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Torque Production and Control Mechanism in Thebrushless Dc Motors

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ABSTRACT: *Smooth and efficient operation of the brushless dc motor relies on the knowledge of the energization sequence of the windings. This sequence which is supplied by motor manufacturers can be obtained by operating the motor in generator mode and employing the technique presented in this paper. The application of this energization sequence, which is a function of rotor position, produces resultant stationary current vectors, which interact with the rotor flux linkage vector to develop electromagnetic torque. this paper is focused on the determination of the energization sequence of the motor, its effect on electromagnetic torque production and the utilization of the torque production mechanism for the classification of the brushless dc motor.*

Keywords: *energization, dynamic performance, cross coupling sequencebrushless motors, commutation, dynamic performance, cross coupling, rotor position*

I. INTRODUCTION

Brushless dc motors are rapidly gaining popularity in the appliance, automotive, aerospace,consumer, medical and industrial automation industries. As a result of the absence of mechanicalcommutators and brushes and the permanent magnet rotor, brushless dc motors have manyadvantages over the brush dc and induction motor [1-6]. Some of the advantages of brushless dcmotors are:

(1) High power density, low inertia and high torque to inertia ratio and high dynamic response due to the small size, low weight and high flux density neodymium-iron-boron permanent magnet rotor.
(2) High efficiency due to the low rotor losses as a result of the absence of current carrying conductors on the rotor and reduced friction and windage losses in the rotor.
(3) Long operating life and high reliability due to the absence of brushes and metallic commutators.
(4) Clean operation due to the absence of brushes, resulting in no brush dust during operation and allowing for clean room applications.

The exceptional features of brushless dc motors described above are responsible for theirwidespread use in many industries; however, a review of the literature did not provide motoroperational characteristics based on the various phenomena occurring in the motor. Since theoperational characteristic of a motor is important for its control, modeling and deriving optimumperformance, this paper is focused on the determination of the energization sequence of themotor, its effect on electromagnetic torque production and the utilization of the torqueproduction mechanism for the classification of the brushless dc motor.

II. ENERGIZATION BRUSHLESS DC MOTORS

The determination of phase winding back emf as a function of rotor position for a three-phasebrushless dc motor was obtained by operating the brushless dc machine in generator mode. Inthis test, a brush dc motor was used as a prime mover to drive the three-phase, two-polebrushless dc machine at constant speed in an anti-clockwise direction. The apparatus used isshown in Fig. 1. The rotating flux of the two-pole brushless dc machine rotor induces voltages ineach phase winding. For a three wire star connected brushless dc machine, the star point is not accessible and the three resistors labeled *R*, in star connection were used to obtain machine phasevoltages from line to the star point *n* formed by the three resistors.

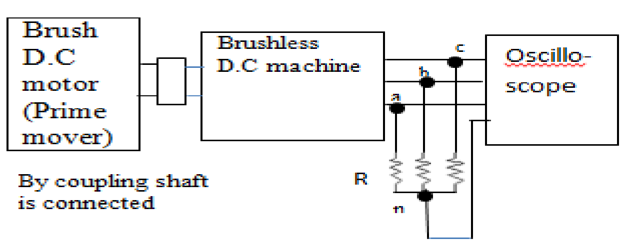

Fig. 1 Brushless DC Machine Operated as a Generator

Fig. 2(a) reveals that two phase voltages are of constant value for 60 electrical degrees and for astar connected stator as shown in Fig. 3, line voltage waveforms can be drawn from two phasevoltages. These line voltage generated waveforms *ebc* , *eca* and *eab* are shown in Fig. 2(b).Since two phase windings of a star connected brushless dc motor are experiencing a constant generated line voltage for 60 electrical degrees, then efficient operation of the motor is obtainedwhen the two energized windings are experiencing their constant back emf.

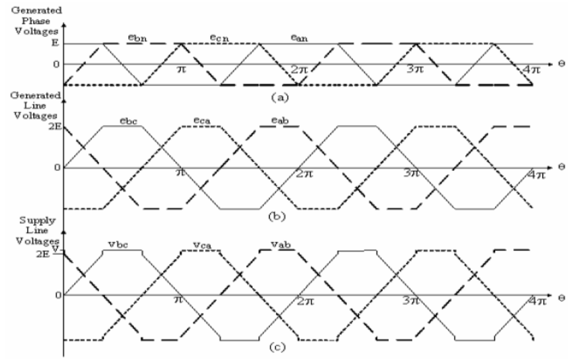

Fig. 2 Brushless DC Motor Voltages (a) Generated Phase Voltages *ean* , *ebn* and *ecn* (b) Generated Line Voltages *ebc* , *eca* and *eab* (c) Supply Line Voltages *Vbc* , *V ca* and *V ab*

Hence, the generated line voltage waveforms shown in Fig. 2(b), which are functions of rotorposition θ, are used to determine the sequence of energization of the motor windings for aparticular direction of rotation. Therefore, for anti-clockwise operation of the brushless dcmotor, using Fig. 2(b), and starting with rotor position at θ = 0°, the winding pairs should beenergized in the sequence *ac, bc, ba, ca, cb, ab* and *ac* again, with each winding pair beingenergized for 60 electrical degrees [8-9]. It must be noted that for clockwise operation of thebrushless dc motor, the sequence of energization of the winding pairs must be reversed andwould take the form *ab, cb, ca, ba, bc* and *ac*.

III. TORQUE PRODUCTION AND OPERATION OF BLDCM USING VECTOR ANALYSIS

The theory of vector analysis of a three-phase stator, justifying the existence and location ofvector currents and voltages and the equality of scalar and vector current magnitudes waspresented in [6].A cross sectional view of a two-pole, three-phase brushless dc motor is shown in Fig. 3. Therotor magnet is shown with a reduced diameter and hence an enlarged air-gap for illustrationpurposes. The two-pole rotor is assumed to be rotating at a constant angular velocity ω rad/sec inan anticlockwise direction. At the instant of observation in Fig. 3, it's d-axis which is defined asthe centre of the south pole is at the position θ = 0°, which corresponds to the θ = 0° point on thehorizontal axes of the waveforms in Fig. 2. At this rotor position θ = 0°, winding pair *ac* wouldbegin to experience their constant back emf *Eac* due to the effect of the rotor magnet on thestator windings as shown in Fig. 2(b). Hence, at this rotor position θ = 0°, winding pair *ac* mustbe energized with a supply voltage of *V ac* volts to oppose the constant back emf *Eac* presently experienced by the windings. The magnitude of the supply voltage must be greater than theconstant back emf developed by the windings as shown in Fig. 2(c) and sufficient to developelectromagnetic torque to sustain the rotor speed.

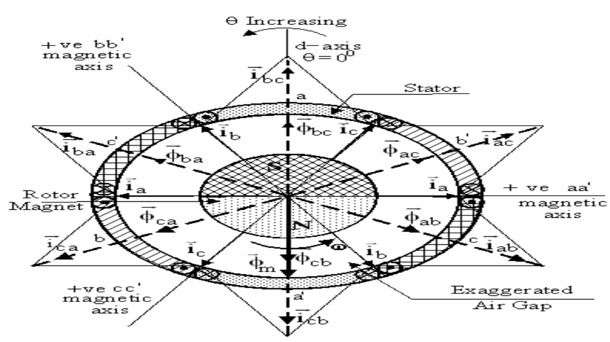

Fig. 3 Stator And Rotor Vectors For Two-Pole, Brushless DC Motor

IV. STATOR WINDING INITIALISATION

The energization of stator winding pair *ac* with supply voltage *V ac* and the resulting phase currents are shown in Fig. 5(a). The energization of winding pair *ac* results in the currents *ia* through winding *aa'* and *ic* through winding *cc'* respectively, where, *ia* = *ic* . These currents establish stationary current vectors *i a* r and *i c* r along the positive magnetic axis of winding *aa'* and negative magnetic axis of winding *cc'* respectively [10]. The vector addition of these two stationary current vectors *i a* r and *i c* r , results in the resultant stationary current vector *i ac* r as shown in Fig. 4.

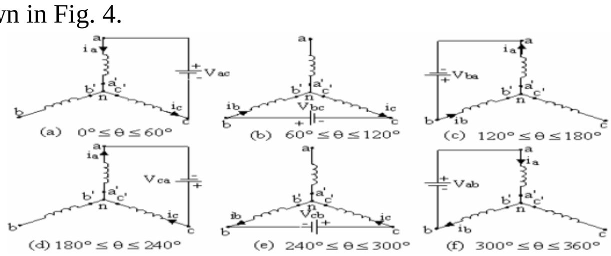

Fig. 4 Energization Sequence of Two-Pole, Three-Phase Stator

At this rotor position θ = 0°, the resultant stationary current vector *i a*r , is displaced from therotor flux vector φr*m* by an angle of 120 electrical degrees. The resultant stationary stator fluxvector φr*ac* , produced by current vector *i ac*r , establishes a magnetic south pole at the arrow headof the φR*ac* vector, while a north magnetic pole exist at the arrow head of the rotor flux vectorφ r*m* . The interaction of these flux vectors φr *ac* and φr*m*develops electromagnetic torque, resultingin the rotor and its flux vector being pulled towards the resultant stationary stator flux vectorφ r*ac* , causing rotation of the motor in an anti-clockwise direction. The electromagnetic torque *Te*rdeveloped by the machine is given by the cross product of peak flux linkage vector λr*m* (where,λ = φr r*m N m*) and current vector *i ac*r [7].

V. TORQUE CHARACTERSTICS

The electromagnetic torque developed by the motor for a fixed statorwinding current *I* for one revolution of the rotor and ignoring the electromagnetic torquedeveloped during commutation is shown in Fig. 5 [7].

Fig. 5 Electromagnetic Torque Developed in One Revolution

The events described above for efficient operation of the two-pole, three-phase brushless dcmotor, showing the range of rotor positions for a pair of windings to remain energized, thecorresponding back emf of the energized windings and the corresponding electromagnetic torquedeveloped

VI. FLUX DEVELOPMENT METHODOLOGY

The relatively stationary current vector of the rotorinteracts with the stationary magnetic field of the stator, developing electromagnetic torque givenby the cross product of these two vectors. Fig. 8(a) shows the brush dc machine stationary flux linkage vector φr *N s* and the relatively stationary rotor current vector *i r*r separated by an angle α.The electromagnetic torque developed.

In Fig. 6(b), the rotor flux vector and stator current vector of the asynchronous machine arerotating at the angular velocity of the supply voltage ω*s* , while the rotor rotates at an angularvelocity ω*m* which is lower than ω*s* . However, the rotor's flux vector and stator current vectorand the rotor of a synchronous machine all rotate and the angular velocity of the supplyvoltage ω*s* as shown in Fig. 6(c).

It is clear from Fig. 6, that dc machines are characterized by stator flux vector and rotor currentvector both occupying a relatively fixed position in the machine space, while, ac machines arecharacterized by rotor flux vector and stator current vector both rotating at the angular velocityof the stator supply voltage within the machine space. The energization of a pair of stator phasewindings of a brushless dc motor for 60 electrical degrees results in the production of a rotating.rotor flux vector and a stationary stator current vector.

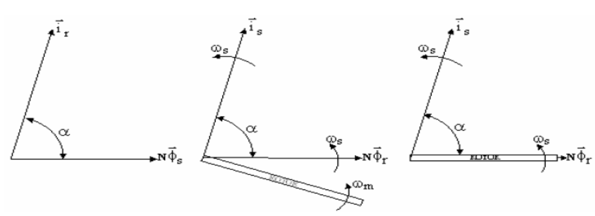

Fig. 6 Flux and Current Vectors of Electrical Machines (a) Brush DC Motor (b) AsynchronousMachine (c) Synchronous Machine

This clearly does not fit the classificationof a dc machine, although the stator windings are energized with a dc supply during this interval.In addition, examination of the rotor flux vector and the stator current vector over a cycle as shown in Fig. 3, also reveal their non-stationary nature, with the stator current vector alwaysleading the rotor flux vector and they complete an electrical cycle in the same time. Further tothis, the line voltage waveforms of Fig. 2 are not dc, but alternating in nature and are similar tothe trapezoidal back emf of the motor when operated as a generator. These properties clearlyindicate that the brushless dc motor is an ac synchronous motor although the stator windings areenergized by dc voltages and the torque-speed characteristics of the motor is similar to that of thebrush dc motor [10].

V. CONCLUSION

Smooth and efficient operation of the brushless dc motor relies on the knowledge of theenergization sequence of the windings. This sequence which is supplied by motor manufacturerscan be obtained by operating the motor in generator mode and employing the techniquepresented in this paper. The application of this energization sequence, which is a function ofrotor position, produces resultant stationary current vectors, which interact with the rotor fluxlinkage vector to develop electromagnetic torque. Hence the vector method of analysis, whenapplied to brushless dc motors, displays the torque production mechanism in the motor andpresents a powerful insight into the physical phenomena occurring in the motor. In addition, thecross product used in the computation of the developed electromagnetic torque of the motor,revealed the importance and necessity of phase winding commutation in order to sustaincontinuous motor operation. Finally, the characterization of the brushless dc motor as an ac or dcmotor was addressed. The characteristics of the motor clearly indicate that it is an acsynchronous motor, although the stator windings are energized by dc voltages and the torque-speedcharacteristics of the motor is similar to that of the brush dc motor.

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