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Full Length Article

Analysis and implementation of power management and control strategy for six-phase multilevel ac drive system in fault condition

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ABSTRACT

This research article exploits the power management algorithm in post-fault conditions for a six-phase (quad) multilevel inverter. The drive circuit consists of four 2-level, three-phase voltage source inverter (VSI) supplying a six-phase open-end windings motor or/impedance load, with circumstantial failure of one VSI investigated. A simplified level-shifted pulse-width modulation (PWM) algorithm is developed to modulate each couple of three-phase VSI as 3-level output voltage generators in normal operation. The total power of the whole ac drive is shared equally among the four isolated DC sources. The developed post-fault algorithm is applied when there is a fault by one VSI and the load is fed from the remaining three healthy VSIs. In faulty conditions the multilevel outputs are reduced from 3-level to 2-level, but still the system propagates with degraded power. Numerical simulation modelling and experimental tests have been carried out with proposed post-fault control algorithm with three-phase open-end (asymmetrical induction motor/R-L impedance) load. A complete set of simulation and experimental results provided in this paper shows close agreement with the developed theoretical background.

1. Introduction

AC power converters are affected by mechanical, thermal, and electrical stresses. These stresses lead to component and system failures [1,2]. Failures include DC-link capacitors, voltage sensors, semiconductor switches and control/gate driver circuits [3–6]. Hence, fault tolerance is mandatory in ac drives power conversion, which ensures fault detection, localization and isolation, allowing continuous propagation [7–10]. Recently, the multi-phase ac machines proved their arrival by the redundancy in configuration, system reliability, and fault tolerance [11–15]. Further, for multiphase ac motor, a minimum of two phases are sufficient to create a rotating field under circumstances when all other phases have failed [11,13].

Multilevel inverters are the prominent alternatives for classical three-phase VSI [16,17], but still the reliability remains lower which is the major drawback [18,19]. Still, the classical three-phase VSI remains the most reliable choice, hence by properly arranging the multiple VSIs, both multi-phase [20,21] and multilevel configuration can be easily constructed [15,22–24].

A novel ac drive structure for six-phase (asymmetrical) open-end winding asymmetric induction machine is proposed with the capability to generate multilevel outputs [25]. But the PWM strategies are adopted by the complex space vector modulation (SVM) by the nearest three-vector approach to generate multilevel output voltages and complex to implement with real time digital signal processors (dsps). In this research paper, the same ac drive configuration is exploited for the developed post-fault condition with a simplified multi-level (level-shifted PWM) modulation applied to regulate each pair of 2-level VSIs to behave similarly to 3-level outputs. Moreover, the PWM scheme is easy to implement in industrial standard dsp [25,26].

The power circuit consists of four standard 2-level VSIs with four isolated DC sources and hence, the system is absolutely free of zero-sequence components as shown in Fig. 1(a). Equivalent circuit in terms of the three-phase space vectors are shown in Fig. 1(b). Benefit of the topology includes the reduction of construction cost by its conventional structure; high reliability and reduced total harmonic

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distortion (THD) with lower *dv/dt* at the outputs; and the reduction of stress in the switches. In particular, topology is a viable solution for the applicability of multiphase-phase ac motor/generator (6-phase, 9-phase, etc.) and renewable energy systems integration for more electric aircraft systems and high-power utilities [12].

Complete ac drive system along the post-fault control strategy algorithm with simplified multilevel PWM scheme is numerically modelled in Matlab/PLECs simulation software. For experimental verifications, the hardware prototype version is implemented with two dsp TMS320F2812 processors and impedance load in open-winding configuration. Set of simulation and experimental results are provided in this paper under different designed testing conditions. Both the simulation and experimental results are always shown in close agreement with developed theoretical background.

This paper is organized as follows: analysis of asymmetrical six-phase open-winding induction motor drive circuit is illustrated in section 2; simplified level-shifted multilevel modulation along with theoretical background and power sharing principles are discussed in section 3; designed post-fault control strategies and predictions are elaborated with theoretical developments in section 4; numerical simulation and experimental implementation results are described with theoretical validation in section 5. Finally, section 6 concludes this research investigation.

2. Analysis of the proposed asymmetrical, six-phase, open-winding induction motor drive

Fig. 1(a) shows the dual three-phase (six-phase asymmetrical) open-winding induction motor fed from four three-phase VSIs with isolated DC sources. Fig. 2(a) correspondingly represents the orthogonal rotating multiple space vectors equivalent circuit [21,27,28]. Complete behavior of the dual three-phase induction machine can be written in stationary reference frames as:

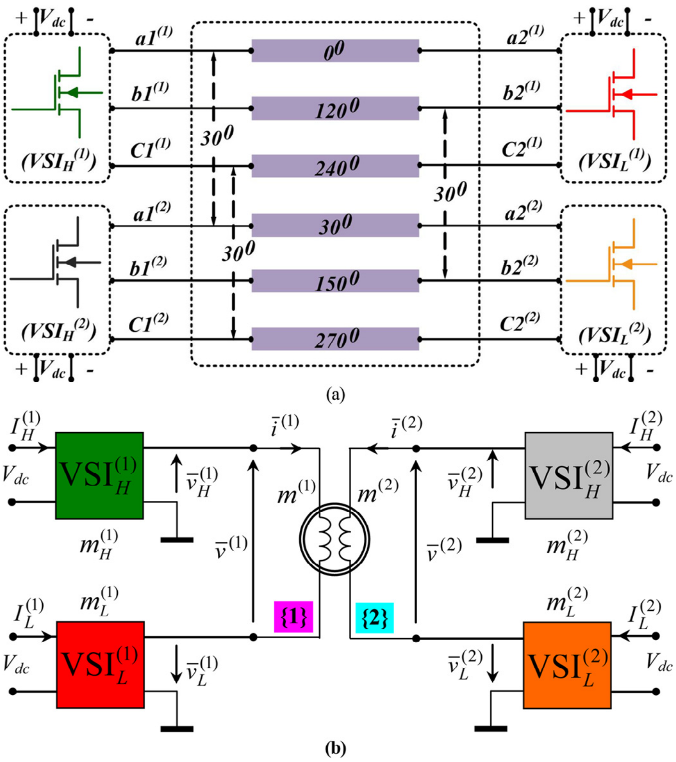

Fig. 1. (a) Investigated configuration of six-phase (quad) asymmetrical open-end windings ac drive. (b) Equivalent three-phase space vectors circuit. (Healthy state.)

$$\bar{v}_{S1} = R_S\bar{i}_{S1} + \frac{d\bar{\varphi}_{S1}}{dt}, \bar{\varphi}_{S1} = L_{S1}\bar{i}_{S1} + M_1\bar{i}_{R1} \tag{1}$$

$$0 = R_R\bar{i}_{R1} - jp\omega_m\bar{\varphi}_{R1} + \frac{d\bar{\varphi}_{R1}}{dt}, \bar{\varphi}_{R1} = M_1\bar{i}_{S1} + L_{R1}\bar{i}_{R1} \tag{2}$$

$$\bar{v}_{S5} = R_S\bar{i}_{S5} + \frac{d\bar{\varphi}_{S5}}{dt}, \bar{\varphi}_{S5} = L_{S\ell}\bar{i}_{S5} \tag{3}$$

$$T = 3pM_1\bar{i}_{S1} \cdot j\bar{i}_{R1} \tag{4}$$

Since all DC sources are isolated, it is understood that the proposed system is free of zero-sequence components. Now, the total power P of the ac motor can be written as the sum of power of the two three-phase open-windings $P^{(1)}$-{1} and $P^{(2)}$-{2} as [25]:

$$\begin{cases} P^{(1)} = \dfrac{3}{2}\bar{v}^{(1)} \cdot \bar{i}^{(1)} \\ P^{(2)} = \dfrac{3}{2}\bar{v}^{(2)} \cdot \bar{i}^{(2)} \end{cases}, \tag{5}$$

$$P = P^{(1)} + P^{(2)} = \frac{3}{2}\left[\left(\bar{v}_H^{(1)} + \bar{v}_L^{(1)}\right)\cdot \bar{i}^{(1)} + \left(\bar{v}_H^{(2)} + \bar{v}_L^{(2)}\right)\cdot \bar{i}^{(2)}\right] \tag{6}$$

The stator windings voltages $\bar{v}^{(1)}$ and $\bar{v}^{(2)}$ are the sum of individual inverter voltages ($\mathrm{VSI_H}^{(1)}$, $\mathrm{VSI_L}^{(1)}$ and $\mathrm{VSI_H}^{(2)}$, $\mathrm{VSI_L}^{(2)}$), expressed as:

$$\begin{cases} \bar{v}^{(1)} = \bar{v}_H^{(1)} + \bar{v}_L^{(1)} \\ \bar{v}^{(2)} = \bar{v}_H^{(2)} + \bar{v}_L^{(2)} \end{cases} \tag{7}$$

There are three degrees of freedom, which allows the total power to be shared equally between the two three-phase open-end windings [25]. By first degree of freedom k_i, sharing of power (current) between two three-windings {1} and {2} is predicted as follows:

$$\begin{cases} \bar{i}^{(1)} = 2k_i\bar{i}_{S1} \\ \bar{i}^{(2)} = 2\alpha^{-1}(1-k_i)\bar{i}_{S1} \end{cases} \tag{8}$$

$$\begin{cases} P^{(1)} = P_H^{(1)} + P_L^{(1)} \cong k_iP \\ P^{(2)} = P_H^{(2)} + P_L^{(2)} \cong (1-k_i)P \end{cases} \tag{9}$$

By second $k_v^{(1)}$ and third $k_v^{(2)}$ the degree of freedom that allows the sharing of power (voltages) between the inverters ($\mathrm{VSI_H}^{(1)}$ and $\mathrm{VSI_L}^{(1)}$) and ($\mathrm{VSI_H}^{(2)}$ and $\mathrm{VSI_L}^{(2)}$) of windings {1} and {2} is predicted as follows:

$$\begin{cases} \bar{v}_H^{(1)} = k_v^{(1)}\bar{v}^{(1)} \\ \bar{v}_L^{(1)} = \left(1-k_v^{(1)}\right)\bar{v}^{(1)} \end{cases} \quad \begin{cases} \bar{v}_H^{(2)} = k_v^{(2)}\bar{v}^{(2)} \\ \bar{v}_L^{(2)} = \left(1-k_v^{(2)}\right)\bar{v}^{(2)} \end{cases} \tag{10}$$

$$\begin{cases} P_H^{(1)} = k_v^{(1)}P^{(1)} \\ P_L^{(1)} = \left(1-k_v^{(1)}\right)P^{(1)} \end{cases} \quad \begin{cases} P_H^{(2)} = k_v^{(2)}P^{(2)} \\ P_L^{(2)} = \left(1-k_v^{(2)}\right)P^{(2)} \end{cases} \tag{11}$$

Hence, the total power can be equally shared among the four VSIs which lead to 25% power demand from each VSI.

3. The PWM modulation strategy for the quad-inverter ac drive system

In order to synthesize the reference voltage vectors $\bar{v}^{(1)}$ and $\bar{v}^{(2)}$, proper multilevel PWM algorithm is required to modulate each couple of VSIs and also to satisfy the power sharing between the two windings [29–31], where techniques that suffer by zero-sequence components require compensation in the PWM strategy.