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An Asymmetrical Six-Phase Induction Motor Drive Operation Using Current Control Methods

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ABSTRACT:

Using the vector space decomposition approach, the currents in a multiphase machine with distributed winding can be decoupled into the flux and torque producing α–β components, and the loss-producing x–y and zero-sequence components. While the control ofα–β currents is crucial for flu.,x and torque regulation, control of x–y currents is important for machine/converter asymmetry and dead-time effect compensation. In this paper, an attempt is made to provide a physically meaningful insight into current control of a six-phase machine, by showing that the fictitious x–y currents can be physically interpreted as the circulating currents between the two three-phase windings. Using this interpretation, the characteristics of x–y currents due to the machine/converter asymmetry can be analyzed. The use of different types of x–y current controllers for asymmetry compensation and suppression of dead-time-induced harmonics is then discussed. Experimental results are provided throughout the paper, to underpin the theoretical considerations, using tests on a prototype asymmetrical six-phase induction machine.

Index Terms—Current control, induction motor drives, multiphase systems.

INTRODUCTION:

USING the vector space decomposition (VSD) approach, an *n*-phase machine can be represented using $n/2$ [or $(n - 1)/2$ for machines with an odd number of phases] orthogonal subspaces, which include one *α–β* subspace and several *x–y* subspaces, and the zero-sequence components [1]. For a machine with sinusoidal magnetomotive force distribution, only the *α–β* components contribute to useful electromechanical energy conversion, while *x–y* and zero-sequence components only produce losses. In most cases, zero-sequence components can be neglected, since the neutral point of the machine is usually isolated so that the zero-sequence currents cannot flow. Due to the existence of additional degrees of freedom, controlling only the torque and flux producing *α–β* currents is insufficient and additional controllers are necessary to nullify the *x–y* currents that may flow due to the machine/converter asymmetry and the inverter dead-time effect [2]. Among the multiphase machines, those with multiple threephase windings (such as 6-phase, 9-phase or 18-phasemachine) are most frequently discussed. While having the benefits of a multiphase machine, the modular three-phase structures allow the use of the well-established three-phase technology. This study hence focuses on the discussion of *x–y* current control for an asymmetrical six-phase machine (30◦ spatial shift between the two three-phase statorwindings)with isolated neutral points.

Existing System:

In the early studies of the asymmetrical six-phasemachines, a double-*dq* or double-stator modeling approach has been utilized to aid the understanding of the machine's operation [3], [4]. Using this model, the two three-phase windings in a six-phase machine are treated separately. Two three-phase decoupling (Clarke) transformations are applied separately on the phase variables for each three-phase winding. This transforms the sixphase variables into two sets of stationary reference frame variables, denoted as $\alpha 1$–$\beta 1$

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and $\alpha2$–$\beta2$ components, for windings 1 and 2, respectively.

Despite the various advantages of the VSD model, the variables are more difficult to interpret physically, unlike in the double-*dq* model where $\alpha1$–$\beta1$ variables are clearly related to the winding 1 and $\alpha2$–$\beta2$ variables to the winding 2 of the machine. It is therefore desirable to provide a better physical interpretation of the VSD model variables by relating them with variables in the double-*dq* model. This can be done by simply comparing the decoupling transformation matrices for the two methods.

Proposed System:

The general structure of the current controllers within the rotor flux-oriented control scheme, considered further on and based on the VSD approach, is shown in Fig. 1. Here, *x–y* currents are not rotationally transformed and are shown as being controlled in the stationary reference frame. As shown in [7], asymmetry in the machine windings or converter can cause large current distortion in the six-phase machine. PWM can also cause current distortion [8], but this effect is marginal if the proper PWM technique is chosen. With the effect from PWM minimized, the machine/converter asymmetry leads to the current flow in the *xy* plane, so proper *x–y* current control has to be used to mitigate the problem. Several *x–y* current control strategies have been proposed as a possible solution, including the use of resonant controllers [9] and PI controllers [10]–[12]. In particular, the PI controller is the favorable choice for *x–y* current control, due to its simple structure and well-known characteristics.

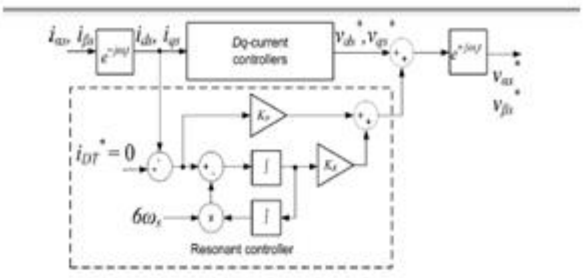

Fig. 3. Dead-time compensator for a three-phase machine using a resonant controller in the synchronous (*d–q*) reference frame.

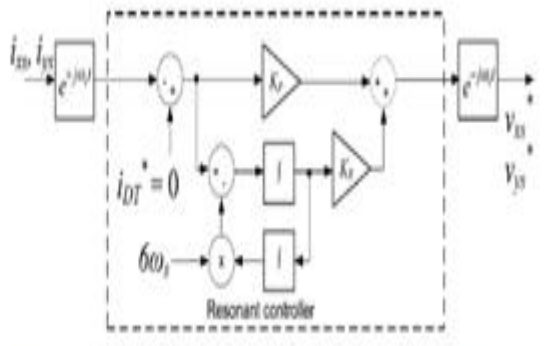

Fig. 4. Dead-time compensator for an asymmetrical six-phase machine using a resonant controller in the antisynchronous (*x–y*) reference frame.

EXPERIMENTAL RESULTS AND DISCUSSION

A. Experimental Setup Overview

Experimental tests are conducted on an asymmetrical sixphase squirrel cage induction machine, configured with two isolated neutral points. It was obtained by rewinding a 1.1-kW, 380-V, 50-Hz machine, with rated current and speed of 1.75 A and 930 r/min, respectively. The machine is supplied using a custom-made eight-phase two-level voltage source converter (VSC), configured for six-phase operation. A dc power supply (Sorensen SGI 600-25) is used to provide the dc-link voltage of 300 V to the VSC. A 5-kW dc machine is mechanically coupled to the six-phase machine and is controlled using ABB DCS800 drive in the torque control mode, to provide loading onto the six-phase machine.

The experimental setup is shown in Fig. 5. The six-phase machine is controlled using indirect rotor fluxoriented control (IRFOC) in the closed-loop speed control mode. The double zero-sequence injection carrier-based PWM [8] is utilized. The complete control algorithm is implemented using dSpace DS1006 system. Switching frequency is 5 kHz, with 6 μs dead time provided by the hardware in the VSC. Machine phase currents and dc-link voltage are measured (using the LEM sensors embedded in the VSCs) through dSpace at a sampling frequency of 10 kHz. Currents are filtered for display purposes using a low-pass filter with the cutoff frequency of 2 kHz.

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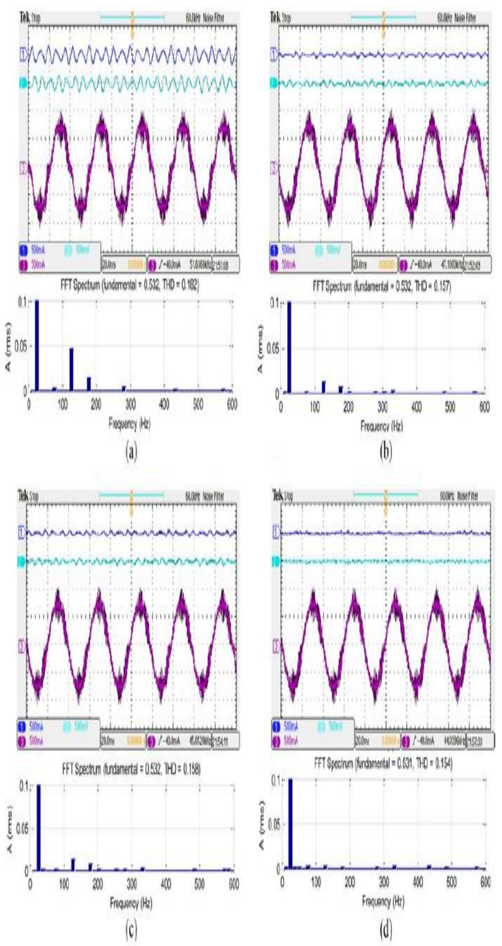

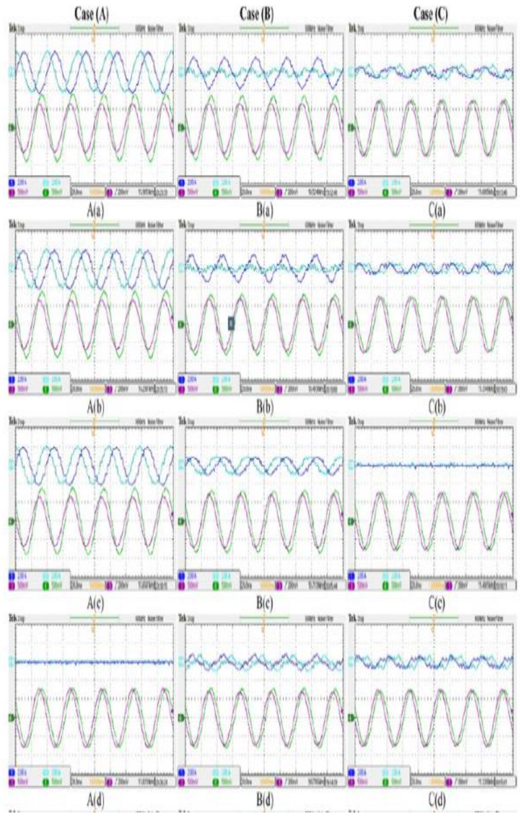

The experimental results are shown in Fig. 12. To facilitate the comparison, results for different types of asymmetry are placed in three separate columns, as indicated with the legend on the top of Fig. 12. Each row shows the results for one particular PI current control method in the *xy* plane. The speed is kept at +500 r/min. For simplicity, the machine is operated without load. The first row shows the results when only *d–q* currents are controlled and no *x–y* current control is provided. This is done by setting the *x–y* voltage references to zero. This scenario would have been perfectly sufficient for the control of the drive had the inverter and the machine been ideal, as explained in in conjunction with a five-phase machine. It can be observed that the different types of asymmetry introduce *x–y* currents that are different not only in their magnitudes.

CONCLUSION

The paper shows that the *x–y* currents in an asymmetrical six-phase machine can be physically interpreted as circulating currents between the two three-phase windings of the machine. By using this concept, the relation between the type of asymmetry in the machine/converter and the currents in the *xy* plane has been established. Subsequently, two important aspects of the *x–y* current control, i.e., asymmetries and dead-time compensation, have been discussed. For dead-time compensation, a resonant controller implemented in the antisynchronous reference frame shows the best performance, as proven on the basis of experimental results. In terms of the asymmetry compensation, it is shown that the inherent machine/converter asymmetry produces *x–y* currents that rotate at fundamental frequency. The *x–y* currents can, however, rotate in the synchronous, antisynchronous, or both directions, depending on the type of the asymmetry present. The effectiveness of asymmetry compensation using PI controllers hence depends on the reference frame in which the control is implemented. Full compensation for all the possible cases is achievable only with the dual-PI controllers (i.e., pairs in both synchronous and antisynchronous reference frames). The validity of the discussion is verified by experimental results.

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