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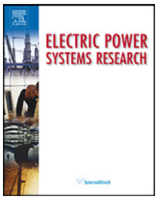

Vector controlled multiphase induction machine: Harmonic injection using optimized constant gains

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ABSTRACT

Torque enhancement by stator current harmonic injection is one possible use of the additional degrees of freedom offered by multiphase machines yielding a near rectangular air-gap flux. The number of injected harmonics depends on the phase order and the corresponding sequence planes. As the number of machine phases increases, the injected harmonic order can be increased where each plane requires two *PI* controllers, to control its current components, resulting in a complicated tuning process. Moreover, the deployment of conventional indirect vector control with multiple *PI* controller fails to maintain a near rectangular air-gap flux with different loading conditions due to synchronization problem between different planes. In this paper, the conventional indirect vector control based on multiple *PI*-controllers is replaced by only two *PI*-controllers to develop the fundamental *dq* voltage components from which the *dq* voltage components for other planes are determined using offline optimized constant gains. The proposed controller makes the tuning process is easier and achieve near rectangular air-gap flux during loading conditions. The proposed controller tested using a prototype eleven-phase induction machine where injection up to the ninth harmonic can be engaged. A comparison between the conventional controller, using multiple *PI* controllers, and the proposed controller is made for third harmonic injection. Practical results are introduced as a conformance to simulation results.

1. Introduction

There is a substantial increase in the interest in multiphase drives which are a serious candidate for applications such as electric ship propulsion, aircraft drives, and locomotive traction. For high power industrial applications, high power ratings for both the motor and its converter are required. However, converter ratings cannot necessarily be increased due to power rating limitations of semiconductor devices [1]. A multiphase machine fed from a multiphase inverter drive which has lower current per phase or designed with a lower voltage for the same total power, could be used for this task [2,3]. Multiphase machines have been surveyed [1,2,4,5]. These references cover many multiphase machine topics such as properties [6,7], modeling [8–12], applications [12–15], advantages [3,6,7,9,15,16] and performance with different control techniques [17–20]. By increasing the number of phases, the torque harmonics decrease [1]. Another advantage of a multiphase machine is that it gives additional degrees of freedom for new applications with high torque density by current harmonic injection into concentrated winding machines [8,21–23]. Harmonic injection not only provides torque enhancement but also produces more robust control [24]. Additionally, injection provides good transient and steady-state performance with near rectangular flux in the air-gap [9,18,25]. Most research is restricted to the five-phase induction machine with two control planes (fundamental and third); however the independent plane concept is valid for any higher number of phases. Speed control techniques for multiphase induction machines are similar to those for the three-phase induction machine. Conventional constant *V/f* scalar control has been studied for the multiphase variable-speed induction motor drive [26–28]. Vector control and direct torque control have been applied to multiphase machines [10,18,29–33]. The difference is the axis transformation calculation which must be adapted to produce *n*-phase voltage or current [1]. The vector control algorithm was based on decoupling the stator phase currents into flux components d_1, d_3,. . . d_{2h-1} and the torque components q_1, q_3,. . . q_{2h-1} where h is the available number of decoupled planes which depends on the machine n phase number [9]. The control objective is to provide independent control of both flux and torque, and to generate a near rectangular air-gap flux. In reference [12], rotor field orientation

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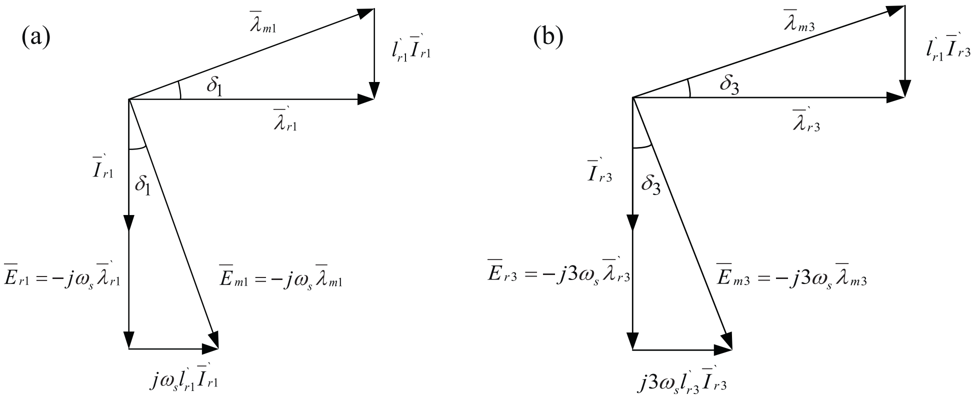

Fig. 1. Phasor diagram for the 1st and 3rd harmonics.

control is applied to a five-phase induction motor with combined fundamental and third harmonic currents to generate a near rectangular air-gap flux. However, the control concept is valid for any number of planes. The *dq* current components of each plane are controlled separately with $n-1$ *PI*-controllers in the voltage decoupling network [12,34]. If the number of injected harmonics is more than two ($n > 5$), the tuning process becomes difficult. Moreover, the use of multiple PI-controllers introduces improper alignment of different harmonic components with the fundamental flux component [23]. With conventional control [18], variable misalignment between fundamental and third air-gap flux components occurs for different mechanical loadings. Some techniques are developed to overcome this problem in five-phase induction machine but with complex controller and questionable stability problems [17]. Other techniques are used to synchronize the flux components in dual induction machine [35].

This paper proposes an indirect vector control algorithm that avoids *PI*-controllers for each non-fundamental plane by calculating the *dq* command signal for each plane from the fundamental *dq* plane. With this technique, the vector control system only has two current controllers. Consequently, the drive system becomes simpler and the alignment between different harmonic components of the applied voltages is guaranteed as they are not obtained from separate *PI*-controllers and will not be affected by mechanical loading.

A prototype eleven-phase machine is used where up to the ninth harmonic can be injected. Practical results confirm MATLAB simulation results.

2. Harmonic injection effect on flux distribution

This section introduces the main concept behind harmonic injection. Firstly, the effect of harmonic injection on flux density distribution is explored. Accordingly, the problem of flux components misalignment due to mechanical loading is then highlighted. For simplicity, the problem is described with third harmonic injection; however, it can be generalized for any harmonic injection order. Finally, GA algorithm is used to determine the optimized flux distribution for harmonic injection up to the ninth. This optimized flux distribution is then used to construct the proposed controller.

2.1. Third harmonic injection effect on air-gap flux density

Harmonic injection can be used to enhance the power density of multiphase machine and achieve a quasi-square flux distribution in the air-gap. Ref. [9,18] introduce an indirect field orientated control for a five-phase induction machine with third harmonic injection, where two *PI* current controllers are used to each plane with a total of four PI controllers to be tuned. This controller aims to align the rotor flux space phasor components, $\overline{\lambda_{r1}}$, $\overline{\lambda_{r3}}$ to the direct axis to obtain an approximate quasi square air gap flux. However, it neglects the difference between the rotor flux and the air gap flux, which is the main control objective rather than rotor flux. In other words, the controller is targeting the air-gap flux by controlling the rotor flux. This difference may be neglected for light loads. As the mechanical load increases this error cannot be tolerated and yields to flux distortion [17]. With third harmonic injection applied, there is no condition that guarantees that the two components of the air-gap flux space phasor ($\overline{\lambda_{m1}}$, $\overline{\lambda_{m3}}$) are aligned where the angle between the air-gap flux and the rotor flux space phasors ($\overline{\lambda_{m1}}$ and $\overline{\lambda_{r1}}$ for the fundamental plane and $\overline{\lambda_{m3}}$ and $\overline{\lambda_{m3}}$ for the third harmonic plane), depends on the mechanical loading, which leads to a variable misalignment between the fundamental and third components of the air gap flux. This problem can be illustrated by the phasor diagram in Fig. 1 and the corresponding air gap flux distribution is indicated in Fig. 2. The desired air-gap flux distribution is shown in Fig. 2a, where both the fundamental and the third space

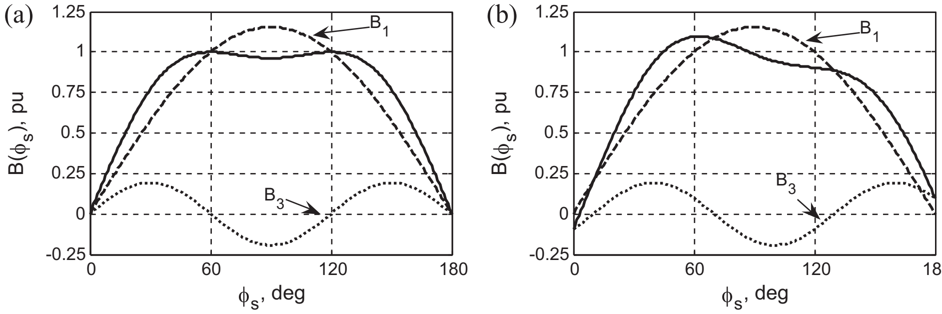

Fig. 2. Flux density distribution and its components (a) aligned and (b) misaligned.