here $a_{r_{F_k}, r_{R_k}}$ represents the fourier series coefficient of a single winding having N turns per winding, while the amplitude of the forward and reverse harmonic field is represented by equation (18).

C. THE (MT-SW) MACHINE MODEL GENERATED TORQUE AND TORQUE RIPPLES

The method used for the calculation of the generated torque in a surface mount PMSM has been given in [16]. The procedure is extended further in this section for the estimation of generated torque and torque ripples under the proposed rules discussed in this paper for the MT-SW designed machine model. According to the Lorentz force law for an isotropic machine, the instantaneous torque of a machine can be calculated as given by (17) while neglecting the cogging torque.

$$T_e = r_{ag} l_{stk} \int_{2\pi} B_{ag} df_{sh} = r_{ag} l_{stk} \int_{0}^{2\pi} B_{pm}\frac{df_{sh}}{d\zeta} d\zeta \quad (19)$$

The air gap radius is represented by r_{ag} while, the machine stack length is given by l_{stk}. Similarly, f_{sh} represents the MMF of the stator, while B_{ag} represents the flux density at the air gape mainly contributed by the permanent magnets of the machine. Subsequently, it can be written in fourier series form as

$$B_{pm}(\zeta) = \sum_{h\neq 2,4,6..}^{\infty} B_h(hp\zeta) \quad (20)$$

$$T_e = \sum_n \sum_h r_{ag} l_{stk} *(\int_{-\pi}^{\pi} f_{sh_F} B_h sin[(1 - \frac{r_{F_k}}{p})\omega t - (r_{F_k} \pm ph)\zeta + \lambda]d\zeta - \int_{-\pi}^{\pi} f_{sh_R} B_h sin[(1 + \frac{r_{R_k}}{p})\omega t + (r_{R_k} \mp ph)\zeta + \lambda]d\zeta) \quad (21)$$

The stator and the rotor generated harmonic components having the same order combine together to produce generated torque. The corresponding forward and reverse stator harmonic components can be calculated by equation (14) for the MT-CSW configurations and by equation (16) for the MT-DSW configurations. The forward and reverse stator MMF harmonic components that interact with the rotor harmonic components to produce torque components satisfy equations (22) and (23) for both the winding configurations.

The corresponding rotor harmonic components for the MT-CSW configurations are given by equation (24), while equation (25) must be satisfied in order to get an integer value of the rotor harmonics.

$$r_{F_k} \pm ph = 0; \quad (1 - \frac{r_{F_k}}{p}) = 0 \quad (22)$$

$$r_{R_k} \mp ph = 0; \quad (1 + \frac{r_{R_k}}{p}) = 0 \quad (23)$$

$$h = \frac{k(C_N S_N M_N)}{p} + 1 \quad (24)$$

$$k = mp; \quad m = 0, 2, 4, \ldots \quad (25)$$

The rotor harmonics h at $h = 1$ and the stator harmonics at $(r_{F_k,R_k}) = p$ results in continuous torque when $m = 0$ for the multi three-phase concentrated winding configuration. Henceforth, for the multi three-phase concentrated winding unit motor machine design, continuous torque occur when the above equations are satisfied while torque ripples occur when $h \neq 1$, therefore given by

$$h = m(C_N S_N M_N) + 1; \quad m = 2, 4, \ldots \quad (26)$$

Moreover, the corresponding rotor harmonic components for the multi three-phase distributed winding configurations are given by equation (27), while equation (28) must be satisfied in order to get an integer value of the rotor harmonics.

$$h = \frac{k(C_N S_N M_N)}{p} + 4 \quad (27)$$

$$k = mp; \quad m = 0, 2, 4, \ldots \quad (28)$$

Similarly, the rotor harmonics h for the multi three-phase distributed winding configurations must be equal to $h = 4$ while, the stator harmonics should satisfy $(r_{F_k,R_k}) = p$ resulting in continuous torque which is possible only when $m = 0$. Henceforth, for the multi three-phase distributed winding unit motor machine design, continuous torque occurs when the above equations are satisfied while torque ripples occur when $h \neq 4$ given by

$$h = m(C_N S_N M_N) + 4; \quad m = 2, 4, \ldots \quad (29)$$

The equation to calculate the mean torque for both types of MT-SW configurations can be expressed by equation (30) for the forward sequence harmonics, while for the reverse sequence harmonics, the same equation is used except for the operator sign changes in equation (21).

$$T_e = r_{ag} l_{stk} f^{sh}_{r_{F_0}} r_{F_0} b_1 sin\gamma \quad (30)$$

IV. VALIDATION OF THE MODULAR TYPE MACHINE WINDING CONFIGURATIONS

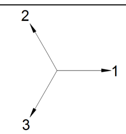
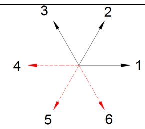
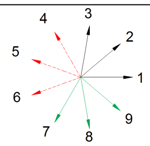
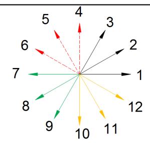
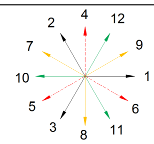
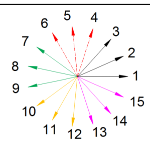
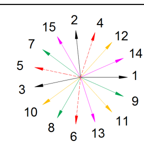
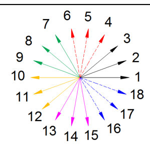
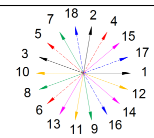
The machine prototype used in this paper has a multi three-phase winding configuration with independent three-phase unit motors symmetrically distributed around the circumference of the stator. The prototype machine under test having, 18 slots and 12 poles, can be divided into six three-phase unit motors in a sector winding design approach. The machine parameters are $C_N = 3$, $S_N = 6$, $P_N = 12$ and $M_N = 1$ having (3-6-12-1) configuration. The two analyzed winding configurations MT-CSW, and MT-DSW, are shown in Fig. 1(c) and Fig. 1(d). At the same time, Table 2 presents the detailed design parameters along with their phasor diagrams for both multi three-phase winding configurations using equation (2) and (3) starting with a single three-phase unit motor machine up to a machine design with six three-phase unit motors.

A. WINDING CONFIGURATIONS AND MACHINE MODEL VALIDATION

This section reports the validation of the prototype multi three-phase unit motor machine model with six independent three-phase unit motors having the proposed winding configurations. The modular type multi three-phase concentrated sector winding (MT-CSW) and multi three-phase distributed sector winding (MT-DSW) winding configurations are investigated, and the MMF harmonic spectrums for both the winding configurations are calculated based on the proposed algorithm presented in section III. Both the normal and post-fault (three-phase unit motors open-circuit fault) operating conditions are analyzed for both types of winding configurations. Fig. 2 presents the manufacturing process of the stator windings for the prototype machine with six three-phase unit motors.

The MT-CSW unit motors machine structure is shown in Fig. 3a, while the three-phase unit motors winding layout and phasor diagram are shown in Fig. 3b and Fig. 3c, respectively. Each three-phase unit motor has three-phase concentrated winding, and the six three-phase units are symmetrically distributed around the machine stator. The harmonic spectrum

TABLE 2. Multi three-phase unit motor machine solutions with winding configurations.

<table>
<tr><th>Machine model</th><th>(MT-CSW) Parameters</th><th>Phasor Diagram</th><th>(MT-DSW) Parameters</th><th>Phasor Diagram</th></tr>
<tr><td>Single three-phase unit motor
C_N-S_N-P_N-M_N
3-1-2-1</td><td>$\vartheta_{coil} = \frac{2\pi}{3}$
$\vartheta_{phase} = \frac{2\pi}{3}$
$\vartheta_{Sec} = 2\pi$</td><td></td><td>Not Feasible</td><td>Not Feasible</td></tr>
<tr><td>Double three-phase unit motors
C_N-S_N-P_N-M_N
3-2-4-1</td><td>$\vartheta_{coil} = \frac{\pi}{3}$
$\vartheta_{phase} = \frac{\pi}{3}$
$\vartheta_{Sec} = \pi$</td><td></td><td>Not Feasible</td><td>Not Feasible</td></tr>
<tr><td>Triple three-phase unit motors
C_N-S_N-P_N-M_N
3-3-6-1</td><td>$\vartheta_{coil} = \frac{2\pi}{9}$
$\vartheta_{phase} = \frac{2\pi}{9}$
$\vartheta_{Sec} = \frac{2\pi}{3}$</td><td></td><td>Not Feasible</td><td>Not Feasible</td></tr>
<tr><td>Quadruple three-phase unit motors
C_N-S_N-P_N-M_N
3-4-8-1</td><td>$\vartheta_{coil} = \frac{\pi}{6}$
$\vartheta_{phase} = \frac{\pi}{6}$
$\vartheta_{Sec} = \frac{\pi}{2}$</td><td></td><td>$\vartheta_{coil} = \frac{\pi}{6}$
$\vartheta_{phase} = \frac{2\pi}{3}$
$\vartheta_{Sec} = \frac{\pi}{2}$</td><td></td></tr>
<tr><td>Five three-phase unit motors
C_N-S_N-P_N-M_N
3-5-10-1</td><td>$\vartheta_{coil} = \frac{2\pi}{15}$
$\vartheta_{phase} = \frac{2\pi}{15}$
$\vartheta_{Sec} = \frac{2\pi}{5}$</td><td></td><td>$\vartheta_{coil} = \frac{2\pi}{3}$
$\vartheta_{phase} = \frac{8\pi}{15}$
$\vartheta_{Sec} = \frac{2\pi}{5}$</td><td></td></tr>
<tr><td>Six three-phase unit motors
C_N-S_N-P_N-M_N
3-6-12-1</td><td>$\vartheta_{coil} = \frac{\pi}{9}$
$\vartheta_{phase} = \frac{\pi}{9}$
$\vartheta_{Sec} = \frac{\pi}{3}$</td><td></td><td>$\vartheta_{coil} = \frac{2\pi}{3}$
$\vartheta_{phase} = \frac{4\pi}{9}$
$\vartheta_{Sec} = \frac{\pi}{3}$</td><td></td></tr>
</table>

(a) (b)

FIGURE 2. Machine prototype(a) Manufacturing process (b)complete machine prototype.

of the stator MMF can be calculated using expression (14-18) from section III. Equation (14) can be applied to get the forward and the reverse sequence of the stator MMF harmonic spectrum for the MT-CSW configuration of the prototype machine design. The simulation results for the stator MMF harmonics are compared with the analytical calculated results as shown in the first plot of Fig. 4a for the MT-CSW under the normal healthy operating condition (all three-phase unit motors synchronously operating). Similarly, the simulation and the analytical calculated results for the MMF harmonics spectrum plots of the prototype machine under post three-phase unit motors open-circuit fault operating conditions are subsequently shown in Fig. 4b, Fig. 4c and Fig. 4d, respectively. Fig. 5a represents the MT-DSW configuration of the prototype machine, with Fig. 5b and Fig. 5c showing the three-phase unit motors winding layout and phasor diagram of the prototype machine. The MMF harmonic spectrum plots using the proposed algorithm for the multi three-phase distributed sector winding configuration are also shown in Fig. 6 under normal and post three-phase unit motors open-circuit fault operating conditions.

B. MAGNETIC FLUX DENSITY AND RADIAL FORCES IN MULTI THREE-PHASE UNIT MOTOR MACHINE

The application of both types of multi three-phase winding configurations and the proposed algorithm leads to a feasible solution of the modular type machine; however, one type of winding configuration can be a much better choice than the other in terms of the MMF harmonic spectra, unbalanced magnetic forces or the generated torque ripples especially for fault-tolerant applications. The evaluation of the magnetic flux density and radial forces will be discussed in this subsection for the multi three-phase unit motor machine design under the MT-CSW and MT-DSW winding configurations.

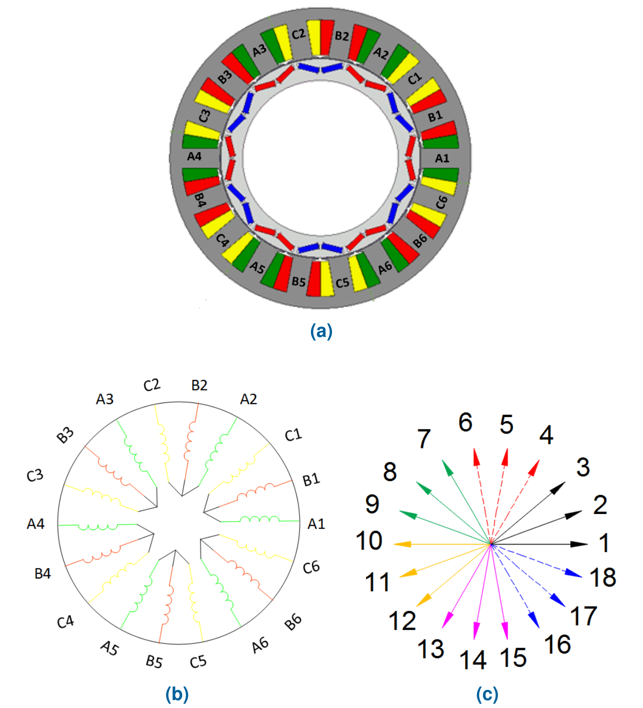


FIGURE 3. Machine design (a) MT-CSW machine structure (b) Three-phase unit motors winding layout (c) Phasor diagram.

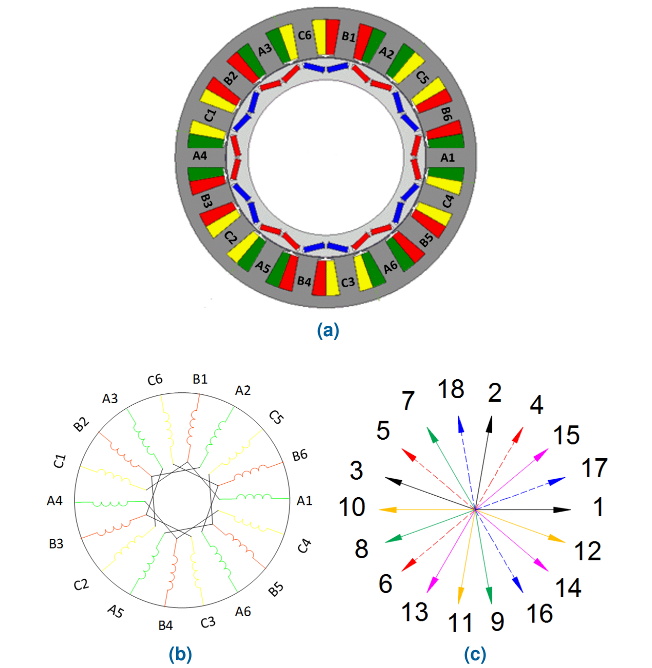


FIGURE 5. Machine design (a) MT-DSW machine structure (b) Three-phase unit motors winding layout (c) Phasor diagram.

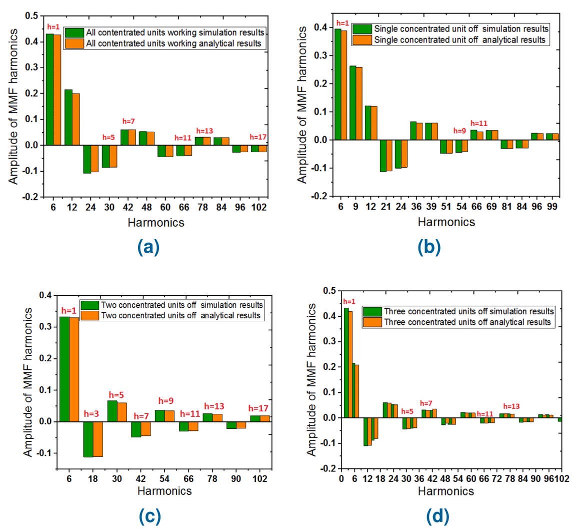


FIGURE 4. Comparison of analytical and simulation results of MMF harmonics for the machine with MT-CSW configurations under multiple operating cases.

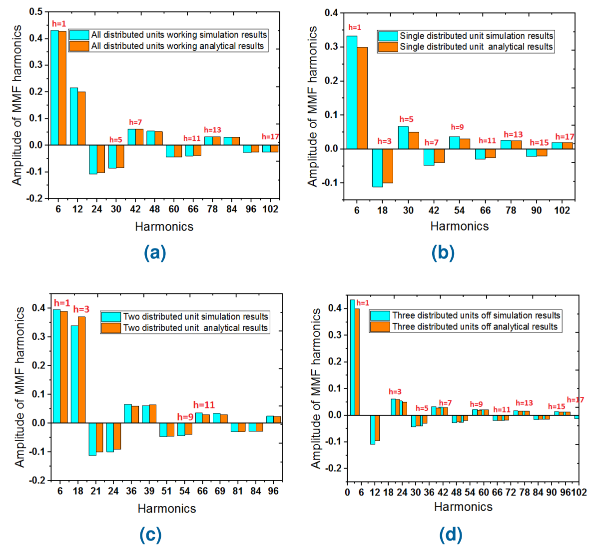


FIGURE 6. Comparison of analytical and simulation results of MMF harmonics for the machine with MT-DSW configurations under multiple operating cases.

FEA is used to analyze the distribution of magnetic flux and radial force density distribution in the prototype machine with six three-phase unit motors having (3-6-12-1) configuration for both the MT-CSW and MT-DSW configurations. Fig. 7 presents the magnetic flux density distribution for the prototype machine with MT-CSW and MT-DSW configurations under the machine's normal and open-circuit fault conditions. Similarly, the plots for the radial flux density harmonics are presented in Fig. 8, while Fig. 9 demonstrates the distribution of radial force density for the prototype machine under normal and different three-phase unit motors open-circuit fault conditions for both winding configurations.

It can be observed from the magnetic flux density plots in Fig. 7a and Fig. 7b and from the harmonic spectrum plots of the radial flux density in Fig. 8a and Fig. 8b along with the radial force distribution in Fig. 9a and Fig. 9b that under normal operating conditions (all three-phase unit motors working), the magnetic behaviour and the distribution

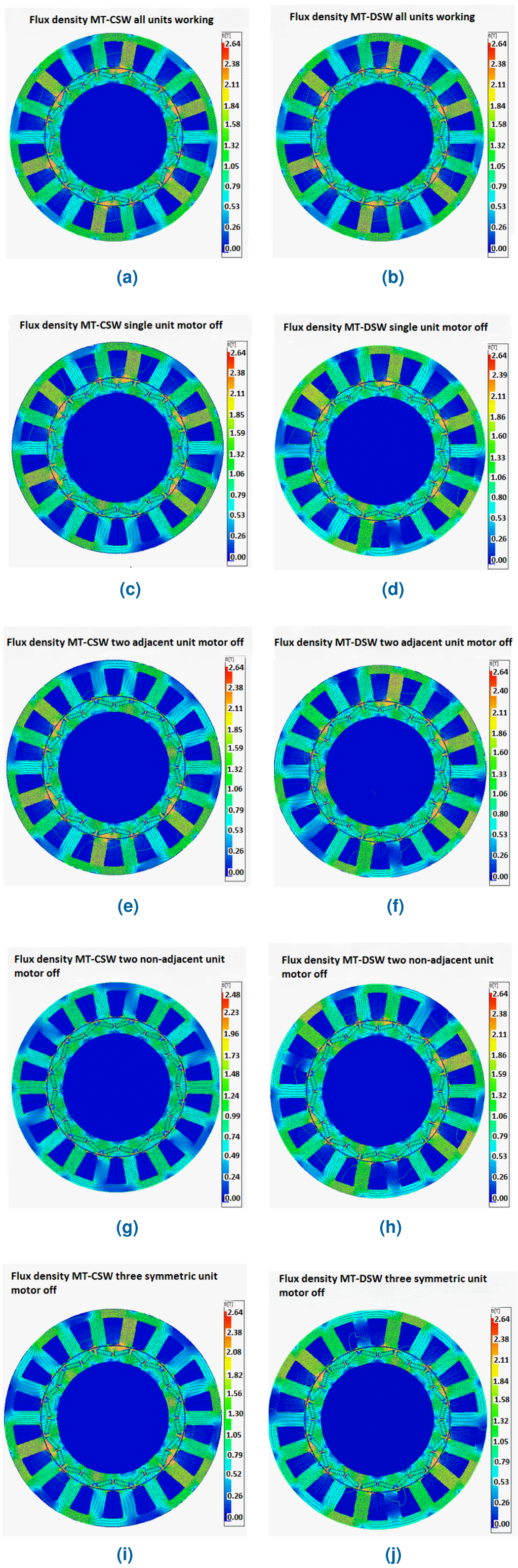


FIGURE 7. Radial flux density harmonics with MT-CSW and MT-DSW configuration under normal and three-phase unit motors open-circuit post-fault operation.

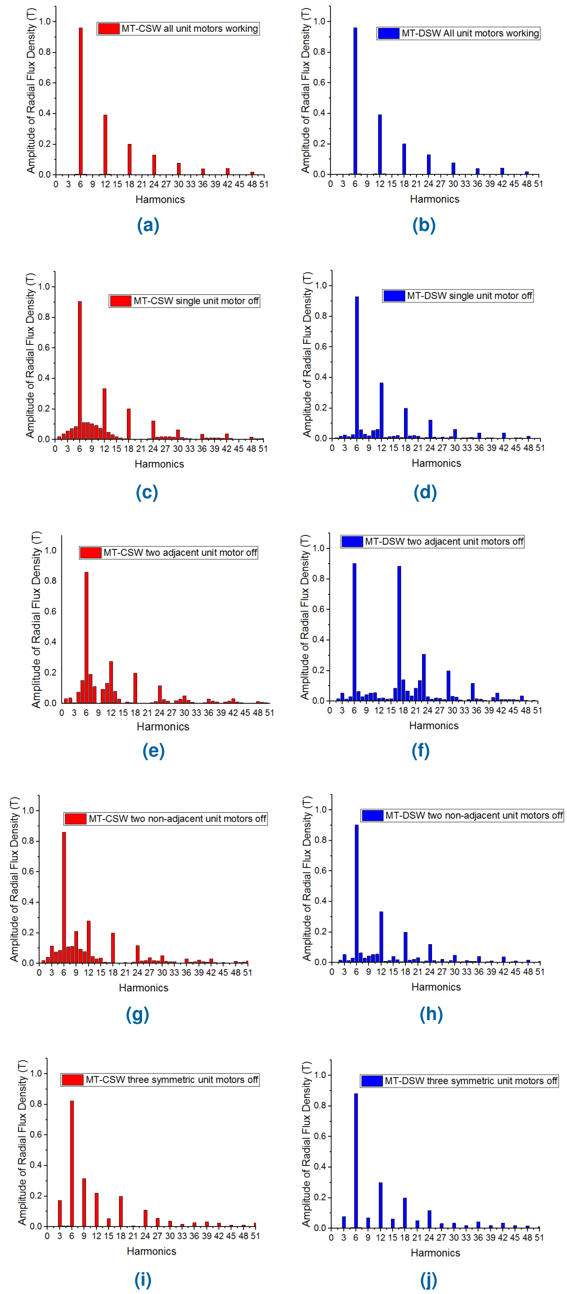


FIGURE 8. Radial flux density harmonics with MT-CSW and MT-DSW configuration under normal and three-phase unit motors open-circuit post-fault operation.

of radial forces in the machine prototype is identical for both multi three-phase winding configurations. However, under three-phase unit motors open-circuit post-fault operation of the prototype machine, there is a considerable difference in the magnetic flux density distribution, the radial flux density harmonic spectrum plots as well as in the distribution of radial force density for both the analyzed winding configurations. The harmonic spectrums plots of the machine radial flux density under unit motors open-circuit fault conditions in Fig. 8 shows that for the MT-CSW, there are more low-order sub-harmonics which are higher in amplitude and more crowded compared to the same kind of fault operation in the MT-DSW configuration of the prototype machine. Similarly,

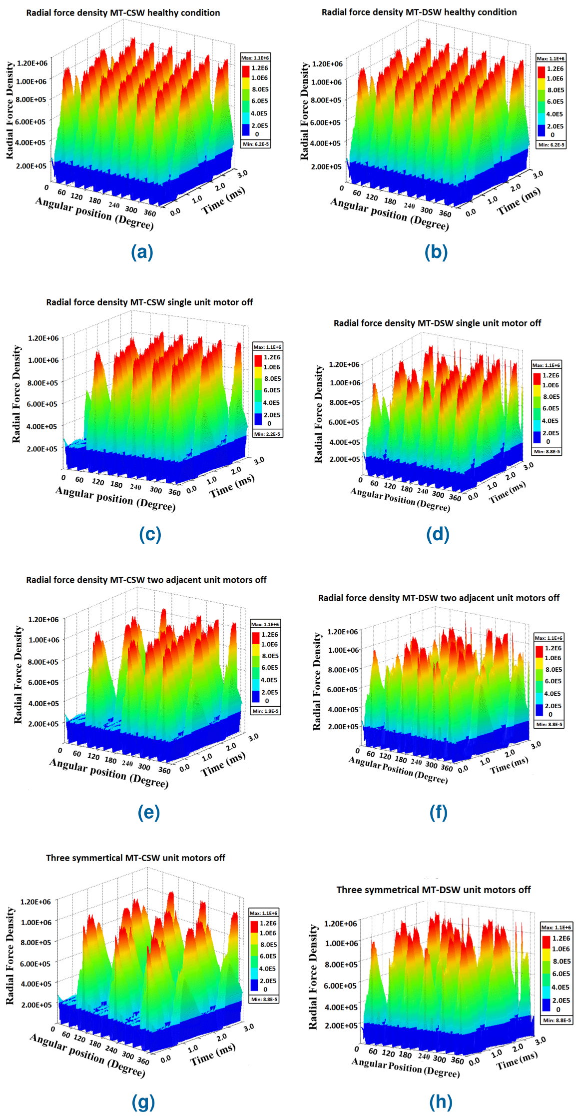
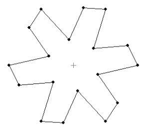
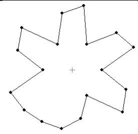
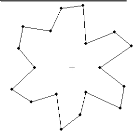
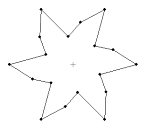
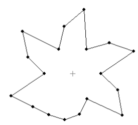
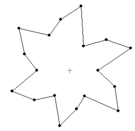
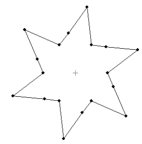
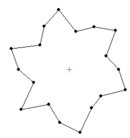
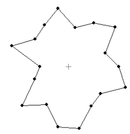
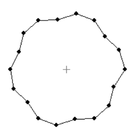
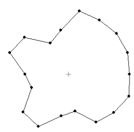
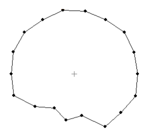
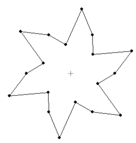
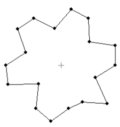
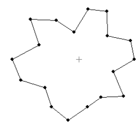
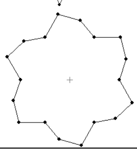
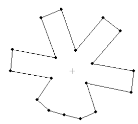
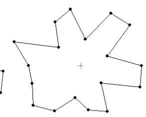


FIGURE 9. Radial force density using transient 2D FEA for MT-CSW and MT-DSW under normal and unit motors open-circuit post-fault operation.

Table 3 illustrates the harmonic orders and force distribution on the stator tooth for the MT-CSW and MT-DSW designs under normal and post three-phase unit motors fault operating conditions. The force distributions on the machine's stator tooth in Table 3 are presented for the normal and single three-phase unit motor open-circuit fault condition of the machine for both the winding configurations.

It can be observed from the plots presented in Table 3 and from Fig. 9 that the distribution of the radial forces under three-phase unit motors open-circuit fault operations are comparatively balanced and smooth for the MT-DSW configurations than the MT-CSW configuration of the prototype machine. Henceforth, the distribution of radial forces in the MT-DSW configuration is comparatively more balanced than the MT-CSW configuration of the machine model under various unit motors open-circuit post-fault operations, while under normal operating conditions, the radial force density distribution is balanced and the same for both the winding configurations. The findings about the machine radial forces, vibration and noise behaviour have been presented in [19].

TABLE 3. Harmonic orders and forces distribution on the stator tooth for MT-CSW and MT-DSW configurations.

Harmonic order	Machine prototype healthy operation	MT-CSW single three-phase unit motor fault	MT-DSW single three-phase unit motor fault
0^{th} harmonic			
12^{th} harmonic			
24^{th} harmonic			
36^{th} harmonic			
48^{th} harmonic			
60^{th} harmonic			

V. TORQUE RESPONSE WITH MT-CSW AND MT-DSW CONFIGURATIONS UNDER NORMAL AND OPEN-CIRCUIT FAULTS

A. NORMAL AND SINGLE THREE-PHASE UNIT MOTOR OPEN-CIRCUIT FAULT

Firstly, the generated torque behaviour under the healthy operation of the prototype machine is investigated for the MT-CSW and MT-DSW configurations under identical operating conditions. Then a single three-phase unit motor open-circuit fault is introduced in the MT-CSW configuration, and the MT-DSW configuration of the modular IPMSM prototype under identical operating conditions.

Fig. 10 illustrates the generated torque for both the winding configurations under the machine's normal and a single three-phase unit motor open-circuit fault operating conditions. The black curve corresponds to the torque generated under normal healthy operating conditions, while the blue curve shows a single three-phase concentrated sector

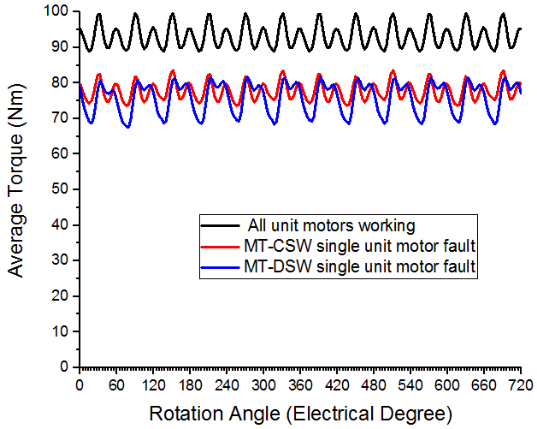


FIGURE 10. Torque comparison under a single unit motor open-circuit fault for the MT-CSW and MT-DSW designs.

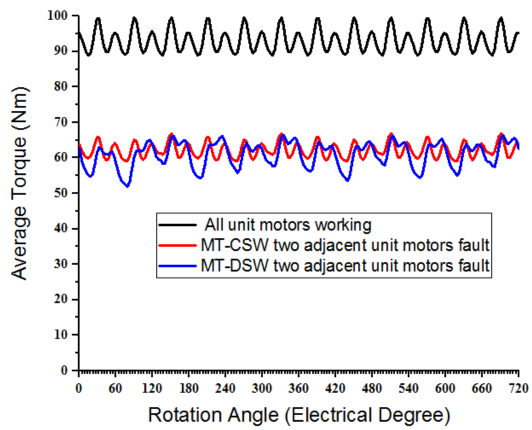


FIGURE 11. Torque comparison under two adjacent unit motors open-circuit fault for the MT-CSW and MT-DSW designs.

winding unit motor open-circuit fault condition. Similarly, the red curve shows a single three-phase distributed sector winding unit motor open-circuit fault condition. It can be observed from Fig. 10 that the generated torque response under healthy operation of the machine for both winding configurations is identical however, under a single three-phase unit motor open-circuit fault operating condition, the torque ripple is comparatively higher for the MT-DSW configuration compared to the MT-CSW configuration of the prototype machine.

B. TWO ADJACENT AND TWO NON-ADJACENT THREE-PHASE UNIT MOTORS OPEN-CIRCUIT FAULT

Two more three-phase unit motors open-circuit fault operating cases are discussed in this subsection by introducing two adjacent and two non-adjacent three-phase unit motors open-circuit faults in the prototype machine for both the winding configurations. The generated torque response for the case of two adjacent three-phase unit motors open-circuit fault condition is shown in Fig. 11 for the MT-CSW and MT-DSW configurations. Similarly, the generated torque

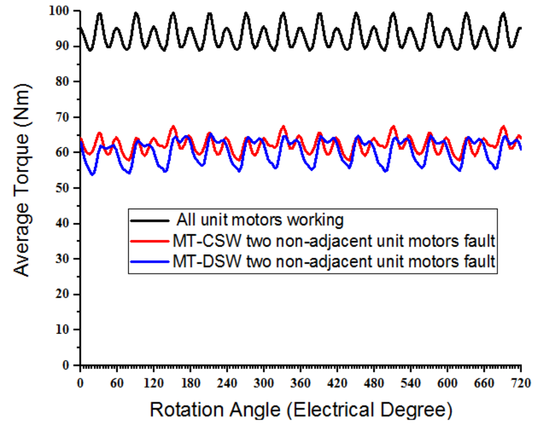


FIGURE 12. Torque comparison under two non-adjacent unit motors fault for the MT-CSW and MT-DSW designs.

response for the two non-adjacent three-phase unit motors fault operation is shown in Fig. 12 for both the winding configurations. It can be observed the generated torque ripples in the MT-CSW design are much lower compared to the MT-DSW design for both adjacent and non-adjacent three-phase unit motors fault operating conditions similar to the previous case. Similarly, it can be observed from Fig. 10, Fig. 11 and Fig. 12 and the data presented in Table 4 that the average generated torque for the MT-CSW is higher compared to the MT-DSW winding configuration under the same operating conditions with different three-phase unit motors open-circuit faults.

C. THREE SYMMETRICAL THREE-PHASE UNIT MOTORS OPEN-CIRCUIT FAULT

Lastly, symmetrical three unit motors open-circuit fault is introduced in the prototype machine, and the generated torque response is studied for the analyzed multi three-phase winding configurations. Fig. 13 presents the generated torque and torque ripple response under three symmetrical three-phase unit motors open-circuit fault conditions for the MT-CSW and MT-DSW design configurations. Here again, the MT-DSW design configuration has higher torque ripples in the generated torque compared to the MT-CSW design configuration. Moreover, Fig. 14 presents the average torque (p.u) and peak-to-peak torque ripple during different three-phase unit motors faults for the MT-CSW design configuration. Similarly, Fig. 15 presents the average torque (p.u) and peak-to-peak torque ripple during different three-phase unit motors fault for the MT-DSW design configuration.

It can be observed from the bar plots in Fig. 14 and Fig. 15 that the torque ripples in the generated torque are comparatively higher for the MT-DSW design under three-phase unit motors open-circuit fault operating conditions. This kind of behaviour is attributed to the more spread nature of the radial force density harmonics in the air gap of the machine prototype under the MT-DSW configuration compared to the MT-CSW configuration. Also the MT-DSW configuration

TABLE 4. Average torque and torque ripple in MT-CSW and MT-DSW designs under normal and open-circuit fault conditions.

Machine operating condition	Average Torque MT-CSW and MT-DSW designs (N.m)	% Torque Ripples in MT-CSW and MT-DSW designs (peak-to-peak)	% Difference in Torque Ripples
All unit motors working	[93.1] - [93.1]	[0.107] - [0.107]	[0]
Single unit motor fault	[77.7] - [75.7]	[0.098] - [0.141]	[43.8]
Two adjacent unit motors fault	[62.1] - [60.9]	[0.077] - [0.144]	[87]
Two non adjacent unit motors fault	[62.2] - [60.5]	[0.095] - [0.114]	[51.5]
Three symmetrical unit motors fault	[46.7] - [44.7]	[0.094] - [0.114]	[51.3]

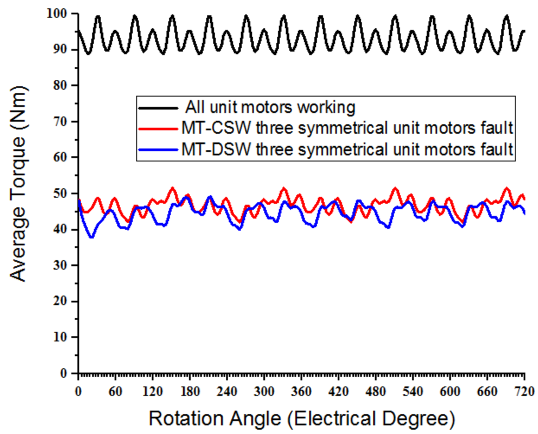


FIGURE 13. Torque under three symmetrical unit motors open-circuit fault for the MT-CSW and MT-DSW designs.

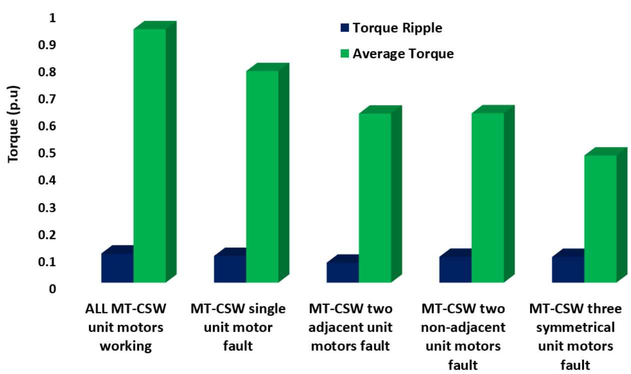


FIGURE 14. Average torque and peak-to-peak torque ripples under different unit motors faults for the MT-CSW design.

has more torque ripple producing harmonic components as presented in Fig. 6 compared to the MT-CSW configuration. Moreover, Table 4 presents a comprehensive comparison of the average torque and torque ripple in MT-CSW and MT-DSW configurations under unit motors normal and open-circuit post-fault operating conditions. Henceforth, it can be deduced that under three-phase unit motors open-circuit fault operations, the torque ripples in the generated torque are much lower for the MT-CSW configuration compared to the MT-DSW configuration of the prototype machine, however, from section IV it was observed that the distribution of the machine radial forces is much smoother for the MT-DSW configuration.

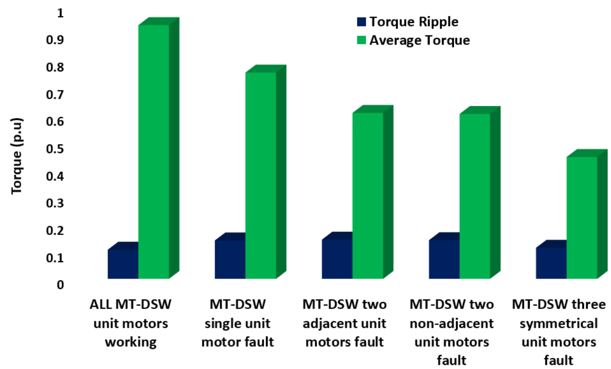


FIGURE 15. Average torque and peak-to-peak torque ripples under different unit motors faults for the MT-DSW design.

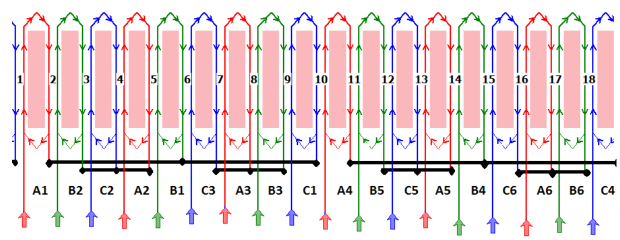


FIGURE 16. Multi three-phase mixed concentrated and distributed sector winding (MT-mixed C&DSW) configuration.

VI. MULTI THREE-PHASE MIXED CONCENTRATED AND DISTRIBUTED SECTOR WINDING CONFIGURATION

A third type of multi three-phase mixed concentrated and distributed sector winding (MT-mixed C&DSW) configuration is proposed in this paper combining, the (MT-CSW) and (MT-DSW) configurations. Fig.16 presents the MT-mixed C&DSW configuration comprising of three-phase concentrated and three-phase distributed sector winding configurations.

A. TORQUE RESPONSE OF THE MT-MIXED C&DSW CONFIGURATION UNDER NORMAL AND UNIT MOTORS OPEN-CIRCUIT FAULT CONDITIONS

In this section, the generated torque response of the mixed C&DSW configuration is investigated under normal operation, when all the three-phase unit motors are synchronously operating together under the same operating condition as well as under the condition when some three-phase units are in off conditions. Fig. 17 presents the generated torque response

TABLE 5. Average torque and torque ripple in MT-Mixed C&DSW designs under normal and open-circuit fault conditions.

Machine operating condition	Average Torque MT-Mixed C&DSW (N.m)	% Torque Ripples (peak-to-peak)			%Difference (Torque Ripples)
		MT-mixed C&DSW	MT-CSW	MT-DSW	
All unit motors working	[93.1]	[0.107]	-	-	Same
Single CSW unit motor fault	[77.7]	[0.097]	[0.098]	-	Almost same
Single DSW unit motor fault	[77.5]	[0.084]	-	[0.141]	[67.8]
Two CSW non-adjacent unit motors fault	[62.2]	[0.094]	[0.095]	-	Almost same
Two DSW non-adjacent unit motors fault	[61.8]	[0.107]	-	[0.114]	[10.7]
Two adjacent unit motors fault	[62.1]	[0.082]	-	[0.144]	[75.6]

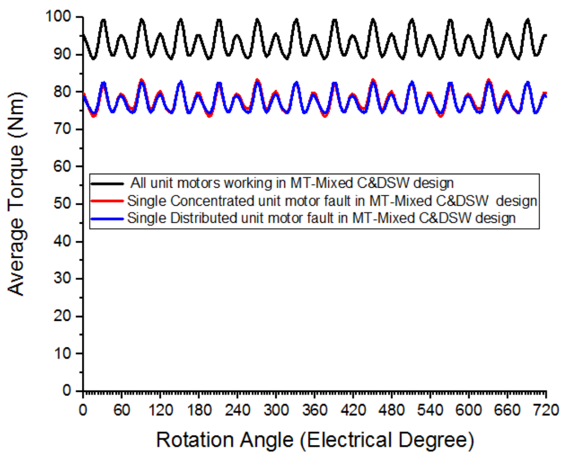


FIGURE 17. Torque comparison under a single CSW and DSW unit motor open-circuit fault in MT-mixed C&DSW design.

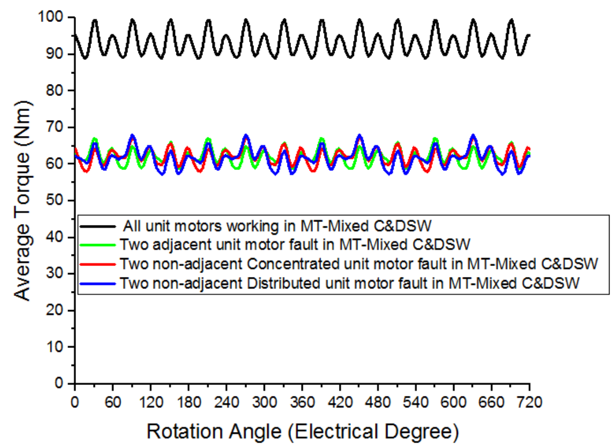


FIGURE 18. Torque under two non-adjacent CSW and DSW unit motors open-circuit fault in MT-mixed C&DSW design.

when all the concentrated and distributed three-phase unit motors are operating normally along with the conditions when a single CSW three-phase unit motor and a single DSW three-phase unit motor is in off condition. The generated torque response of the MT-mixed C&DSW configuration is also investigated when two adjacent unit motors and two non-adjacent CSW three-phase unit motors are in off conditions while the remaining three-phase unit motors are synchronously operating.

Similarly, the operating case when two non-adjacent DSW three-phase unit motors are in off condition is also studied for its generated torque response. Fig. 18 shows a comparison plot of the generated torque when two adjacent unit motors and two non-adjacent CSW and DSW unit motors are in off conditions. Table 5 presents values of the average torque and torque ripple in multi three-phase mixed C&DSW configurations under normal and post three-phase unit motors fault operating conditions. From the comparison data presented in Table 5 for the mixed C&DSW configuration and from the data presented in Table 4 for the MT-CSW and MT-DSW configurations, it can be observed that the average generated torque has increased for the distributed sector unit motors open-circuit faults in the mixed C&DSW configuration. Similarly, the torque ripples have also reduced under the same kind of fault and same operating conditions in the mixed C&DSW configuration. Moreover, the normal operation of all the three analyzed winding configurations is exactly the same under the same operating conditions, however, under unit motors, open-circuit fault operating condition the average torque is higher, and the torque ripples are much lower for the mixed C&DSW configuration compared to the other two winding configurations especially the MT-DSW configuration.

VII. CONCLUSION

This paper presents the design concept and guidelines for the multi three-phase unit motors machine. The main focus is on a six three-phase unit motor machine design with three slots and a pole pair making a single independent unit motor. However, this approach can be generalized to any repetition of the basic three-phase unit motor to form a multi three-phase unit motor machine design. The proposed analytical algorithm allows predicting the stator MMF harmonic spectrum and the generated torque and torque ripples in any multi three-phase unit motors machine design under normal and open-circuit post-fault operating conditions. Moreover, two separate multi three-phase winding design configurations (MT-CSW) and the (MT-DSW) have been studied. The harmonic spectrum plots, the distribution of radial force density, the generated torque and torque ripple response under normal and post three-phase unit motors open-circuit fault operating conditions have been thoroughly investigated for both the multi three-phase winding configurations. Detailed FEA has been conducted to investigate and compare the different analyses presented. The main research findings from this analysis are listed as under

1) It can be observed from the analysis presented that the magnetic flux density, radial forces and the generated torque response under the healthy operating conditions of the multi three-phase unit motor machine is basically the same for both of the analyzed winding configurations. However, the magnetic flux density, radial forces and the generated torque response under unit motors open-circuit fault operation of the prototype machine is considerably different for both the analyzed multi three-phase sector winding configurations. The magnetic flux density for the MT-CSW has more subharmonics which are more crowded in nature compared to the MT-DSW configuration under unit motors open-circuit fault operation. Moreover, the radial force density distribution are also comparatively less uneven and unbalanced for the MT-DSW configuration compared to the MT-CSW configuration under different three-phase unit motors open-circuit fault operation.
2) The generated average torque in the MT-CSW configuration is a little higher compared to the MT-DSW configuration of the machine prototype under the same operating conditions. Similarly, the torque ripples in the generated torque are much lower for the MT-CSW design compared to the MT-DSW design configuration under any number of three-phase unit motors open-circuit faults.
3) The MT-mixed C&DSW configuration, a combination of the MT-CSW and MT-DSW configuration, is also investigated for the generated torque and torque ripples under the same unit motors open-circuit fault conditions. Its normal working operation is the same as the other two analyzed multi three-phase winding configurations. Moreover, the MT-mixed C&DSW configuration combines the advantages of the MT-CSW and MT-DSW winding configurations; henceforth it can be considered a better choice under three-phase unit motors open-circuit post-fault operation, particularly for applications requiring fault-tolerance.

The research findings presented in this paper can better help machine designers in selecting a multi three-phase winding configuration for a multi three-phase unit motor machine design which can be applied according to application specific requirements with particular focus on the unbalanced magnetic forces and the generated torque ripples under three-phase unit motors open-circuit post-fault operation.

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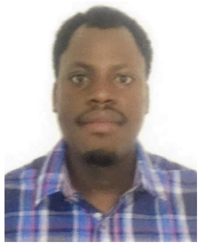

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