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COMMUTATIONAL MODELING AND SIMULATION OF BRUSHLESS DIRECT CURRENT (BLDC) MOTOR.

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Abstract

Brushless DC (BLDC) motors are becoming more popular in modern applications due to their superior efficiency, reliability and small size. The optimization of commutation techniques is necessary to optimize the performance of most BLDC motors. This research evaluates and contrasts various commutation methods, such as trapezoidal, sinusoidal design, and field-oriented control (FOC), to determine their effects on motor efficiency, torque ripple and overall performance. The study's initial step involves examining the current state of commutation methods, with emphasis on their theoretical aspects and practical applications. Each method is tested under different load conditions and operational scenarios through experimental setups. Measurements of torque ripple, efficiency, electromagnetic interference, and thermal characteristics are included in the analysis. It investigates the cost and benefits of trapezoidal commutation, while examining whether it reduces torque ripple and noise with sinusoidal design. However, its effectiveness is uncertain. Field-oriented control is examined for its advanced capabilities in accurately controlling torque and speed. Real-time testing and simulation tools are utilized by the study to verify the findings. Results indicate that trapezoidal commutation is adequate for basic applications, but sinusoidal and FOC methods are highly effective and smoother, particularly in high-performance and precision applications. Finally, this paper provides suggestions on selecting suitable commutation methods that are compatible with specific application requirements and operational conditions.

Key Words: BLDC Motor, Computational Modeling, Simulation, Commutation and Trapezoidal Commutation.

1.0 Introduction

Brushless DC (BLDC) motors are one of the dominating technologies in electric motors due to their high efficiency, reliability and compact design. BLDC motors overcome the problems of traditional brushed DC motors, as they operate with electronic commutation rather than mechanical brushes and a commutation, which results in long life time, low maintenance cost and high efficiency [1]. The heart of any BLDC motor optimization is perfection of commutation methods used for closing the switches on corresponding motor phases synchronized with rotor positioning [2]. This paper aims at performing comparative study & optimization among different commutation techniques trapezoidal/Six Step Commutation – ZC/ZM (Zero Crossing/Zero Magnitude), sinusoidal & FOC (Field Oriented Control) along with improvement performance parameters of BLDC Motor. Brushless DC Motors are used in various applications ranging from domestic appliances & automotive systems to industrial automation fields & aerospace technology [3]. Their first advantage is in the absence of brushes which make wear and tear parts in motors. Brushed DC motors mechanically commutate the current into the stator windings through a structure called channel, which rewires periodically while motor rotates. The second advantage is that by using electronic commutation, they obtain better efficiency and reliability what leads them to be widely applicable at areas which demand high quality products - better durability, higher control accuracy or higher-speed stability [4]. Commutation process consists on feeding currents to selected windings so that resulting magnetic field created by stator reaction force would link or couple (attraction) with an opposite pole positioned on rotor [5]. To achieving specified torque level the field effect is multiplied by or divided with current proportionally to other two legs of currents as phases' direction changed every 60° rotational electrical degree (such interference are enabled by specific connection technique) while pseudo square voltages occur at brushless DC machine input terminals generated by an appropriate controller designed specifically for driving such motors executing properly timed switching operation in relation to Halls output signals or zero-crossing instant called back-EMF detection method [6].The most simple way (in terms of cost and technical conditions), two out of three-phases are led during entire revolution while triangular developed in this way current waveform flows through energized windings [7].

However, trapezoidal commutation still has some disadvantages. There is large torque ripple and acoustic noise associated with the currents switching operation, which limit its application in precision and high performance fields [8]. The torque ripple is generated by the current switch mechanism during commutation; due to this switch phenomenon in the current flow-direction, the motor drives total output pulsation [9]. For an example, if there is a lot of torque ripple generation at low speed stage of motor drive operation, it brings effect to smoothness of motor operation. Moreover, attenuation vibration and noise issues will also be aroused.

To overcome these problems sinusoidal commutation (sine wave commutation) has been introduced to generate smoother sinusoidal current waveform signal profile by continuously changing the current value in all three phases [10]. High frequency triangular voltage input generates a rotational magnetic field in PMSM at every 60 electrical degrees i.e. 360 mechanical degrees interval and cause non-zero resultant torque [11]. Even rotor mechanical angle does not exactly match stator electrical angle for certain angles less than 60 or greater than 180 degree [12]. By approximating ideal sinusoidal two-phase back EMF signal profile shape (obtained from nth Harmonic Extraction Algorithm method develop), sinusoidal rotor position can be improved gradually without abrupt change of stator winding energizing based on continuous applied voltage value increment/decrement between pre- and post-estimated phase windings associated with angular clock of respective increments/decrements as each sampling time step injected into quadrature AC winding coil pair [13]. This reduces greatly the output pulsation from coaxial linear summation effect between variation foundation shifting pulse width modulation triangular wave input reference signal together with actual modified fundamental pumping triangular wave-like driving voltage source command such as SPWM creating little zero-output region i.e. triangle corner over other identical dedicated non-zero output zone surrounding it due to those linearity exceptional mechanism application [14]. Contrarily, sinusoidal commutation performs a rotation magnetic field with zero output torque ripples by using high-resolution encoder to provide rotor position feedback for the rotor position tracking control and sine wave equation generation. As result, more sophisticated corresponding stator winding energizing pulse width modulation control algorithms along with higher positional resolution encoder are required for sinusoidal commutation [15].

Field oriented control (FOC), also known as vector control, is the most advanced type of commutation for BLDC motors. It does this by decoupling the stator current into two components: one that produces torque and another that produces flux [16]. The stator current's torque-producing component controls mechanical torque in the motor while its flux-producing component regulates the motor's magnetic field [17]. This transformation from three-phase to a two-axes coordinate system, called d-q axes, is mathematically derived using a transformation array like Clark/Park transform. FOC offers very high performance in terms of efficiency, dynamic response and smooth operation. Most importantly when applying maximum torque per ampere BLDC motor exhibits higher efficiency across all loads [18][19][20]. Nonetheless, it is difficult to apply as it requires complicated microcontrollers or digital signal processors.

The optimization techniques require a balance among simplicity, cost, and performance. Each technique has its own advantages and challenges. The suitable method can be selected depending on the application. To make a better comparison with respect to torque ripple, efficiency, EMI and thermal between trapezoidal, sinusoidal and FOC are obtained theoretically [21]. Trapezoidal is still employed in cost sensitive application such as home appliance and basics industry. Sinusoidal and FOC have been increasingly used in high performance requirement or precision in electric vehicle, robotic and aerospace systems [22]. The increasing ability of microcontroller will enhance the availability and viability of advanced commutation methods. In future with more efficient algorithms are developed as well as sensorless control purposes [23][24]. Therefore the commutation optimization is important way to reach the full potential of BLDC motors.

This paper presents a complete comparison among trapezoidal sinusoidal and FOC including their pros' cons by considering overall specifications impact for one type of drives based on this comparison results allows users determine which method delivers best result for their drive regarding specifications they want it based on.

The methodology for investigation and optimization of suitable commutation techniques for BLDC motors is carried out by defining the problem, developing a mathematical equation for analysis, developing the motor model, setting up simulation, data collection for the optimization, validation of the results obtained. BLDC has many inputs (voltage), outputs (current) and state variables (voltages across switches). So, since there are many control loops involved, this made the functioning process complex. The simulation tool used is Maxwell 2D. This work presents detail comparative analyses on trapezoidal, sinusoidal and FOC technique of commutation for brushless Direct Current motors. The best optimization method is then selected and applied. These result generated ideas for more compact, reliable, efficient different torque response and durability such as fan, pump/compressor, EV etc. Control system hence forth improving advanced technology in multiple doma.

MODELING OF BRUSHLESS DIRECT CURRENT INDUCTION MOTOR

METHODOLOGY

The methodology investigates and optimizes for suitable commutation techniques for BLDC motors, is carried out by defining the problem, developing mathematical equations for analysis, developing the motor model, setting up simulation, data collection for the optimization, and validation of the results obtained

B. Model Equations

(a). Voltage Equation for BLDC

$$V = Ri + L\left(\frac{di}{dt}\right) + Ea \qquad 3.1$$

$whre\ V = Terminal\ voltage\ of\ BLDC, R = Resistance, i = Current, L = Inductance\ and\ Ea = Back\ EMF$

(b). Torque Equation for BLDC

$$T = \left(\frac{1}{2}\right) * N * B * I * Sin(\theta) \qquad 3.2$$

Where T = Torque, N = Number of turns, B = Magnetic field strength, I = Current, (θ) = Angle between current and magnetic field.

(c) Motion Equation for BLDC

$$J\left(\frac{dw}{dt}\right) + Bw = T \qquad 3.3$$

Where J = Moment of inertia, w = Angular velocity, Damping coefficient, T = Torque

(d) Electromagnetic Torque Equation for BLDC

$$Te = \left(\frac{3}{2}\right) * N * B * I * Sin(\theta) \qquad 3.4$$

Where Te = Electromagnetic torque, N = Number of turns, B = Magnetic field strength, I = Current and (θ) = Angle between current and magnetic field.

These equations are applicable to the design of the stator, rotor, pole and shaft of the selected motor in question.

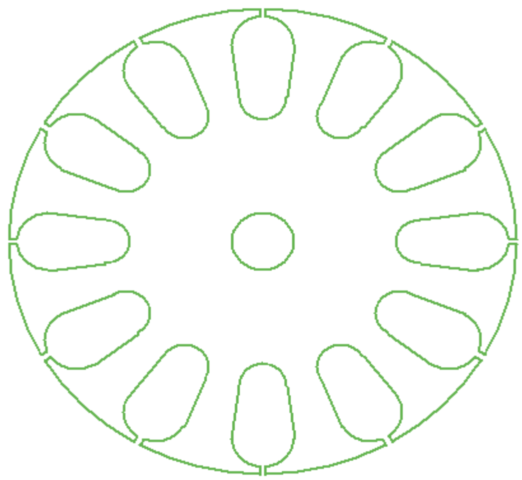

Figure 1.0: BLDC Rotor and Shaft

Figure 1.0 represents the modeled BLDC motor showcasing its stator and rotor part. All

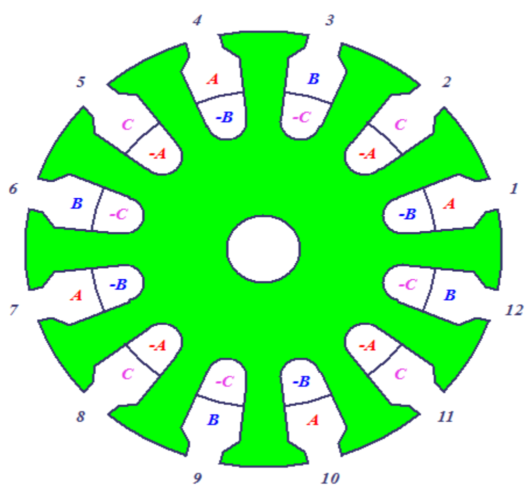

Figure 2.0: BLDC Stator with windings

Figure 2.0 shows the winding part of the motor. It is based on this components that every other component is developed upon. All dimensions are in millimeter (mm).

3. Discussion of Results

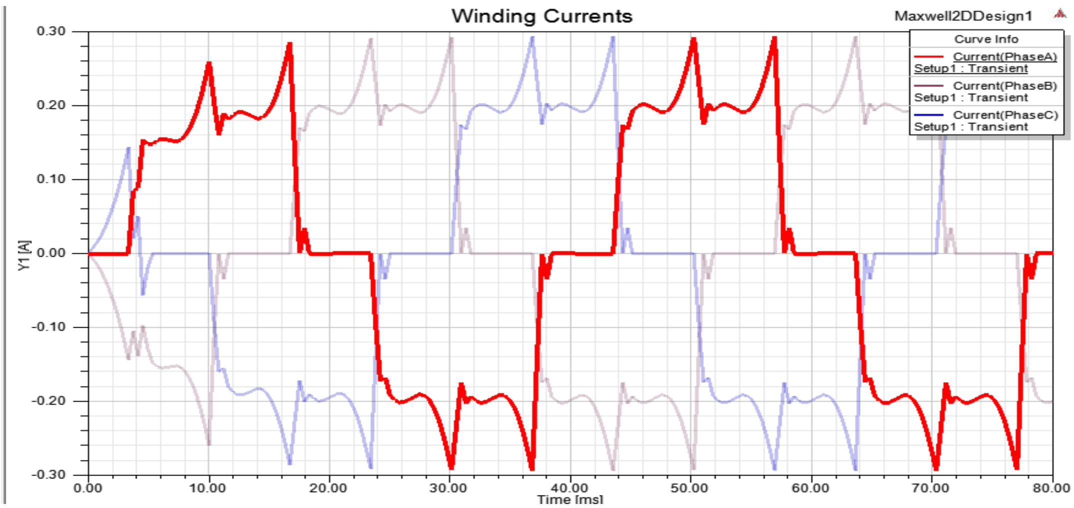

Figure 3.0: Simulated Phase A current windings with respect to reactance.

Figure 3.0 represents the simulated phase A current windings with respect to reactance of the motor, This movement started from the point zero and progressed to maximum of +30% and -30% in that order. This is to affirm that the performance of BLDC motor is in an AC pattern.

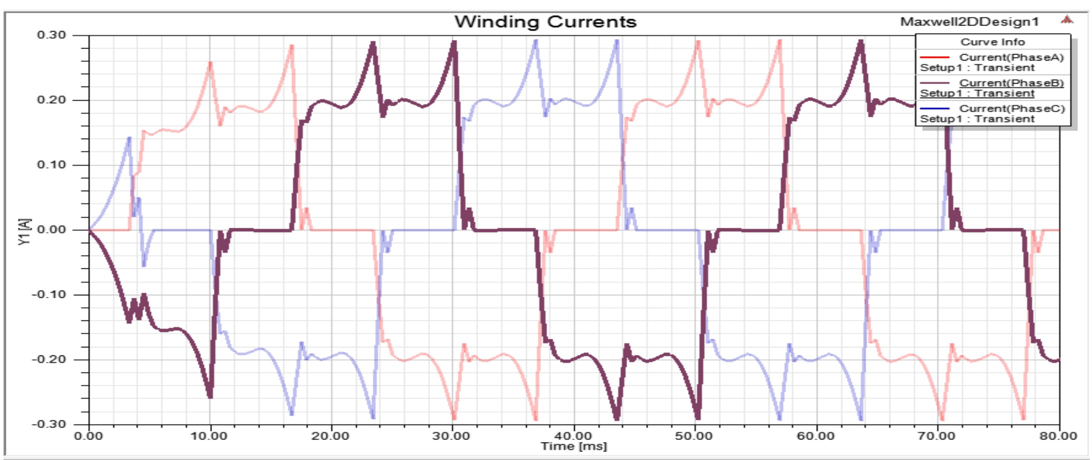

Figure 4.0: Simulated Phase B current windings with respect to reactance.

Figure 4.0 represents the simulated phase B current windings with respect to reactance of the motor. This movement started from the point zero and progressed to maximum of +30% and -30% in that order. The time range is from 0.00 to 80.0 ms. This is to affirm that the performance of BLDC motor is in an AC pattern.

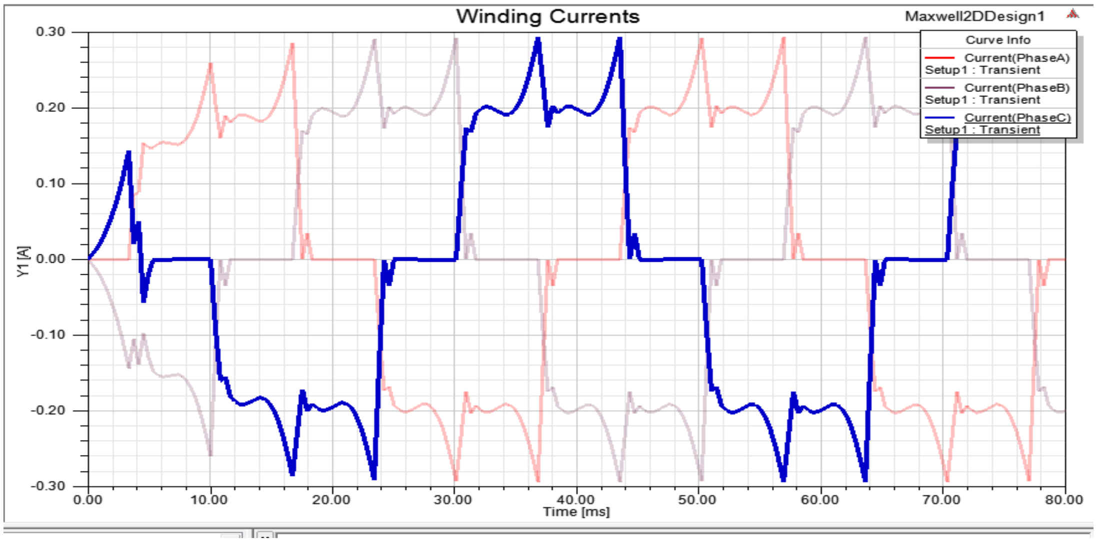

Figure 5.0: Simulated Phase C current windings with respect to reactance.

Figure 5.0 represents the simulated phase C current windings with respect to reactance of the motor, This movement started from the point zero and progressed to maximum of +30% and -30% in that order. The time range is from 0.00 to 80.0 ms. This is to affirm that the performance of BLDC motor is in an AC pattern.

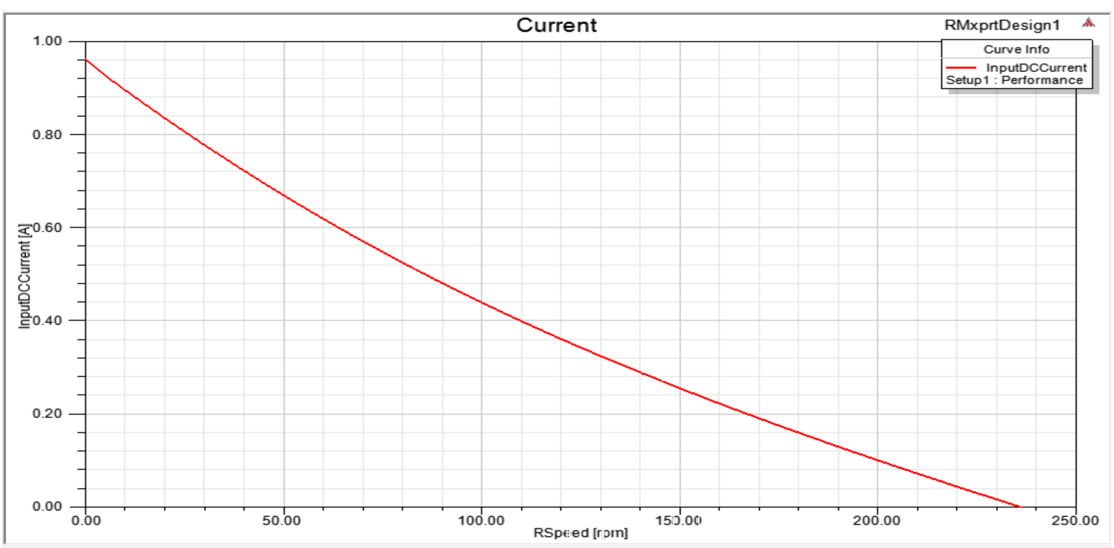

Figure 6.0: Simulated Phase input current windings with respect to reactance

In figure 6.0 is the simulated phase input DC current that gives rise to the different winding currents in the Maxwell 2D due to the transient's effect and the reactance within the BLDC motor. The maximum input DC current was 99% of the total current and the corresponding motor speed was 245rpm. This performance is ideal for the smooth running of a brushless DC motor.

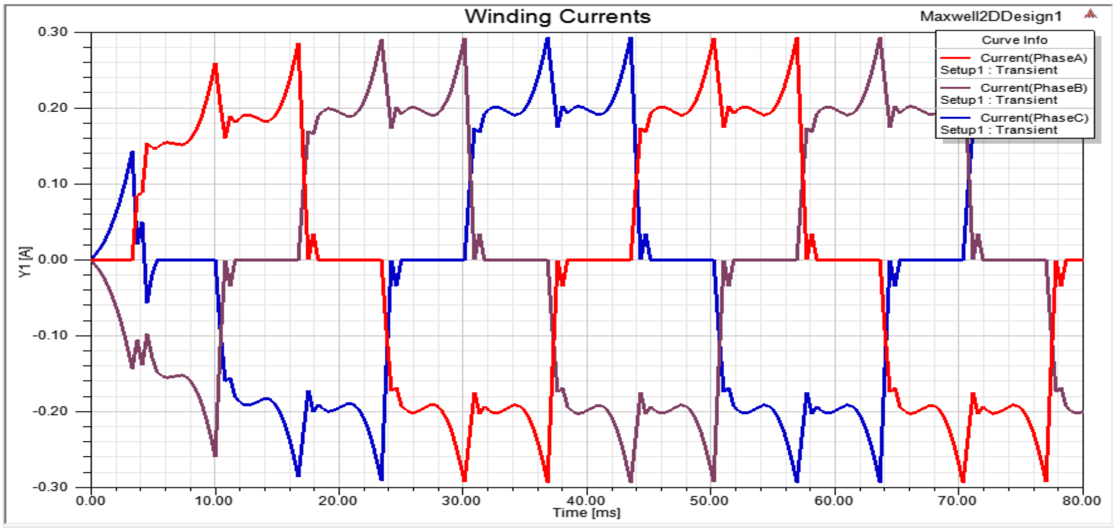

Figure 7.0: Simulated Phase A, B & C current windings with respect to reactance.

Figure 7.0 presents the simulated phase A, B & C current windings with respect to the motor reactance. The maximum and minimum display are at +30% and -30% respectively. This performance occurred at a corresponding time of 0.00ms to 80.0ms. The undulating propagation of the winding current is due to the motor's reactance effect. However, for a BLDC motor, this winding current effect under transient is uniformly distributed due to the absence of brush losses.

Figure 8.0: Simulated motor transient speed with respect to reactance.

In figure 8.0 is the simulated motor transient speed with respect to reactance. This speed is constant throughout the motor performance with respect to the time taken. The motor moving speed started from 185.75rpm and progressed to 187.75rpm as used in RMXPrt tools design of the selected motor. Under different commutations, this speed characteristics of the BLDC motor varies.

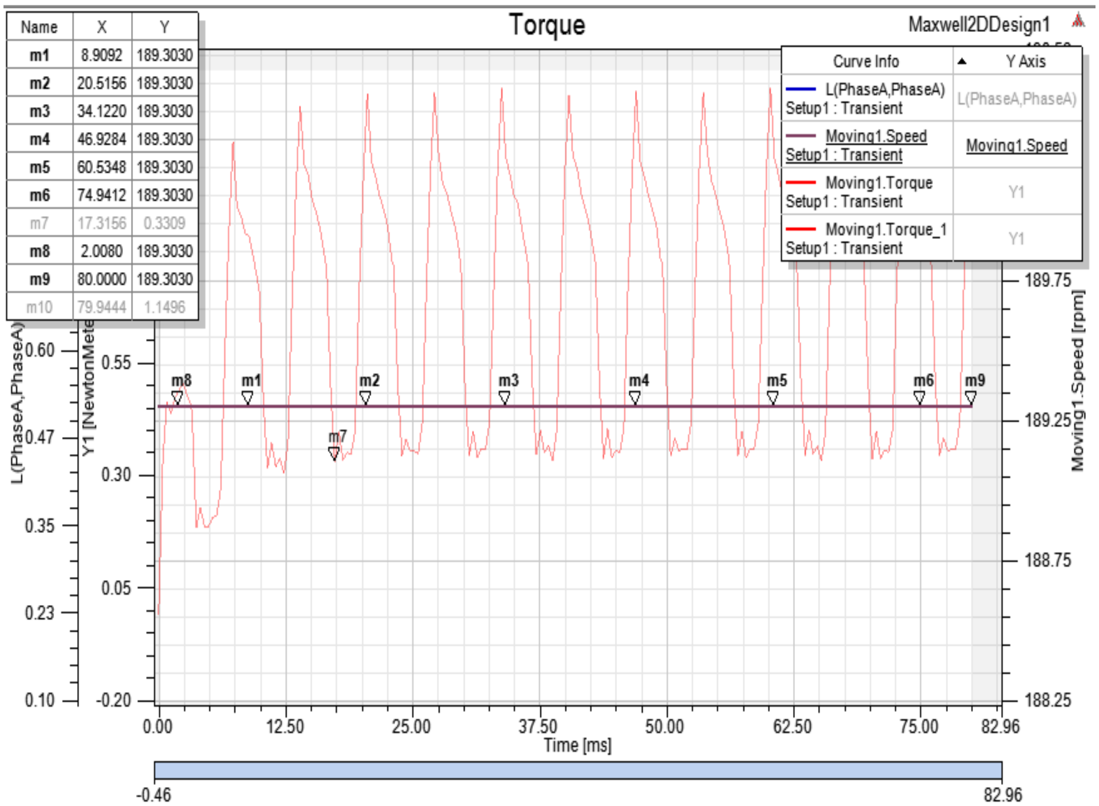

Figure 9.0: Simulated speed of BLDC under different commutation techniques.

In figure 9.0 is the simulated speed of BLDC under different commutation techniques. The different speed performance of the selected motor caused the different ripples represented by M1,M2,M3,M4,M5,M6,M7,M8,M9 and M10. Each of the techniques corresponds to 1% or 2% increment in the speed value. The time taken for this ranged from 0.00ms to 82.96ms. Since the maximum time taken is less than 100ms, then the system performance is commutatively ideal. The simulated results reflect the true physical performance of the BLDC motor under different commutation techniques

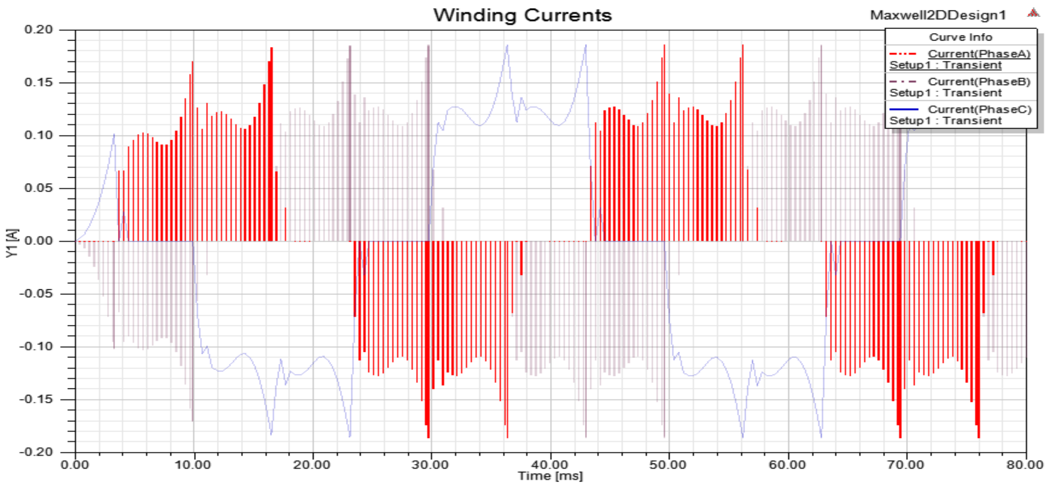

Figure 10. ce in phase A.

Figure 10.0 presents the simulated BLDC performance under FOC commutation with respect to reactance in phase A. The sections labeled with red are the affected phase A regions. Under the FOC speed control, the motor commutation produces bidirectional view with maximum performance at +20% and minimum at -20%. It takes a time frame of 80.0ms for this FOC commutation technique to realize. This entire process is due to the motor reactance.

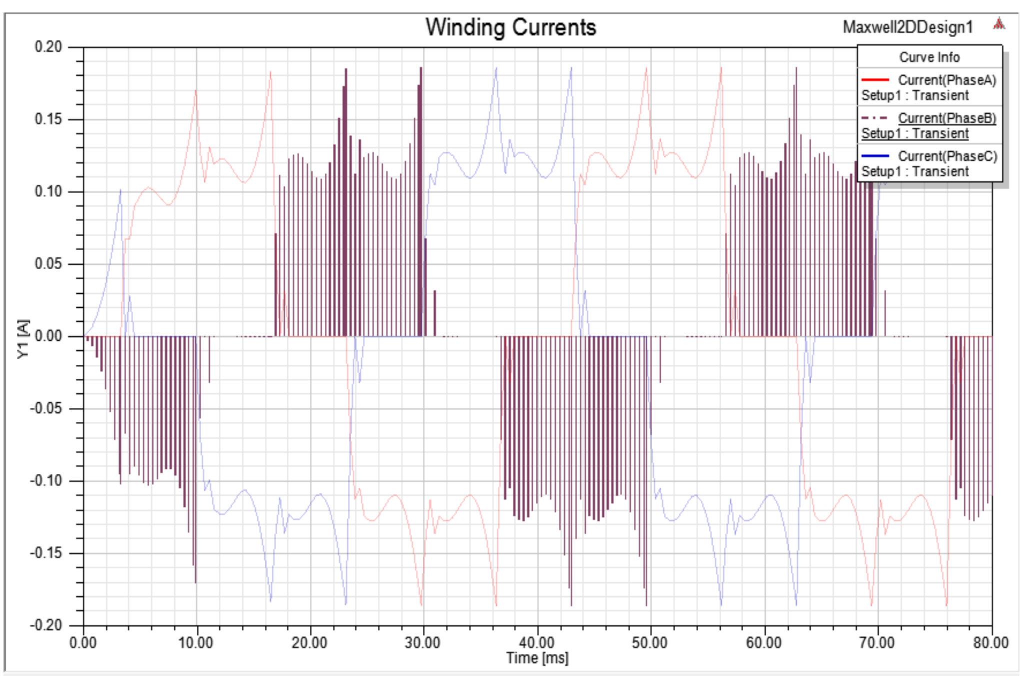

Figure 11.0*:* Simulated BLDC performance under Trapezoidal commutation with respect to reactance in phase B

Figure 11.0 presents the simulated BLDC performance under trapezoidal commutation with respect to reactance in phase B. The sections labeled with gray are the affected phase B regions. Under the trapezoidal speed control, the motor commutation produces bidirectional view with maximum performance at +20% and minimum at -20%. It takes a time frame of 80.0ms for this trapezoidal commutation technique to realize. This entire process is due to the motor reactance.

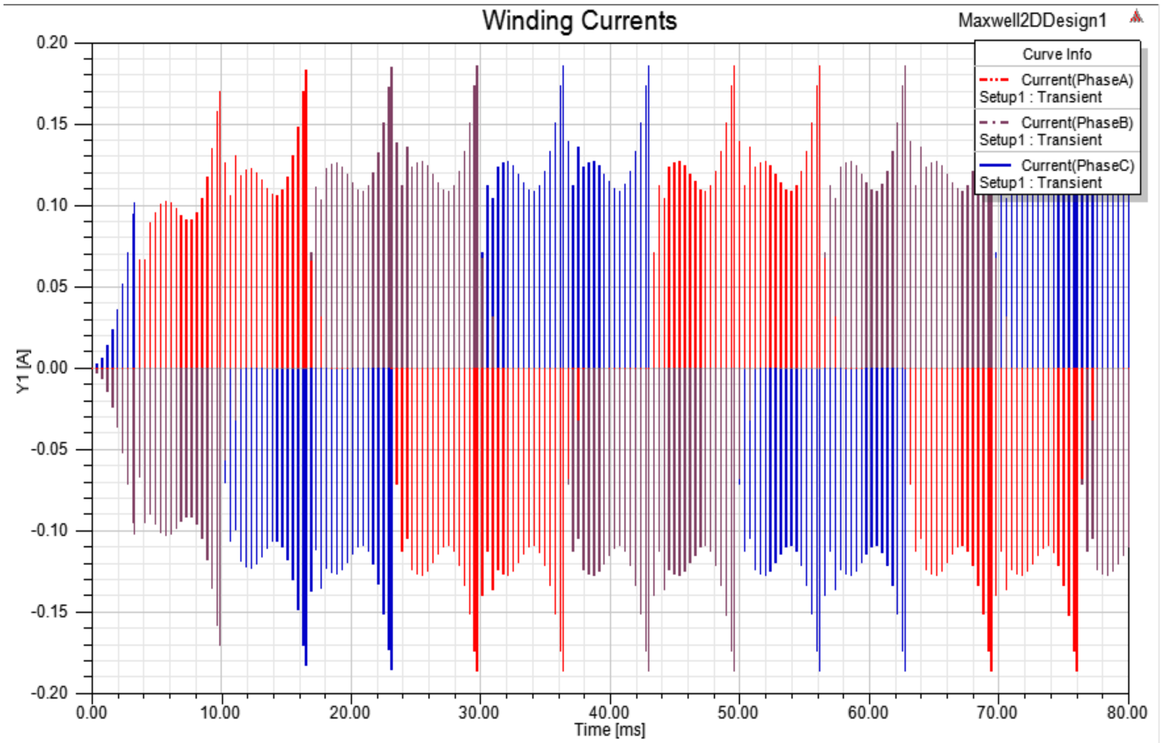

Figure 12.0: Simulated BLDC performance under Sinusoidal commutation with respect to reactance in phase C.

Figure 12.0 presents the simulated BLDC performance under sinusoidal commutation with respect to reactance in phase C. The sections labeled with red are the affected phase C regions. Under the sinusoidal speed control, the motor commutation produces bidirectional view with maximum performance at +20% and minimum at -20%. It takes a time frame of 80.0ms for this sinusoidal commutation technique to realize. This entire process is due to the motor reactance.

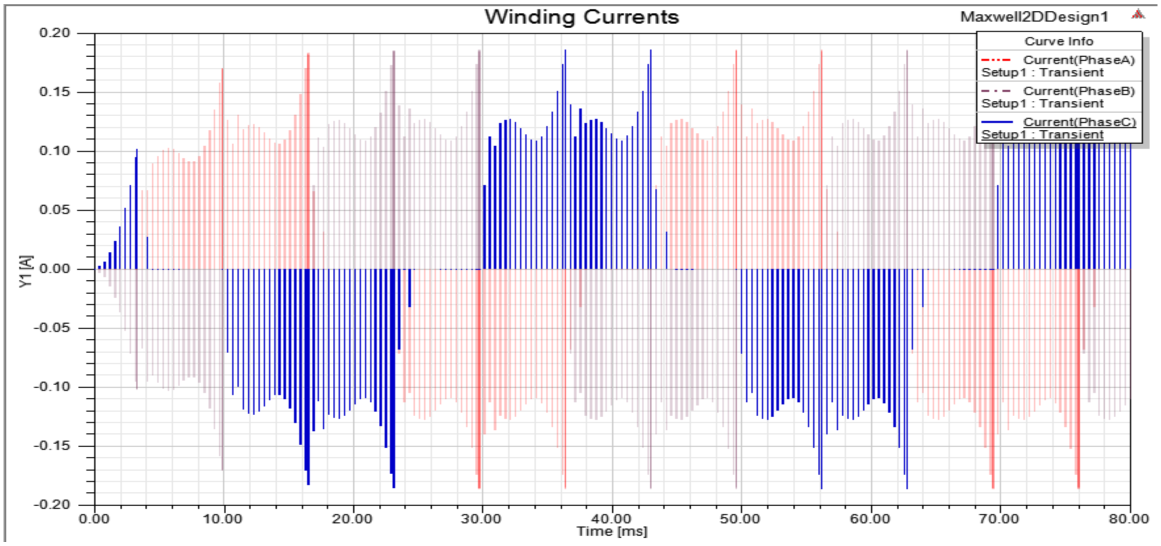

Figure 13.0: Simulated BLDC performance under FOC, Trapezoidal and Sinusoidal commutation with respect to reactance in phase A, B & C.

In Figure 13.0 is the simulated BLDC performance under FOC, Trapezoidal and Sinusoidal commutation with respect to reactance in phase A, B & C. This output form is due to its reactance. The time frame for this to occur was 80.00ms. The uniformity of these combined commutation techniques showed that BLDC motor can be effectively controlled.

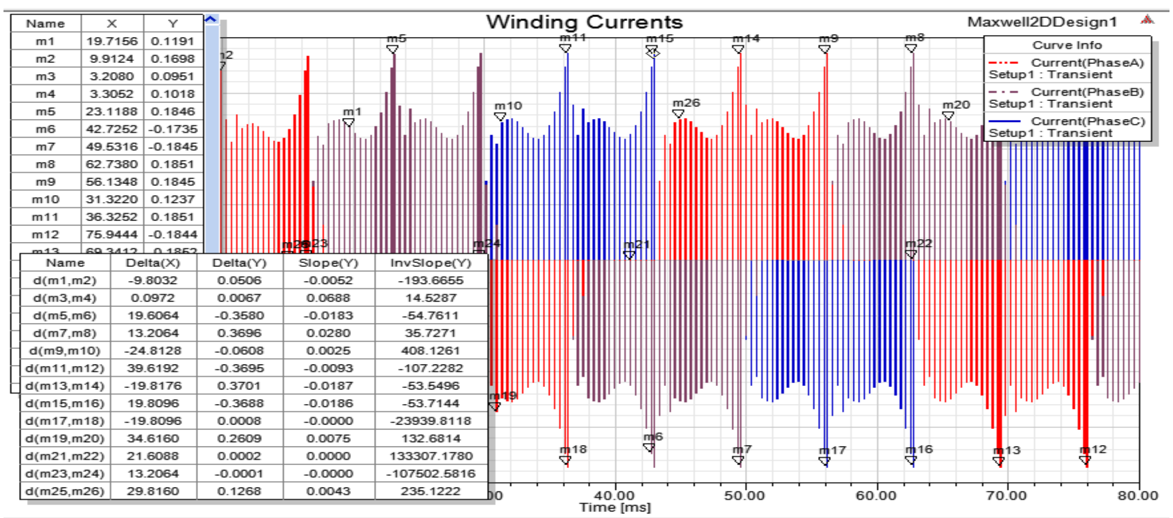

Figure 14.0: Simulated BLDC commutation performance with respect to reactance

In figure 14.0 is the simulated BLDC commutation performance with respect to reactance. These variations are presented as delta X and delta Y respectively. The different level of commutations are represented with M1,M2,M3,M4,M5,M6,M7,M8,M9,M10,M11,M12,M13,M14,M15,M16,M17,M18,M19,M20,2

1,M22,M23 and M24 respectively. The time for this reactance effect to occur on the motor performance was 80.0ms.

Conclusion:

Commutation effect and optimization of BLDC motor was carried out with respect to the different techniques such as field oriented control, trapezoidal control and sinusoidal control. To achieve the desired level of control, the trapezoidal commutation is selected as the best among the three compared controls methods.

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