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Enhance Direct Torque Control for Double Fed Induction Motor

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Abstract—Direct torque control is a variable-structure control strategy with simplicity, fast response, and tolerance to motor parameter variation, which provides direct control of stator flux and electromagnetic torque by optimally selecting the inverter states in each sampling period. For five-phase drives, the increased number of voltage vectors offers greater flexibility in optimizing the selection of the inverter states, thereby accomplishing more precise control of the stator flux and torque. Nevertheless, the large number of inverter states means that a more elaborate and complex selection criterion is needed. The following two aspects, which are not issues for three-phase drives, are taken into account in designing switching-table-based direct torque control for five-phase drives. First, the low-frequency harmonic currents due to the auxiliary vector plane need to be eliminated. Second, full utilization of the dc-link voltage is desired. A novel switching-table-based direct torque controller fulfilling these objectives is proposed and is combined with a speed-adaptive variable-structure observer. Experimental results substantiate the effectiveness of the proposed sensorless direct torque controller.

Index Terms—Direct torque control, five-phase induction motor drive, speed-adaptive variable-structure observer.

1. INTRODUCTION

The interest in multiphase motor drives has substantially increased during the last decade because of the potential advantages that they offer for certain applications. The main driving forces behind this accelerated development are associated with three specific application areas [1]: electric ship propulsion, “more electric” aircraft, and traction (locomotive, electric vehicles, and hybrid electric vehicles). Two distinct features make multiphase drives an attractive possibility for these applications. First, the required power is three. Therefore, high power (locomotive traction and marine propulsion) and high current (electric and hybrid electric vehicles) can be realized using power electronic devices with a limited power and current range. Second, more control variables can be manipulated to afford improved fault tolerance [2]–[6]. Additionally, multiphase motors also provide high-quality torque with lower torque ripple [7], torque density improvement [8]–[11], and multimotor control [12]–[16].

Direct torque control provides direct control of the stator flux and torque. The method provides a systematic solution for improving the operating characteristics of not only the motor but also the voltage source inverter. By optimal selection of the inverter switch states in each sampling period, direct torque control achieves rapid and effective control of the stator flux and torque. For multiphase drives, the additional inverter states permit greater flexibility in their selection and, therefore, finer adjustment of flux and torque. In three-phase drives, on the other hand, the control is implemented by only eight possible inverter states. Adversely, a large number of inverter states means that a more elaborate selection criterion is required. For this reason, minimal research has been presented on switching-table-based direct torque control of multiphase drives. Five-phase induction motor direct torque control has been reported [11], but no selection criterion of the inverter states was given. Various switching-table-based direct torque control techniques for split-phase induction machines have been discussed and implemented [17], [18] with good torque and flux regulation performance but without solving the phase current distortion problem. Thus, switching-table-based direct torque control for multiphase drives is a topic requiring further research [17]. A selection criterion has been presented for direct torque control of five-phase interior permanentmagnet motor drives [19]. The control method has two serious drawbacks. First, the low-frequency current space vector in the auxiliary inverter vector plane was not eliminated. Second, the dc-link voltage was not fully utilized, which means that the maximum fully fluxed motor speed is lower than expected.

A novel direct torque control scheme for five-phase induction motor drives is proposed. Two novel features are presented. First, the concept of the virtual voltage vector is presented, which eliminates low-frequency harmonic currents and simplifies analysis. Second, speed information is introduced into the selection of the inverter states. The dc-link voltage is then fully utilized, and the torque ripple is reduced. For a multiphase drive intended for high-power propulsion applications, the cost of a shaft speed sensor is not an issue. However, installation and maintenance of the shaft sensor is cumbersome for a high-power motor. Moreover, system reliability is likely to be degraded, particularly when the sensor is subjected to hostile environments [20]. A speed-adaptive variable-structure observer is used here to estimate flux and speed information from the stator voltages and currents. The software speed sensor is more reliable and affordable than the real sensor that it replaces.

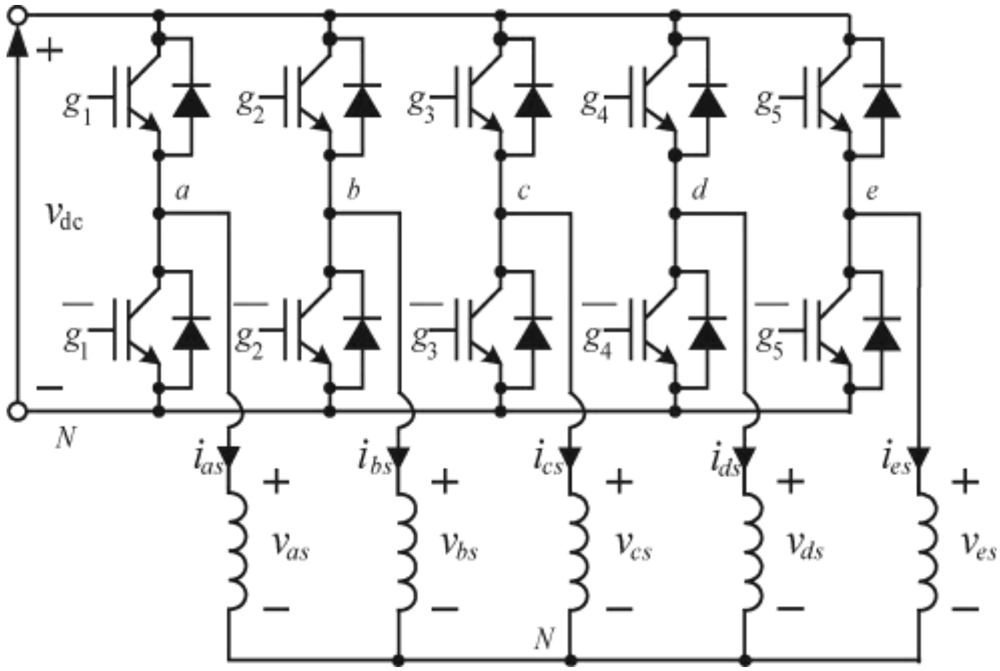

Fig. 1.Inverter for a five-phase induction motor drive.

II. MOTOR MODEL

The typical isolated neutral five-leg inverter configuration is used to drive a star-connected five-phase squirrel-cage induction motor, as shown in Fig. 1. A two-pole five-phase induction motor with quasi-concentrated phase windings, as described in [8], is used, and its specifications are tabulated in Appendix A. The electromagnetic torque can be derived from the partial variation of the coenergy with respect to rotor position

$$T_e = -\frac{5}{2}\frac{P}{2}\mathrm{Im}\left(L_{m1}\underline{i}^*_{dq1s}\underline{i}_{dq1r} + 3L_{m3}\underline{i}^*_{dq3s}\underline{i}_{dq3r}\right).$$

For simplicity, magnetic coupling of the leakage fluxes has not been taken into account during the modeling process, which leads to identical stator leakage inductances in the two rotating spaces. The differences in values between r_{r1} and r_{r3}, and between L_{lr1} and L_{lr3}, need to be recognized. These differences

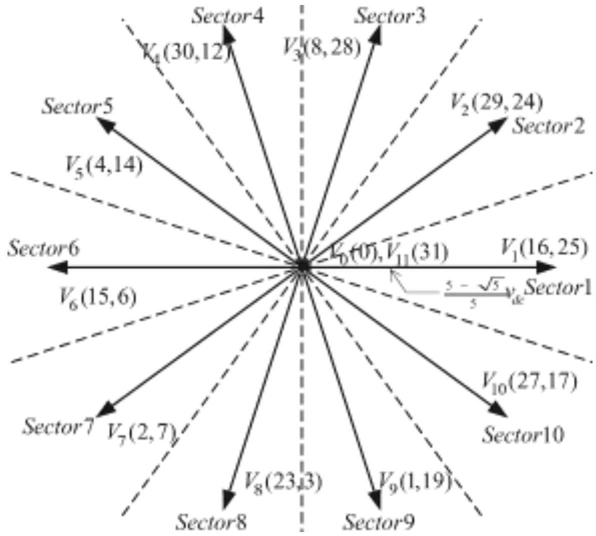

Fig. 2.Ten active virtual voltage vectors and ten sectors in the $\alpha1$–$\beta1$ space.

are determined by the fundamental- and third-harmonic components within the stator winding function. For the motor used, these differences can be determined by parameter expressions derived in [8].

From the presented model, it is seen that the five-phase induction motor behaves as a dual stator winding induction motor consisting of a squirrel-cage rotor and a stator with two separate windings wound with a dissimilar number of poles (2/6). These two separate windings (with same resistances and leakage inductances) are fed from the d_1–q_1 and d_3–q_3 voltages, respectively. Because of the decoupling effect produced by windings with different pole numbers, the flux and torque associated with each separate winding can be independently regulated by controlling the d_1–q_1 and d_3–q_3 voltages, respectively.

It is observed from (5)–(12) that the two space harmonics can be separately or simultaneously energized. A modulation strategy for separate excitation has been developed [21], which produces one active reference voltage vector in the α_1–β_1 space and one null reference voltage vector in the α_3–β_3 space. For simultaneous excitation, two active reference voltage vectors, namely, $\underline{v}_{\alpha\beta 1s}$ and $\underline{v}_{\alpha\beta 3s}$, can be transformed to five reference phase voltages v_{as}–v_{es} by the inverse transformation of (1) and (2). Then, a neutral voltage, maximizing the dc-link utilization, can be injected to find the five reference pole voltages. The reference pole voltages are compared with a carrier waveform to generate the modulation for each inverter leg.

III. RESULTS AND DISCUSSION

As mentioned in the proposed direct torque controller, demagnetization by a nonzero voltage vector encountered in the low-speed region is avoided if four active virtual voltage vectors near the boundary of sector 1 or its radial boundary extension are selected for flux and torque adjustment, as seen in Fig. 5(a) and in the unshadowed part of Table I. To demonstrate the demagnetization by nonzero voltage vectors, the proposed direct torque controller is deliberately modified to use four far active virtual voltage vectors in the low-speed region. Instead of the unshadowed part of Table I, the shadowed part is deliberately used at 100-r/min (below the speed threshold ω_{r_th} = 500 r/min) no-load operation. The experimental waveforms are shown in Fig. 3. The stator flux linkage is maintained at around 0.23 Wb, which is below the reference value (0.4 Wb). Fig. 10 shows experimental waveforms for the proposed method, which

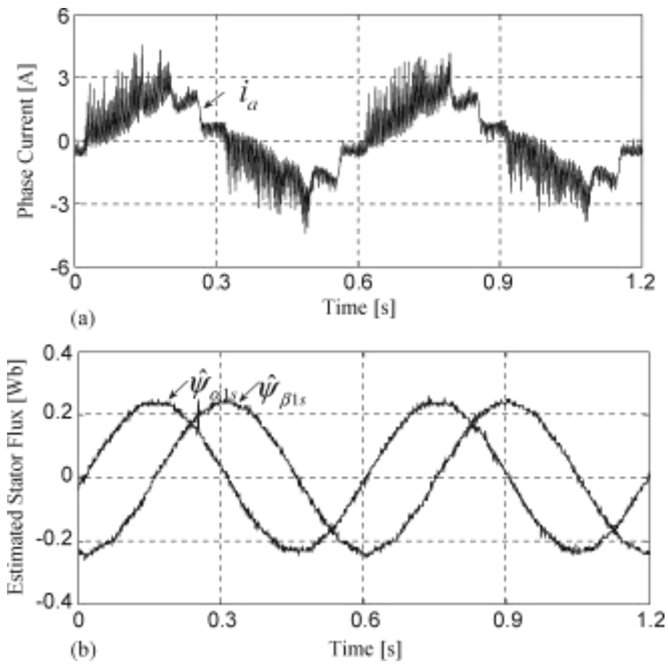

Fig. 3. Experimental waveforms for the sensorless direct-torque-controlled drive deliberately using far active virtual voltage vectors during low-speed operation. (a) Phase *a* current. (b) Estimated $\alpha 1$–$\beta 1$-space stator flux linkage. The graphs show the demagnetization by nonzero voltage vectors.

uses the unshadowed part of Table I in this low-speed region. Both the phase current and the rated stator flux linkage of 0.4 Wb are accurately controlled.

IV. CONCLUSION

This paper introduces and validates an enhanced combined 24 sectors DTC-ANFIS approach for a DFIM powered by a 3-level NPC inverter. The DFIM model and other details of the combined 24 sectors DTC-ANFIS have been presented. The 24 sectors DTC-ANFIS represents an enhancement over the 24 sectors DTC, notably seen in reduced torque ripple, improved current quality, minimized flux ripple, lower THD values, and enhanced dynamic responses in speed, torque, and flux.

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