Impact of Neutral Point Current Control on Copper Loss Distribution of Five Phase PM Generators Used in Wind Power Plants

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***Abstract*—Efficiency improvement under faulty conditions is one of the main objectives of fault tolerant PM drives. This goal can be achieved by increasing the output power while reducing the losses. Stator copper loss not only directly affects the total efficiency, but also plays an important role in thermal stress generations of iron core. In this paper, the effect of having control on neutral point current is studied on the efficiency of five-phase permanent magnet machines. Open circuit fault is considered for both one and two phases, and the distribution of copper loss along the windings are evaluated in each case. It is shown that only by having access to neutral point, it is possible to generate less stator thermal stress and more mechanical power in five-phase permanent magnet generators. Wind power generation and their applications are kept in mind, and the results are verified via simulations and experimental tests on an outer-rotor type of five-phase PM machine.**

***Index Terms*—brushless motors, permanent magnet motors, variable speed drives, energy conservation, motor drives.**

I. INTRODUCTION

Regarding their high efficiency and compactness, permanent magnet (PM) machines are gaining more interest in the field of wind power generation and electrical vehicles. Absence of field windings and rotor currents in PM machines not only reduces the required maintenance, but also increases the efficiency and robustness [1-2]. On the other hand, fault tolerant concept is an important issue in applications where the process cannot be stopped due to additional cost penalties or safety reasons [3].

PM drive faults can be generally categorized as actuator faults, airgap irregularities, rotor magnet faults, and stator winding faults [4]. Among these categories, stator winding open-circuit fault and semiconductor failures are the most common ones [5].

Compared with standard three-phase systems, multi-phase drives present better fault tolerant capabilities. These systems are able to maintain operational in the case of one or even two faulty phases. In addition having more phases results in several advantages such as lower current per phase, lower power per inverter leg, and lower amplitude and higher frequency of generated torque ripple. Rotor configuration can also be important in generation of electrical torque. Because of their rotor saliency, interior permanent magnet (IPM) machines are able to produce an additional reluctance torque and have higher torque density [6-7].

Depending on their stator winding configuration, the induced back electromotive force (EMF) of a PM machine can be sinusoidal or trapezoidal. These categories are respectively famous as permanent magnet synchronous machines (PMSM) and brushless direct current (BLDC) machines. In the case of five-phase BLDC machines, third harmonic of current can also be used to modify the generated electrical torque [8-9]. The combination of slot number, winding distribution and phase number is evaluated in [10] to reduce the generated torque pulsation in a five-phase IPM machine.

Fault tolerant characteristics of five-phase drives are interesting in high safety applications. Following the idea of operating under faulty conditions, several fault-tolerant strategies have been proposed in literature [9] [11]. A comparative study is conducted in [12] to analyze the impact of stator winding layers under faulty conditions. One and two opened phases are considered and appropriate current references are analytically calculated under each condition. In [13] the operation with only two healthy phases is studied by connecting the neutral point of a three-phase machine to the DC bus. To reduce the generated torque ripple, stator current references are shifted by 60º in this study.

Optimum fault tolerant control is developed in [14-15] to improve the generated output torque of five-phase PM machines, and at the same time, to limit the stator ohmic loss which can provoke thermal stress and damage the machine. A vectorial method for real time computation of appropriate current references is developed in [16], which is in accordance with the obtained results of [15].

Fundamental and third harmonic of stator currents are considered in [16] to improve both amplitude and quality of generated torque under faulty conditions of five-phase BLDC machines. Continuing this study, the same authors have examined different configurations of stator winding for postfault operation. Although, all this work is completed while assuming an isolated neutral point for the machine, but it is shown that by controlling the third harmonic of stator currents, it is possible to improve torque quality and reduce the ripples [4].

In this paper, the effect of having control on neutral point current is studied on generated heat in the machine due to stator currents. In other words, the impact of neutral point current control is evaluated on machine output power and stator winding copper loss.

Having an isolated neutral point, the total sum of stator

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phase currents must always be zero. As a result, in previous studies it is tried to have a symmetric rearrangement of the phase currents with respect to the fault [17-18]. Having access to neutral point, this condition can be ignored, and reference values of stator currents can be chosen independently to maximize the output power and at the same time to limit the total amount of stator copper loss. For a specific amount of output power, minimum stator copper loss is obtained when stator current third harmonics are set to zero [16] [19]. As a result, only first component of stator currents are considered in this paper to simplify the calculations. For a fixed value of stator copper loss, reference values of stator current are optimized to maximize the average of transferred power. Experimental tests are completed which verify the theoretical developments.

II. Analytical Model of a Five Phase BLDC

In this section, BLDC machine model is calculated on the assumption of having a symmetric five-phase winding configuration, no iron saturation, and P poles. Let us start with the general equation of machine´s electrical dynamics which is:

$$[V_s] = r_s[I_s] + \frac{d}{dt}[\Lambda_s] \tag{1}$$

where Vs is voltage matrix of stator winding terminals, Rs and Is are resistance and current respectively. Λs is the magnetic flux linkage of stator windings which is generated by stator currents and rotor magnets.

$$\Lambda_s = L_{ss} I_s + \Lambda_{PM} \tag{2}$$

where L_{ss} represents stator inductance matrix.

The magnetic flux of rotor magnets in a BLDC machine airgap can be estimated by its first and third harmonic components:

$$\Lambda_{PM} = \lambda_{pm1}\begin{bmatrix} \sin(\theta) \\ \sin(\theta - \frac{2\pi}{5}) \\ \sin(\theta - \frac{4\pi}{5}) \\ \sin(\theta - \frac{6\pi}{5}) \\ \sin(\theta - \frac{8\pi}{5}) \end{bmatrix} + \lambda_{pm3}\begin{bmatrix} \sin(3\theta) \\ \sin 3(\theta - \frac{2\pi}{5}) \\ \sin 3(\theta - \frac{4\pi}{5}) \\ \sin 3(\theta - \frac{6\pi}{5}) \\ \sin 3(\theta - \frac{8\pi}{5}) \end{bmatrix} \tag{3}$$

where λ_{pm1} and λ_{pm3} are first and third harmonic components of rotor magnetic flux, and $\theta = wt$ is rotor electrical angle. Electrical parameters of stator windings can be transferred into synchronous rotating frames. This results in a simpler and more conceptual control in a DC environment. Considering first and third harmonics, the transformation equation is written in (4) at the beginning of the next page. Using this transformation, stator voltages and currents will be transferred into $d_1 - q_1$ and $d_3 - q_3$ planes which respectively rotate at synchronous speed, and its third multiple. Multiplication of (1) by T results in the related electrical equations of BLDC machine in two reference frames. These equations can be summarized as:

$$V_{ds1} = r_s i_{ds1} - \omega\lambda_{qs1} + \frac{d\lambda_{ds1}}{dt} \tag{5}$$

$$V_{qs1} = r_s i_{qs1} + \omega\lambda_{ds1} + \frac{d\lambda_{qs1}}{dt} \tag{6}$$

$$V_{ds3} = r_s i_{ds3} - 3\omega\lambda_{qs3} + \frac{d\lambda_{ds3}}{dt} \tag{7}$$

$$V_{qs3} = r_s i_{qs3} + 3\omega\lambda_{ds3} + \frac{d\lambda_{qs3}}{dt} \tag{8}$$

where r_s is the stator resistance, and ω is the electrical rotational velocity. These equations will be used in vector control of BLDC machine. Generated electrical torque will be calculated as:

$$T_e = \frac{5}{2}\frac{P}{2}\left[\lambda_{m1} i_{qs1} + 3\lambda_{m3} i_{qs3}\right] \tag{9}$$

III. Open Circuit Fault in Five Phase PM Machines

Control of PM machines under faulty conditions has been considered in many studies. The main objective of these studies is generally to improve the amplitude and quality of generated torque in postfault conditions. In addition if neutral point is disconnected, the total sum of stator phase currents must always be equal to zero:

$$i_A(t) + i_B(t) + i_C(t) + i_D(t) + i_E(t) = 0 \tag{10}$$

As a result, it is usually tried to have a symmetric rearrangement of stator phase currents with respect to the fault [17-18]. While calculating appropriate reference values of stator currents, machine thermal limits should also be kept in mind. Stator current peak values can lead to saturation or thermal stress along the iron core. Total amount of stator copper loss can be used to limit the operational temperature of the machine which in addition leads to reduced values of generated torque under faulty conditions [16].

Optimized current reference values for maximizing the generated output power are summarized in Table I and Fig. 1 [20]. In all of these conditions, total amount of stator copper loss is limited to its nominal value. Under faulty conditions, the missing part of stator magnetic field should be compensated by the remaining healthy phases. Moreover, due to machine´s thermal limitations, stator copper loss should be limited to its nominal value.

If neutral point of the machine is accessible, equation (10) can be ignored, and this allows us to have more freedom in calculating proper amplitude and phase angle of stator currents under faulty conditions.

Regardless of iron core saturation, if the total amount of stator copper loss is limited in a BLDC machine, the maximum output power will be achieved when the third harmonic of stator currents is set to zero [19]. As a result and to simplify the calculations, only first component of stator currents is considered to generate the maximum power. Under healthy mode operation, rotating magnetic field of stator in the airgap has constant amplitude. After missing one of the phases, its missing part in the stator magnetic field can be compensated by introducing additional current subphasors in the remaining healthy phases.

$$F_{d_1q_1d_3q_3o} = T\, F_{abcde}$$

$$T_{dqo}\left(wt\right)=\frac{2}{5}\begin{bmatrix} \cos(\omega t) & \cos(\omega t-2\pi/5) & \cos(\omega t-4\pi/5) & \cos(\omega t-6\pi/5) & \cos(\omega t-8\pi/5) \\ -\sin(\omega t) & -\sin(\omega t-2\pi/5) & -\sin(\omega t-4\pi/5) & -\sin(\omega t-6\pi/5) & -\sin(\omega t-8\pi/5) \\ \cos 3(\omega t) & \cos 3(\omega t-2\pi/5) & \cos 3(\omega t-4\pi/5) & \cos 3(\omega t-6\pi/5) & \cos 3(\omega t-8\pi/5) \\ -\sin 3(\omega t) & -\sin 3(\omega t-2\pi/5) & -\sin 3(\omega t-2\pi/5) & -\sin 3(\omega t-2\pi/5) & -\sin 3(\omega t-2\pi/5) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (4)$$

TABLE I. APPROPRIATE CURRENT PHASORS WITH ISOLATED NEUTRAL POINT

Number of Missing Phases		Current Amplitudes (PU)				
		A	B	C	D	E
0 (Healthy)	Amplitude	1	1	1	1	1
	angle	0	-72°	-144°	144°	72°
1	Amplitude	0	1.12	1.12	1.12	1.12
	angle	-	-36°	-144°	144°	36°
2 (Adjacent)	Amplitude	0	0	1.04	1.68	1.04
	angle	-	-	-72°	144°	0°
2 (Nonadjacent)	Amplitude	0	0.89	0	1.45	1.45
	angle	-	-72°	-	180°	36°

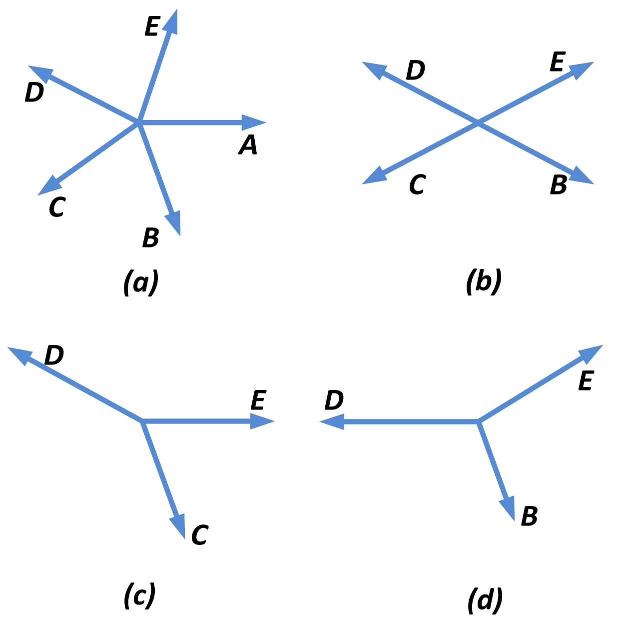


Figure 1. Appropriate current references while machine neutral point is not connected and stator copper loss is kept under its nominal value, (a) healthy mode operation, (b) one faulty phase, (c) two adjacent faulty phases, (d) two nonadjacent faulty phases

As shown in Fig. 2, if there is an open circuit fault in phase A, the missing part of stator magnetic field $\vec{F}\left(\vec{I}_A\right)$ should be compensated by magnetic field of four additional current terms in the remaining healthy phases namely $K_b i_A(t)$, $K_c i_A(t)$, $K_d i_A(t)$ and $K_e i_A(t)$ where K_b, K_c, K_d and K_e are scalar constants, and $i_A(t)$ is the instantaneous amplitude of phase A current:

$$\vec{F}\left[i_A(t)\right]_{phase\ A} = \vec{F}\left[K_b i_A(t)\right]_{phase\ B} + \vec{F}\left[K_c i_A(t)\right]_{phase\ C} + \vec{F}\left[K_d i_A(t)\right]_{phase\ D} + \vec{F}\left[K_e i_A(t)\right]_{phase\ E} \quad (11)$$

Following this concept, in the case of one faulty phase, modified reference currents can be considered as:

$$\begin{aligned} I'^*_A &= 0 \\ I'^*_B &= I^*_B + k_b I^*_A \\ I'^*_C &= I^*_C + k_c I^*_A \\ I'^*_D &= I^*_D + k_d I^*_A \\ I'^*_E &= I^*_E + k_e I^*_A \end{aligned} \quad (12)$$

Considering fundamental component of stator currents, equation (11) should be satisfied on d_1-axis:

$$I_A\cos(wt) = K_b I_A \cos(wt-\frac{2\pi}{5}) + K_c I_A \cos(wt-2\frac{2\pi}{5}) + K_d I_A \cos(wt-3\frac{2\pi}{5}) + K_e I_A \cos(wt-4\frac{2\pi}{5}) \quad (13)$$

Equation (11) on q_1-axis can be extended as:

$$I_A\sin(wt) = K_b I_A \sin(wt-\frac{2\pi}{5}) + K_c I_A \sin(wt-2\frac{2\pi}{5}) + K_d I_A \sin(wt-3\frac{2\pi}{5}) + K_e I_A \sin(wt-4\frac{2\pi}{5}) \quad (14)$$

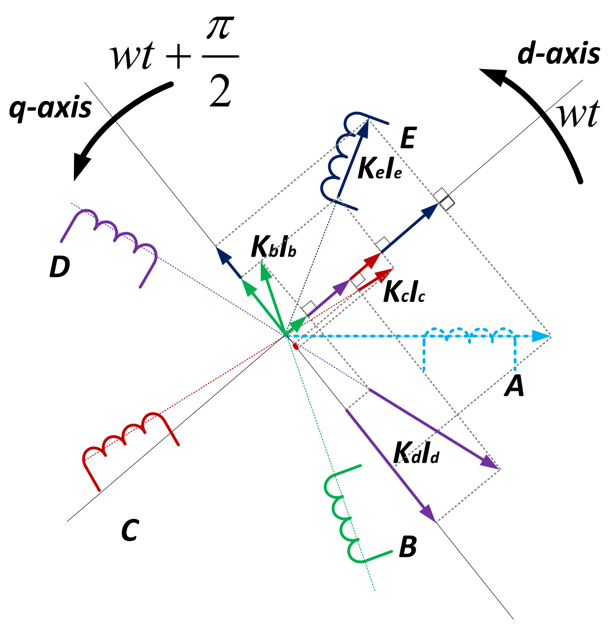


Figure 2. Compensation of phase A magnetic field by additional subphasor currents in the remaining healthy phases

In other words, at each moment, the projection of additional magnetic fields in the remaining healthy phases should compensate the missing effect of phase A current in both d and q-directions.

Having the reference values of d_1 and q_1 currents, and using reverse transformation T, equation (12) can be written as:

$$I_A'^* = 0$$
$$I_B'^* = \left[K_b\cos(wt) + \cos(wt - \frac{2\pi}{5})\right]I_d^* - \left[K_b\sin(wt) + \sin(wt - \frac{2\pi}{5})\right]I_q^*$$
$$I_D'^* = \left[K_d\cos(wt) + \cos(wt - 3\frac{2\pi}{5})\right]I_d^* - \left[K_d\sin(wt) + \sin(wt - 3\frac{2\pi}{5})\right]I_q^*$$
$$I_E'^* = \left[K_e\cos(wt) + \cos(wt - 4\frac{2\pi}{5})\right]I_d^* - \left[K_e\sin(wt) + \sin(wt - 4\frac{2\pi}{5})\right]I_q^* \quad (15)$$

The same routine can be followed in the case of having two faulty phases. This time, additional current terms should be added to three remaining healthy phases to compensate the missing part of stator magnetic field. New reference currents in the case of two adjacent faulty phases can be considered as:

$$I_A'^* = 0$$
$$I_B'^* = 0$$
$$I_C'^* = I_C^* + k_{c1}I_A^* + k_{c2}I_B^*$$
$$I_D'^* = I_D^* + k_{d1}I_A^* + k_{d2}I_B^*$$
$$I_E'^* = I_E^* + k_{e1}I_A^* + k_{e2}I_B^* \quad (16)$$

where K_{c1}, K_{d1} and K_{e1} are defined to compensate the missing magnetic field of phase A, and K_{c2}, K_{d2}, and K_{e2} are defined to compensate the missing effect of phase B. Considering (4) and this compensation on both d_1 and q_1-axis, it can be written:

$$I_A\cos(wt) + I_B\cos(wt - \frac{2\pi}{5}) = (K_{c1}I_A + K_{c2}I_B)\cos(wt - 2\frac{2\pi}{5}) +$$
$$+(K_{d1}I_A + K_{d2}I_B)\cos(wt - 3\frac{2\pi}{5}) + (K_{e1}I_A + K_{e2}I_B)\cos(wt - 4\frac{2\pi}{5}) \quad (17)$$
$$I_A\sin(wt) + I_B\sin(wt - \frac{2\pi}{5}) = (K_{c1}I_A + K_{c2}I_B)\sin(wt - 2\frac{2\pi}{5}) +$$
$$+(K_{d1}I_A + K_{d2}I_B)\sin(wt - 3\frac{2\pi}{5}) + (K_{e1}I_A + K_{e2}I_B)\sin(wt - 4\frac{2\pi}{5}) \quad (18)$$

By knowing the reference current values in d_1-q_1 directions and by using the reverse T transformation, equation (16) can be written as:

$$I_A'^* = 0$$
$$I_B'^* = 0$$
$$I_C'^* = \left[K_{c1}\cos(wt) + K_{c2}\cos(wt - \frac{2\pi}{5}) + \cos(wt - 2\frac{2\pi}{5})\right]I_d^{*\prime} -$$
$$-\left[K_{c1}\sin(wt) + K_{c2}\sin(wt - \frac{2\pi}{5}) + \sin(wt - 2\frac{2\pi}{5})\right]I_q^*$$
$$I_D'^* = \left[K_{d1}\cos(wt) + K_{d2}\cos(wt - \frac{2\pi}{5}) + \cos(wt - 3\frac{2\pi}{5})\right]I_d^* -$$
$$-\left[K_{d1}\sin(wt) + K_{d2}\sin(wt - \frac{2\pi}{5}) + \sin(wt - 2\frac{2\pi}{5})\right]I_q^*$$
$$I_E'^* = \left[K_{e1}\cos(wt) + K_{e2}\cos(wt - \frac{2\pi}{5}) + \cos(wt - 3\frac{2\pi}{5})\right]I_d^* -$$
$$-\left[K_{e1}\sin(wt) + K_{e2}\sin(wt - \frac{2\pi}{5}) + \sin(wt - 2\frac{2\pi}{5})\right]I_q^* \quad (19)$$

On the other hand, in the case of missing two nonadjacent phases, modified stator current phases can be considered as:

$$I_A'^* = 0$$
$$I_B'^* = I_B^* + k_{b1}I_A^* + k_{b2}I_C^*$$
$$I_C'^* = 0$$
$$I_D'^* = I_D^* + k_{d1}I_A^* + k_{d2}I_C^*$$
$$I_E'^* = I_E^* + k_{e1}I_A^* + k_{e2}I_C^* \quad (20)$$

where K_{b1}, K_{c1} and K_{e1} are defined to compensate the missing magnetic field of phase A in the airgap, and K_{b2}, K_{c2} and K_{d2} are considered to do the same act for faulty phase C. Considering T transformation, the following equations should be satisfied to compensate the missing part of magnetic field on both d_1 and q_1-axis:

$$I_A\cos(wt) + I_C\cos(wt - 2\frac{2\pi}{5}) = (K_{b1}I_A + K_{b2}I_C)\cos(wt - \frac{2\pi}{5}) +$$
$$+(K_{d1}I_A + K_{d2}I_C)\cos(wt - 3\frac{2\pi}{5}) + (K_{e1}I_A + K_{e2}I_C)\cos(wt - 4\frac{2\pi}{5}) \quad (21)$$
$$I_A\sin(wt) + I_C\sin(wt - 2\frac{2\pi}{5}) = (K_{b1}I_A + K_{b2}I_C)\sin(wt - \frac{2\pi}{5}) +$$
$$+(K_{d1}I_A + K_{d2}I_C)\sin(wt - 3\frac{2\pi}{5}) + (K_{e1}I_A + K_{e2}I_C)\sin(wt - 4\frac{2\pi}{5}) \quad (22)$$

and new reference values of each phase can be written as:

$$I_A'^* = 0$$
$$I_B'^* = \left[K_{b1}\cos(wt) + K_{b2}\cos(wt - 2\frac{2\pi}{5}) + \cos(wt - \frac{2\pi}{5})\right]I_d^{*\prime} -$$
$$-\left[K_{b1}\sin(wt) + K_{b2}\sin(wt - 2\frac{2\pi}{5}) + \sin(wt - \frac{2\pi}{5})\right]I_q^*$$
$$I_C'^* = 0$$
$$I_D'^* = \left[K_{d1}\cos(wt) + K_{d2}\cos(wt - 2\frac{2\pi}{5}) + \cos(wt - 3\frac{2\pi}{5})\right]I_d^* -$$
$$-\left[K_{d1}\sin(wt) + K_{d2}\sin(wt - 2\frac{2\pi}{5}) + \sin(wt - 3\frac{2\pi}{5})\right]I_q^*$$
$$I_E'^* = \left[K_{e1}\cos(wt) + K_{e2}\cos(wt - 2\frac{2\pi}{5}) + \cos(wt - 4\frac{2\pi}{5})\right]I_d^* -$$
$$-\left[K_{e1}\sin(wt) + K_{e2}\sin(wt - 2\frac{2\pi}{5}) + \sin(wt - 4\frac{2\pi}{5})\right]I_q^* \quad (23)$$

In the next step K constants should be optimized to maximize the output power, i.e, to maximize the average value of electrical torque, and at the same time, to limit the stator copper loss to its nominal value.

This optimization is completed offline by considering all possible combinations of K constants and computing machine´s output power and stator copper loss in each case. For-loops are used in the executed code to consider all possible combinations of K constants. In addition, by using (12), (16) and (20) stator reference currents are calculated for each condition. Figure 3 and Table II contain the optimized current phasors under different faulty conditions and while having access to stator winding neutral point.

Reference values of Tables I and Table II are calculated to maximize the average of generated electrical torque, and at the same time, to keep the stator copper loss under its nominal value. Stator copper loss can be calculated as:

$$P_{loss} = r_sI_A^2 + r_sI_B^2 + r_sI_C^2 + r_sI_D^2 + r_sI_E^2 \quad (24)$$

In (24) r_s is the stator winding resistance, and I is the effective value of stator phase currents.

Using these reference values and assuming that $r_s = 0.1\,\Omega$, pu values of output power and generated copper loss are shown in Fig. 4.

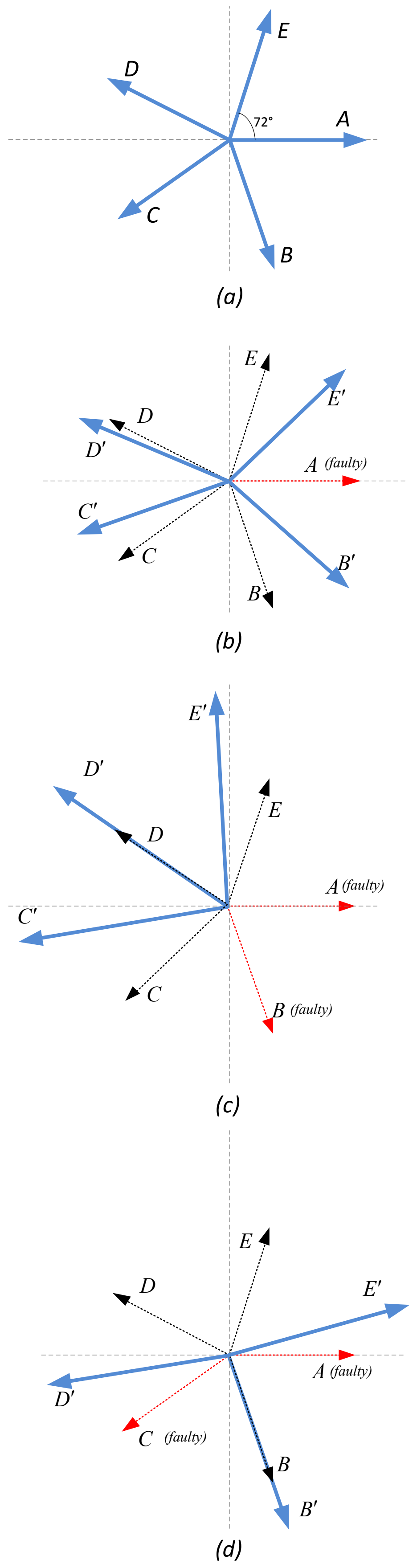


Figure 3. Appropriate current references while having access to neutral point, (a) healthy mode operation, (b) one faulty phase, (c) two adjacent faulty phases, (d) two nonadjacent faulty phases

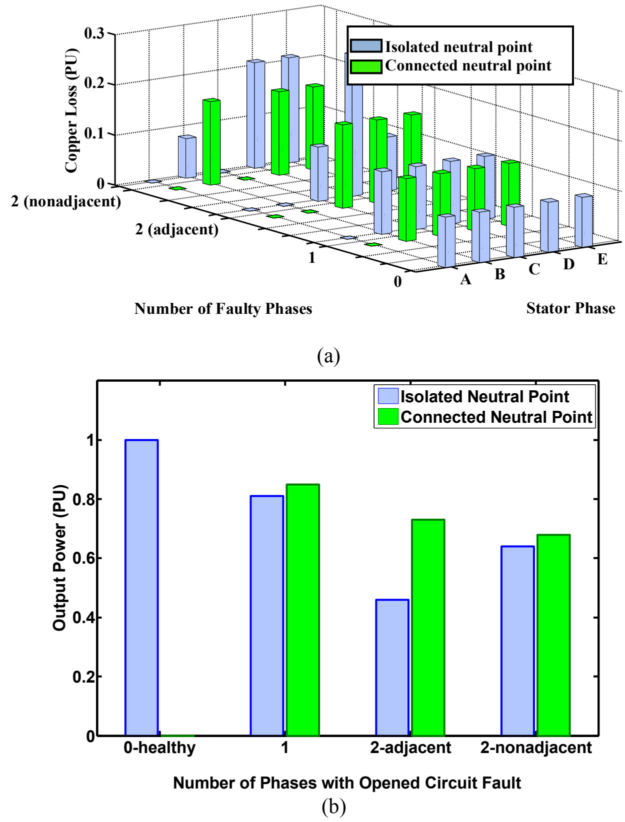


Figure 4. (a) pu values of stator copper loss (b) pu values of generated output power

As it can be seen, having control on neutral point current, stator current amplitudes are moderated and maximum value of generated copper loss is reduced in phase windings. This reduction itself means less thermal stress along the stator core. In addition, as it is possible to independently choose the electrical phase of stator current references, generated output power of the machine is increased which results in higher efficiency. This power improvement is 5% in the case of having one faulty phase, 72% while having two adjacent faulty phases, and 7% in the case of two nonadjacent faulty phases.

TABLE II. OPTIMIZED CURRENT PHASORS WHILE HAVING CONTROL ON NEUTRAL CURRENT

Number of Missing Phases		Current Amplitudes (PU)				
		A	B	C	D	E
0 (Healthy)	Amplitude	1	1	1	1	1
	Angle	0	-72°	-144°	144°	72°
1	Amplitude	0	1.12	1.12	1.12	1.12
	angle	-	-45.6°	-154°	154°	45.6°
2 (Adjacent)	Amplitude	0	0	1.29	1.29	1.29
	angle	-	-	-168°	144°	96°
2 (Nonadjacent)	Amplitude	0	1.29	0	1.29	1.29
	angle	-	-72°	-	-168°	24°

Winding losses are summarized in Fig. 4 for each condition.

IV. EXPERIMENTAL EVALUATION

To evaluate the theoretical developments, experimental tests are conducted on a commercial type of five-phase BLDC machine. Figure 5 presents the general configuration of our test bench.

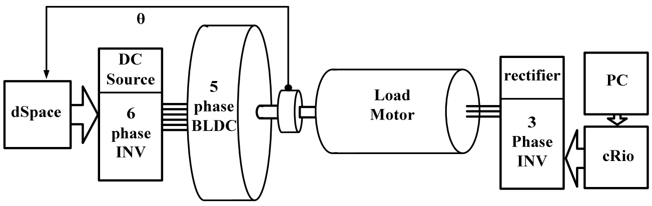


Figure 5. General test bench configuration

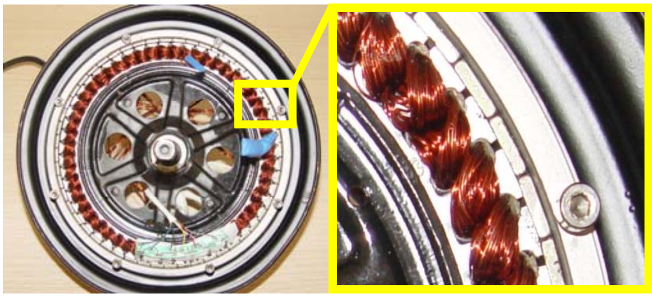


Figure 6. Five-phase BLDC machine configuration

TABLE III: MEASURED PARAMETERS OF FIVE-PHASE BLDC MACHINE

Parameter		value
Number of Pole Pairs		26
Stator Resistance		0.1 Ω
Stator Inductance	Laa	1500 *uH*
	Lab	35 *uH*
	Lac	42*uH*
Nominal Torque		32 *Nm*
Nominal Current Frequency		43.3 Hz
Permanent Magnet Flux		0.0178 *Wb*

Figure 6 shows the internal structure of five-phase BLDC machine. The stator incorporates a double-layer fractional-slot winding accompanied by an outer-rotor which allows us to directly mount the machine inside the wind turbine structure in wind power plants. Due to its high number of pole pairs, the magnets are simply installed on rotor surface. This structure reduces the production costs of PM generator. Machine´s parameters are summarized in Table III.

Machine phase terminals and its neutral point are fed by a six-phase inverter with a 48 volt dc-bus and 5 kHz of switching frequency. Controlling algorithm is realized by DS1005 dSpace board. Figure 7 illustrates the general block diagram of current control. Current reference values are compared with their real values, and the resultant errors are used in controllers to compute reference values of V_{d1}^*, V_{q1}^*, V_{d3}^*, V_{q3}^*, V_o^*. Using T transformation of (4), the reference values of phase voltages are computed and passed to space vector modulation (SVM) block.

To realize the modulation concept, it is possible to use Space vectors in two rotating planes. Voltage vectors in these two planes can be divided to three categories: 1) large vectors labeled by L, 2) medium vectors labeled by M, and small vectors labeled by S.

Two large vectors and two medium vectors (known as 2L+2M method), or four large vectors (known as 4L method) can be used to generate the required reference voltages by the inverter to control the electrical machine. Comparison of these two methods is beyond the scope of this paper, however 2L+2M method generates lower THD at higher modulation indexes and is applied in this study [21] [22].

An incremental encoder and 5 current clamps are used to close position and current loops. The speed is fixed by a commercial three-phase PMSM which is driven independently by a three-phase AC drive (famous as SINAMICS S120). A real-time controller (known as cRio) is used as an interference between host computer and three-phase inverter. Constructed six-phase inverter and the mechanical link between load and five-phase BLDC machine are shown in Fig. 8. Stator currents under healthy and each faulty condition are summarized in Fig. 9.

Equation (24) is used to calculate stator copper loss during one period. Measured values of stator currents are used for this calculation.

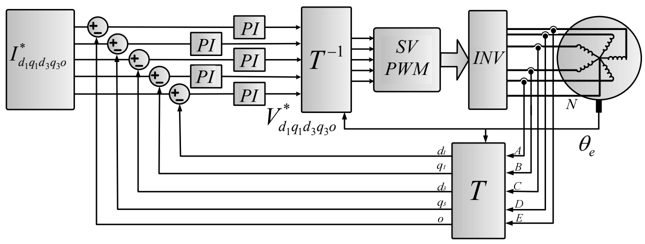
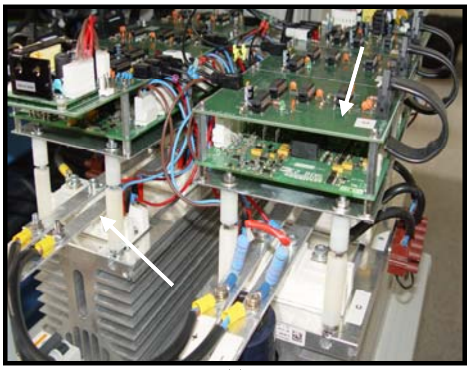


Figure 7. General block diagram of current control in two rotating reference frames

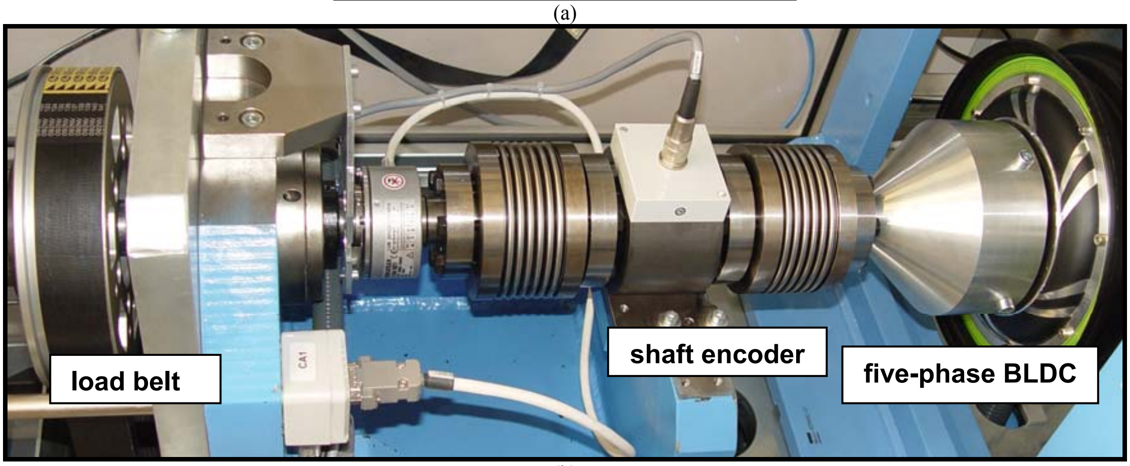
TABLE IV. REAL VALUES OF STATOR COPPER LOSS UNDER HEALTHY AND DIFFERENT FAULTY CONDITIONS

Missing Phases	Neutral Point	Copper Loss in one electrical cycle (Joule)				
		A	B	C	D	E
0 (Healthy)	Isolated	4.05	3.96	4.08	4.12	4.11
1	Connected	0	4.92	4.59	5.41	5.35
	Isolated	0	4.69	4.93	4.53	5.27
2-Adjacent	Connected	0	0	6.21	6.82	6.38
	Isolated	0	0	5.32	9.22	5.40
2-nonadjacent	Connected	0	6.55	0	6.50	6.48
	Isolated	0	4.55	0	7.74	7.63

Although the total amount of copper loss in the machine is limited to its nominal value, but as calculated previously, having control on neutral point current, can help to generate more power and less copper losses in the stator windings. In addition, as it can be seen from Table IV and Fig. 4-(a), having access to neutral point results in more uniform copper loss in the remaining healthy phases. This modification of copper loss distribution results in less thermal stress (hot spots) along the stator core and reduces the probability of iron saturation along the stator core.

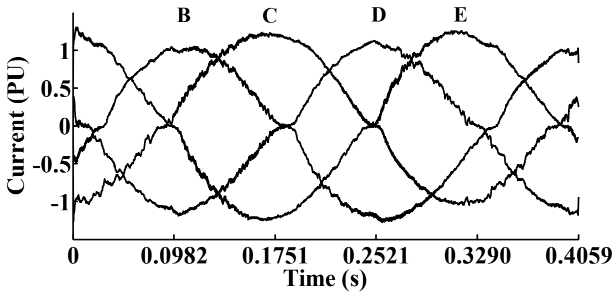


(a)

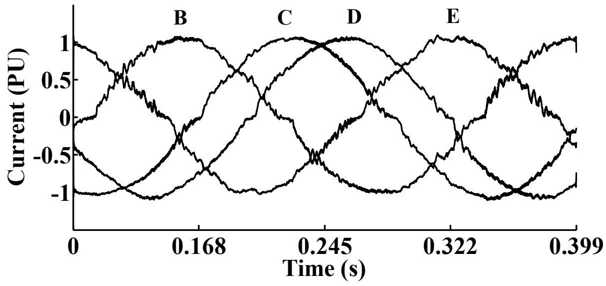


(b)

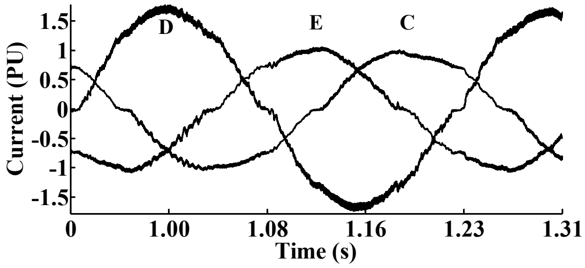
Figure 8. (a) Six-phase inverter, (b) Mechanical link between load belt and five-phase BLDC machine



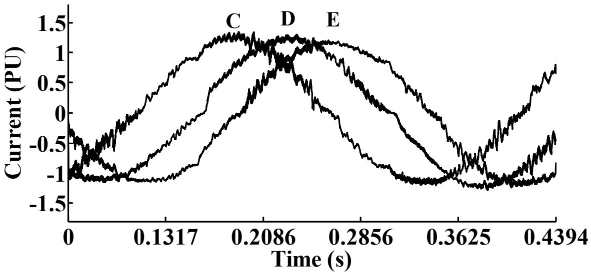
(a)



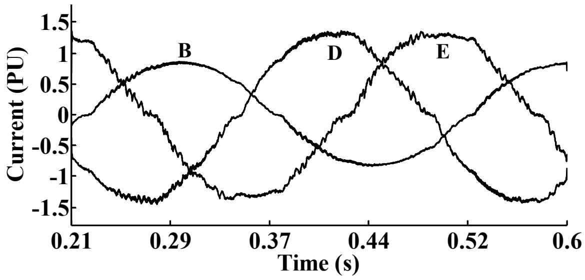
(b)



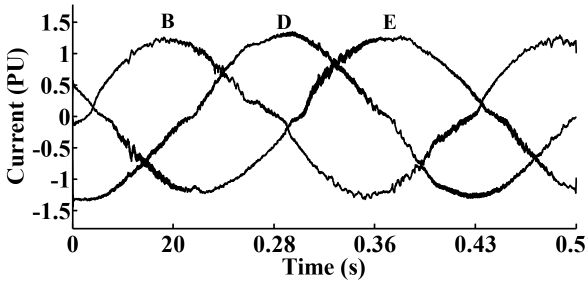
(c)



(d)



(e)



(f)

Figure 9. Stator currents under different conditions, (a) one faulty phase and isolated neutral, (b) one faulty phase and connected neutral, (c) two adjacent faulty phases and isolated neutral, (d) two adjacent faulty phases and connected neutral, (e) two nonadjacent faulty phases and isolated natural, (f) two nonadjacent faulty phase and connected natural.

V. CONCLUSION

In this paper, the impact of neutral point current control is studied on the efficiency of five-phase PM generators of wind power plants under healthy and faulty conditions. Continuous operation of PM machine is considered in the case of missing one, two adjacent, and two nonadjacent phases. Stator copper loss is limited to its nominal value, and optimized current references are calculated to increase the average value of output power and thus machine efficiency.

Having control on neutral point current provides more freedom in reference calculation of stator currents. This additional freedom can help us to improve the average value of generated output power for the same amount of stator copper loss. This improvement is noticeable (72%) in the case of having two adjacent faulty phases. In addition, it is shown that only by having access to machine neutral point, it will be possible to moderate the maximum amplitude of stator currents in the remaining healthy phases. More uniform current amplitudes result in less thermal stress (hotspots) along the stator core and reduces the probability of iron saturation along the stator iron core.

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