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Abstract This paper proposes a decentralized control strategy for multiphase open-winding permanent magnet synchronous motors (OW-PMSMs). The main goal is to achieve high levels of fault tolerance on the control part. Indeed, multiphase motors are well known for their fault tolerance and reliability, but a centralized control loses this advantage in case of control system fault. This work tries to reduce dependencies between each winding of an OW-PMSM by proposing a decentralized control strategy where each motor winding has its own control system. To obtain desired torque, each winding current must track a sinusoidal current reference. A flatness-based control is used to improve the tracking dynamics. Simulations on a three-phase OW-PMSM are performed in health and fault conditions. Results validate the proposed decentralized control strategy and show a high availability of the controlled OW-PMSM drive.

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1. Introduction

Historically, the world of electric motors is developed around three-phase motors, especially those wired in star. Their ease of manufacture and control make them very popular in the industry.

In the field of electric mobility, efficiency, mass and reliability become critical criteria for motor choice. For example, in electric aviation field, system reliability and fault tolerance are very critical. The low redundancy of three-phase motors leads to exploring other solutions and mainly multiphase motors. In the literature, many works analyze the reliability of these motors [1, 2]. In [3], the availability of a motor defined as the electrical/mechanical energy conversion capability is introduced. The availability for multiphase permanent magnet synchronous motors (PMSMs) is analyzed in [3] for stator winding and open-circuit faults which represent a large part of faults in electrical machines [4].

To improve the availability of multiphase PMSMs, the best way is to separate electrically each winding. This motor type is called an open-winding permanent magnet synchronous motor (OW-PMSM). Multiphase OW-PMSMs have thus high availability and have also more degrees of freedom in wiring connection and control [2]. Those additional degrees of freedom allow to increase motor performances and fault tolerance capability [5, 6, 7]. However, OW-PMSM availability may be dropped if a centralized control is down. Indeed, a fault on the control part will make the whole system faulty. To preserve OW-PMSM availability even in the event of control part fault, a decentralized control [8] can be used where each winding has its own independent control system.

Currently proposed control strategies for multiphase OW-PMSMs are based on an integrated modular motor driver (IMMD) but with centralized [9] or partially decentralized control [10]. Decentralized control is mainly proposed for N-three-phase machines with N-three-phase modules [11]. Each module is controlled independently. A fault on one control part makes the corresponding three-phase module out of operation. This induces the fault of three phases together in the motor.

To our knowledge, there is no fully decentralized control strategy, i.e. one independent control by winding for OW-PMSMs. In this paper, we propose to control each winding with an independent control part. In this case, a winding fault induces only the loss of the faulty winding, contrary to IMMD where a complete winding group is lost. The decentralized control strategy implies two main issues. The first one is the control synchronization. This issue can be solved by sharing the rotor position sensor information for each control part. The second issue is that the current reference for each winding is a sine wave. This requires a high tracking dynamic for the current control. Our approach is to use a flatness-based control [12] that has been used usefully for power systems to obtain high performance [13].

The paper is organized as follows: Section 2 describes a general OW-PMSM and its modelling. Then, Section 3 exposes the decentralized control strategy. In Section 4, the proposed control strategy validation is carried out by simulation in health and fault conditions on a three-phase OW-PMSM.

2. Open-winding PMSM and its model

The first part of this section describes an open-winding motor. The second part is focused on the modelling of a single winding. The third one details the overall motor model, integrating all independent windings.

a. *Open-winding motor*

A non-salient N-open-winding PMSM is considered with P pole pairs. N windings are regularly distributed around the rotor at mechanical angles α_n such as $\alpha_n = (n-1)\frac{2\pi}{N}$ $\forall n \in [1;N]$. A current I_n is passing through each winding n (Fig. 1).

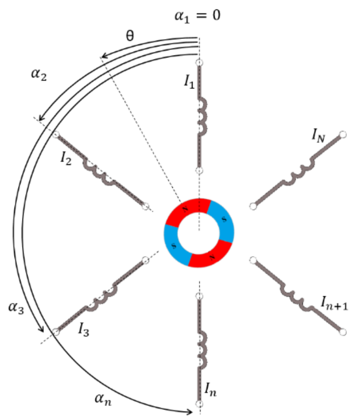

FIG. 1: SCHEMATIC REPRESENTATION OF A SIX-WINDING OPEN-WINDING PMSM

In the electric reference, two directions are defined: direct direction (d) in front of a rotor pole and quadrature direction (q) between two rotor poles. Stator flux generated between two rotor poles (quadrature direction) generates torque. Stator flux generated in front of rotor pole (direct direction) impacts on machine saturation level and allows to increase rotation speed using flux weakening strategy. Fig. 2 illustrates these directions in the physical mechanical reference for a four-pole rotor (P=2).

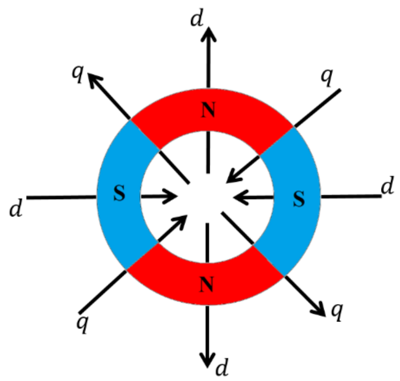

FIG. 2: DIRECT AND QUADRATURE DIRECTIONS FOR A FOUR-POLE ROTOR

When a stator winding is in the direct direction, its impact is only on motor magnetization. When the same winding is in the quadrature direction, its impact is on motor torque. Between both directions, both impacts are combined.

b. *Winding model*

The motor is assumed to work in a non-saturated condition. Moreover, all inductances and mutual inductances are considered as constant values due to non-salient rotor. Under these assumptions, each winding n is then modeled by a constant inductance L_n in series with a constant resistance R_n, a back-EMF and mutual inductances. The back-EMF coming from rotor flux variation is considered as a sinusoidal waveform, defined as (1).

$$EMF_n = K_{e_n}\Omega\, sin(P(\theta + \alpha_n)) \qquad (1)$$

Where $K_{e_n}$is the back-EMF constant, Ω is the rotor speed and θ the rotor angular position.

The others $(N-1)$ windings m induce electromotive forces V_{M_n} in the winding n by their mutual inductances $M_{n/m}$ (mutual inductance between the winding n and m with $m \in [1;N]\backslash n$). It is given by (2).

$$V_{M_n} = \sum_{\forall m \in [1;N]\backslash n} M_{n/m}\frac{dI_m}{dt} \qquad (2)$$

The resulting voltage on winding terminals n is named V_n:

$$V_n = R_n I_n + L_n \frac{dI_n}{dt} + K_{e_n} \Omega \, sin\big(P(\theta + \alpha_n)\big) + \sum_{\forall m \in [1;N] \backslash n} M_{n/m} \frac{dI_m}{dt} \quad (3)$$

I_n winding current projected on both d and q directions defines two components: I_{d_n} and I_{q_n}.

$$I_{d_n} = I_n \cos(P(\theta + \alpha_n)) \quad (4)$$

$$I_{q_n} = I_n \sin(P(\theta + \alpha_n)) \quad (5)$$

That allows to define the instantaneous electromagnetic torque T_n generated by winding n expressed by (6).

$$T_n = K_{e_n} I_n \sin(P(\theta + \alpha_n)) \quad (6)$$

c. Whole motor model

An N-open-winding motor is composed of N electrically independent (i.e. insulated) windings. The electrical state equation of the overall motor is given as follow:

$$\frac{d}{dt}[I] = [L]^{-1}([V] - [R][I] - \Omega[K_e][\gamma]) \quad (7)$$

With the inductance matrix $[L]$, the resistance matrix $[R]$, the current vector $[I]$, the winding voltage vector $[V]$, the back-EMF constant vector $[K_e]$ and $[\gamma]$ defined as follows:

$$[L] = \begin{bmatrix} L_1 & M_{1/2} & \cdots & M_{1/N-1} & M_{1/N} \\ M_{2/1} & L_2 & & M_{2/N-1} & M_{2/N} \\ \vdots & & \ddots & \vdots & \\ M_{N-1/1} & M_{N-1/2} & \cdots & L_{N-1} & M_{N-1/N} \\ M_{N/1} & M_{N/2} & & M_{N/N-1} & L_N \end{bmatrix} \quad (8)$$

$$[R] = diag[R_1 \quad R_2 \quad \cdots \quad R_{N-1} \quad R_N] \quad (9)$$

$$[I] = [I_1 \quad I_2 \quad \cdots \quad I_{N-1} \quad I_N]^T \quad (10)$$

$$[V] = [V_1 \quad V_2 \quad \cdots \quad V_{N-1} \quad V_N]^T \quad (11)$$

$$[K_e] = diag\big[K_{e_1} \quad K_{e_2} \quad \cdots \quad K_{e_{N-1}} \quad K_{e_N}\big] \quad (12)$$

$$[\gamma] = \begin{bmatrix} \sin(P(\theta + \alpha_1)) \\ \sin(P(\theta + \alpha_2)) \\ \vdots \\ \sin(P(\theta + \alpha_{N-1})) \\ \sin(P(\theta + \alpha_N)) \end{bmatrix} \quad (13)$$

Moreover, the resulting total electromagnetic torque is the sum of all torque generated by each winding:

$$T_{em} = \sum_{\forall n \in [1;N]} T_n = [I]^T [K_e][\gamma] \quad (14)$$

At last, the mechanical part of the motor and associated load is simply described in this paper by:

$$\frac{d\Omega}{dt} = \frac{1}{J}(T_{em} - T_u) \quad (15)$$

$$\frac{d\theta}{dt} = \Omega \quad (16)$$

with J the mechanical inertia and T_u the load torque.

3. Proposed current control strategy

This part presents the proposed control strategy to track the current references. Generally, the mechanical dynamic is very slow regarding the current dynamics. So, it can be neglected for the current control loop design.

a. Current references

To control the motor torque, current references $I_n{}^*$ are needed for each winding n. The sinusoidal expression can be expressed as:

$$I_n{}^* = I_{d_n}{}^* \cos(P(\theta + \alpha_n)) + I_{q_n}{}^* \sin(P(\theta + \alpha_n)) \quad (17)$$

$I_{d_n}{}^*$ and $I_{q_n}{}^*$ are the direct and quadrature current reference amplitude. The stator flux created by $I_{d_n}{}^*$ and $I_{q_n}{}^*$ corresponds to the direct and quadratic directions respectively presented in Fig. 2.
Without flux weakening and because of non-salient rotor, the direct current amplitude $I_{d_n}{}^*$ can be chosen as zero. And, when the back-EMF parameters K_{e_n} and the quadrature current amplitudes $I_{q_n}{}^*$ are the same on each winding, $I_{q_n}{}^*$ is linked with the electromagnetic torque:

$$T_{em}{}^* = \frac{N K_{e_n}}{2} I_{q_n}{}^* \quad (18)$$

$I_{q_n}{}^*$ can be generated by speed control loop or fixed by user to obtain the desired torque $T_{em}{}^*$.
The control goal is to track the reference (17) for every winding n.

b. Flatness-based control

Fitting a sinusoidal reference requires a high dynamics and especially when frequency, i.e. rotor speed, rises. If a classic proportional-integral (PI) controller is used to fit this reference with high dynamics, its overall robustness decreases. We propose to use a flatness-based control.
The concept of flat systems was introduced by Fliess and al. using the formalism of differential algebra [12].
A system is considered flat if there exists a flat output y that all state variables and control variables can be expressed as

a function of the flat output and its successive derivatives. In a flat system, by knowing the system's behavior, the desired trajectory for the flat output can be used to generate control of the system [12].
For each winding n, the chosen flat output is $y = I_n$, the control variable is $u = V_n$ and the state variable is $x = I_n$. Obviously, $x = y$ and according to (3), u can be expressed as a function of y and $\frac{dy}{dt}$, so each winding can be considered as a flat system and the control can be written as:

$$u_n = yR_n + \frac{dy}{dt}L_n + K_{e_n}\Omega\sin\big(P(\theta+\alpha_n)\big) + \sum_{\forall m\in[1;N]\backslash n} M_{n/m}\frac{dI_m}{dt} \tag{19}$$

Where, Ω and I_m are considered as known variables.
Then, to track the current reference $y^* = I_n{}^*$ and to ensure that the tracking errors

$$e = y - y^* = I_n - I_n{}^* \tag{20}$$

asymptotically vanish, a feedback control law is proposed:

$$\left(\frac{dI_n}{dt} - \frac{dI_n{}^*}{dt}\right) + G_1(I_n - I_n{}^*) + G_2\int(I_n - I_n{}^*)dt = 0 \tag{21}$$

Or

$$\frac{dI_n}{dt} = \frac{dI_n{}^*}{dt} - G_1(I_n - I_n{}^*) - G_2\int(I_n - I_n{}^*)dt \tag{22}$$

Where integral action is added to eliminate disturbances and to compensate the model errors. The control parameters are chosen as $G_1 = K\omega$ and $G_2 = \omega^2$, with K and ω the desired damping ratio and natural frequency respectively of the current tracking error dynamics.

c. Control schematic

To compute the control voltage of (19), it is necessary to know currents in other windings (I_m $\forall m \in [1;N]\backslash n$) and rotor position θ and speed Ω. The currents can be estimated using the motor model. θ is measured at each sampling time. Ω is calculated from θ. θ and Ω are considered constant during the sampling period since the mechanical dynamics is neglected. Fig. 3 represents the proposed control strategy for one winding.

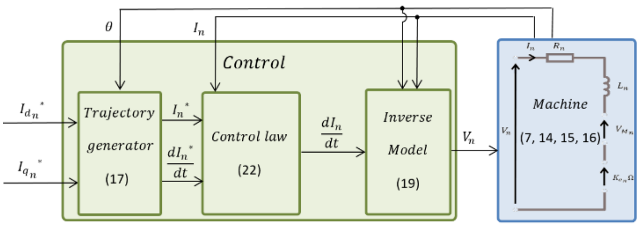

FIG. 3: ONE WINDING CONTROL SCHEMATIC

For each winding, the control law is the same using the corresponding parameters and sharing the same θ. Following figure is a schematic of the control for a 6-winding motor.

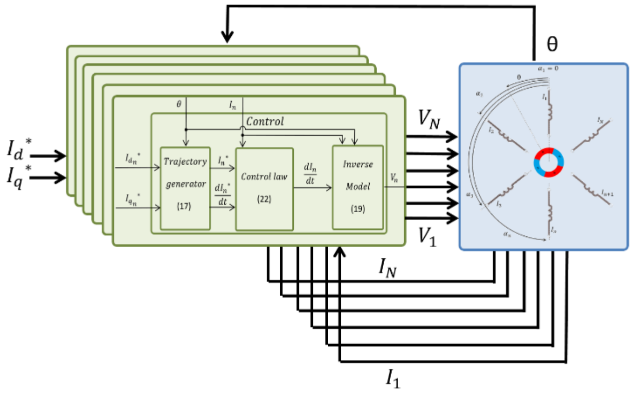

FIG. 4: 6-WINDING OPEN-WINDING MOTOR CONTROL SCHEMATIC

4. Results

The main goal of this part is to validate the proposed control strategy using simulation. The presented method is applied to a three-phase OW-PMSM with three independent windings.
The simulated motor has the following parameters for $n \in [1;3], m \in [1;3]\backslash n$.

L_n	R_n	$M_{n/m}$	K_{e_n}	Ω_{nom}	P_{nom}
0.11 mH	0.22 Ω	0.03 mH	0.012 V/RPM	4000 RPM	6 kW

TAB. 1: MOTOR PARAMETERS

Simulations are made using Matlab/Simulink. Power electronic pulses are not taken into account. The overall inertia is $J = 0.0015$ kg.m² and a friction torque $T_f = 0.0037$ Nm/rad/s, i.e.: $T_u = T_f\,\Omega$. G_1 and G_2 are computed with $K = 100$ and $\omega = 1000$. Simulation time is $10^{-7}s$ and control time is $10^{-4}s$. Those values are used for all simulations. Firstly, a simulation is made in healthy mode. Then an open-circuit fault is applied to the phase one.

a. Healthy mode

In a steady state simulation condition, $I_{q_n}{}^*$ references are set at 1A. The motor speed reaches 1250 round per minute (RPM) in steady-state.

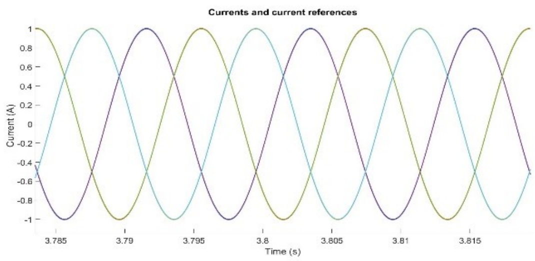

FIG. 5: WINDING CURRENTS AND THEIR REFERENCES USING PROPOSED CONTROL

For steady-state conditions, Fig. 5 shows the winding currents (yellow, blue and red curves) and their reference (blue, purple and green curves) when the proposed flatness-based control is applied. It can be seen that the output currents are very close to their reference. It confirms that the currents are well tracking without phase delay even at high speed. With a standard PI controller where the control parameters are settled to have a trade-off between tracking dynamics and control robustness, a phase delay between each reference and its output current can be observed as shown in Fig. 6. For the same current references $I_{q_n}{}^*$, motor speed reaches only 955 RPM in steady-state.

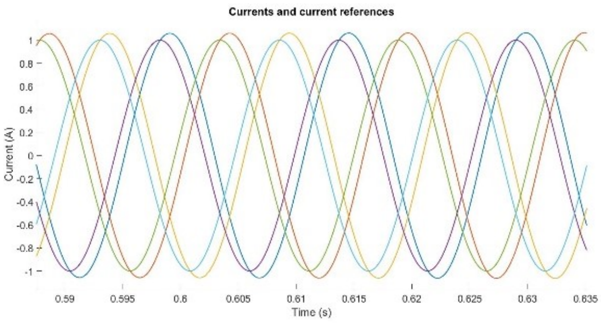

FIG. 6: WINDING CURRENTS AND THEIR REFERENCES WITH A STANDARD PI- CONTROL

The phase delay decreases system efficiency and induces control instability. Therefore, a PI-based control is not suitable for this kind of control.

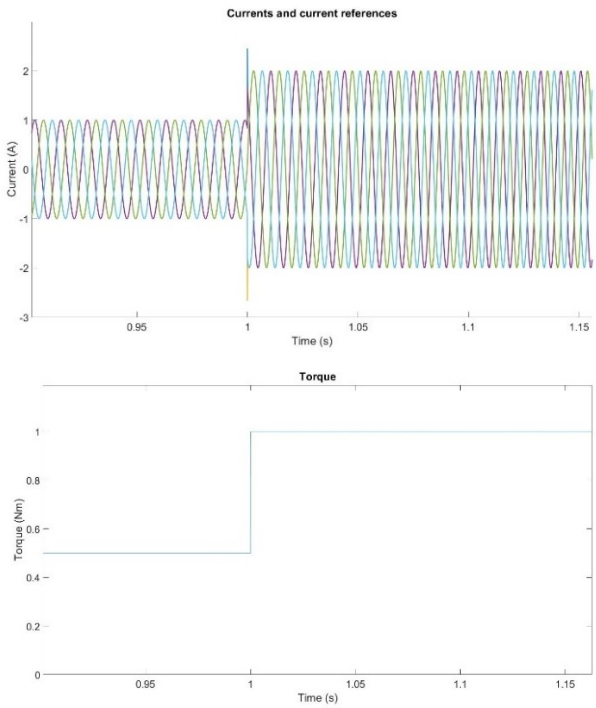

FIG. 7: WINDING CURRENTS AND TORQUE DURING $I_{q_n}{}^*$ REFERENCE STEP

For transient simulation condition, after a reference change of $I_{q_n}{}^*$, for example from 1A to 2A at t=1s, the proposed flatness-based control strategy allows winding currents to rapidly track their new reference (Fig. 7). The quick dynamics of the torque change can be also appreciated.

b. Fault case

The main goal of the decentralized control strategy is to provide a high redundancy level. It is possible to know what happen in fault case using simulation.
The motor has only three open windings. If one of them is faulty, there are two left which can continue to generate a rotating field [3].

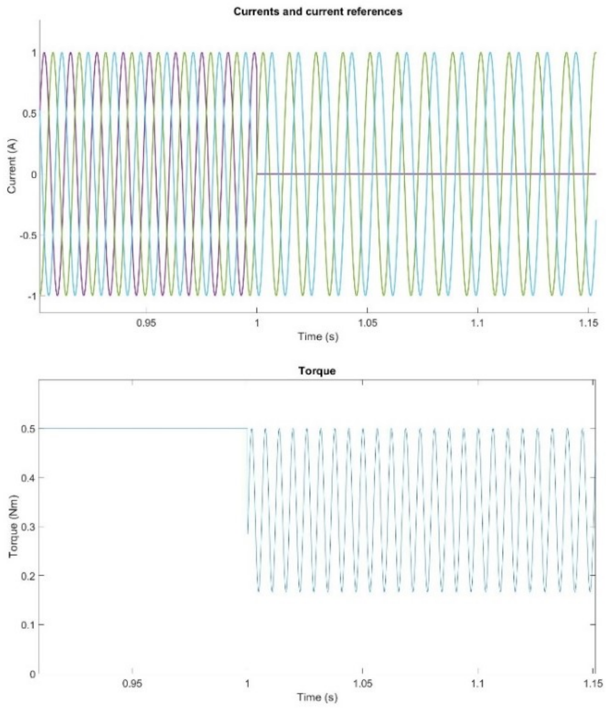

FIG. 8: WINDING CURRENTS AND THEIR REFERENCES AFTER ONE OPEN-WINDING FAULT

The motor is running at 1250 RPM. At t=1s, an open-circuit on winding 1 is simulated for the motor by forcing the current of the winding 1 to zero while the three current references continue to be applied (Fig. 8). It can be seen that from this moment, both remaining currents continue to run machine, but the mean torque decreases and a torque oscillation appears. This is due to the control strategy which doesn't take into account the fault of the machine. Further works will be focus on the current reference generation to improve the control performance for fault mode operation conditions.

5. Discussion

To improve reliability of the proposed decentralized control strategy, it can be completed by adding a rotor angular position observer by using current sensor. Indeed, the fact that there is only one rotor angle sensor implies that if it is faulty, the rotor angle value is lost. A rotor angular position observer can be used as sensor backup for each winding. That allows each winding control part to be work independently regarding the physical sensor and continue to run even if the position sensor is faulty.
Using current analysis, it would be possible to know if others independent control parts are faulty. Future works will try to detect this kind of fault and estimate motor parameter variations. A good fault detection and parameter variation estimation will improve current control performances and motor reliability.

6. Conclusion

A decentralized control strategy has been proposed. The main utility of this strategy is to fully use the availability of OW-PMSMs. It makes electrically independent the control of each motor winding. The high dynamic winding current tracking is performed by the flatness-based control. It offers better control performances compared to a classical PI controller and thus improves the motor efficiency. Simulation validations have been carried out and validate the concept for health and fault conditions. The results show that a three-phase OW-PMSM can continue to work even if one open-circuit fault is happened contrary to a classical three-phase PMSM. Future works will experiment this control strategy on a multiphases OW-PMSM.

References

1. W. Dai, J. Sun, Y. Chi, Z. Lu, D. Xu, N. Jiang, "Review of Machining Equipment Reliability Analysis Methods based on Condition Monitoring Technology", Applied Sciences, 9(14):2786 07-2019.
2. N. Ky Nguyen, D. Flieller, X. Kestelyn, T. Josè dos Santos Moraes, E. Semail. "Analytical Optimal Currents for Multiphase PMSMs Under Fault Conditions and Saturation", IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, pp. 3197-3203.
3. L. Dassonville, J.Y. Gauthier, X. Lin-Shi, A. Makki, A. Siccardi, "Availability analysis and quantification of electrical multiphase motors, " IEEE IECON, 2021, pp. 1-6.
4. Chahmi, M. Bendjebbar, B. Raison. "Fault detection in electrical drives -approach signal". 2014 International Conference on Electrical Sciences and Technologies in Maghreb(CISTEM 2014) , Nov 2014, tunis, Tunisia. Electrical Sciences and Technologies in Maghreb (CIS-TEM), 2014 International Conference on, pp.1 - 6, 2014
5. N. Ky Nguyen, F. Meinguet, E. Semail, X. Kestelyn, "Fault-Tolerent Operation of an Open-End Winding Five-Phase PMSM Drive with Short-Circuit Inverter Fault", 2013, DOI 10.1109-TIE.2014.2386299, IEEE Transactions on Industrial Electronics, pp. 1-11.
6. X. Kestelyn and E. Semail, "A vectorial approach for generation of optimal current references for multiphase permanent-magnet synchronous motors in real time", 2011, IEEE Trans. Ind. Electron., vol. 58, no. 11, pp. 5057–5065.
7. S. Dwari and L. Parsa, "Fault-tolerant control of five-phase permanent magnet motors with trapezoidal back emf", 2011, IEEE Trans. Ind. Electron., vol. 58, no. 2, pp. 476–485.
8. "Difference Between Centralized vs Decentralized vs Distributed network," Crypto Post Gazette, Feb. 02, 2020. https://berty.tech/blog/decentralized-distributed-centralized
9. C. Lin et Y. Tzou, "An Innovative Multiphase WM Control Strategy for a PMSM with Segmented Stator Windings, " 978-1-4799-6735-3/15/$31.00 ©2015 IEEE, 2015, pp. 270-275.
10. Z. Gao, D. Jiang, W. Kong, C. Chen, H. Fang, C. Wang, D. Li, Y. Zhang and R. Qu, "A GaN-Based Integrated Modular Motor Drive for Open-Winding Permanent Magnet Synchronous Motor Application, " IEEE, Transactions on Industry Applications, 2018, pp. 73-79.
11. Galassini, A. Costabeber, C. Gerada et A. Tessarolo, " Distributed Speed Control for Multi-Three Phase Electrical Motors with Improved Power Sharing Capability, " 978-1-5090-2998-3/17/$31.00 IEEE, 2017, pp. 2492-2497.
12. M. Fliess, J. Levine, P. Martin, and P. Rouchon, "Flatness and defect of nonlinear systems: Introductory theory and examples," International Journal of Control, vol. 61, pp. 13–27, 06 1995
13. M. Soheil-Hamedani, M. Zandi, R. Gavagsaz-Ghoachani, B. Nahid-Mobarakeh, and S. Pierfederici, "Flatness-Based Control Method: A Review of its applications to Power Systems," in Electronics, Drive Systems & Technologies Conference (PEDSTC 2016), 16-18 Feb. 2016.