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DESIGN AND SIMULATION CONTROL SPEED OF BRUSHLESS DC 7 HP USING DIRECT TORQUE METHOD WITH RIPPLE SUPPRESSION

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Abstract

The last decade, electric cars have grown so rapidly. One of the driving parts in electric cars is the Brushless DC Motor (BLDC). The use of BLDC motors is needed because this motor has low mechanical losses, this is because the motor does not use brushes. However, in operation, there is still a ripple that is complained by the control or drive of the motor so that the efficiency of the motor rotation output torque and speed is not perfect. One way to operate a BLDC motor is by direct torque control method. The Direct Torque Control method became popular for controlling BLDC motors because it provides a fast dynamic torque response, the variables controlled in this DTC are flux and torque. Direct torque control (DTC) is a method used to control torque and speed on a motor with a variable frequency drive (VFD). This method is a calculation that includes estimating motor flux and torque based on the voltage and current on the stator. In the stator, the flux is estimated based on the stator voltage while the torque is estimated from the stator flux estimator and motor current.The input values measured to the DTC control are the current and voltage of the motor. The torque output of this DTC has a fairly high ripple along with the application of a larger load so that changes in motor load affect ωr. Ripple Torque that affects the speed of the rotor must be given an additional circuit, namely Ripple Suppression. This additional circuit will suppress the ripple so that the torque and speed rotation of the BLDC motor will be better. Therefore, this research will discuss the design and simula tion of the BLDC motor using the direct torque control method with ripple suppression which is expected to produce more efficient output from the BLDC motor due to the torque ripples on the motor have been reduced by the ripple suppression circuit. From the research results, it can be seen that the efficiency of BLDC motors increases by 2 to 3 percent at starting time and increases by around 1.5 percent at steady state.

1. Introduction

There are several methods in controlling BLDC motors, namely the six-step method and the sinusoidal method. The six-step method is the method most often used, but this method is quite simple so it is easy to implement, this method is called six-step because it is able to convert sinusoidal waves into trapezoidal or square waves that resemble sinusoidal waves. The second method is the sinusoidal method where this method creates a sinusoid wave to grind the motor by generating a rotating field on the BLDC motor, this control gets data input from the hall sensor to regulate the provision of sources to the stator. However, the two methods still have shortcomings, for the six-step method there is a high RMS or Root Mean Square, this is because the PWM used in this method is a PWM square with a certain frequency which results in AC waves that are blocked by trapezoids. The sinusoidal method has disadvantages including a complicated algorithm in generating sinusoidal PWM signals and then greater losses of drive switching. From the two methods, both still have ripples found at the output of the controller before entering the BLDC motor.

Seeing the disadvantages of the existing method, one of the motor operating techniques is direct torque control (DTC), compared to the two existing methods, DTC has an advantage which makes up for the weaknesses of both existing methods, one of the advantages of DTC is that it does not require PWM pulse generation, another advantage is that DTC can run without the need for coordinate transformation and current regulators (Salah et al., 2011) . DTC is a technology with a sensor less type, this technique is also a close loop control type where this control will provide feedback that makes the output a comparison with the input to obtain an error. However, the output of DTC still produces torque ripples or torque ripples along with the increasing load, this is because the inputs measured by DTC are currents and voltages with variables used are torque and flux. So that the DTC must be added a series of ripple suppression with the aim that the ripple torque produced will be suppressed so that the rotation of the BLDC motor can be more perfect.

The design and Hardware In Loop (HIL) verification of a novel intelligent Super-twisting Sliding Mode Speed Controller (STSMSC) based on a Sugeno-Takagi Fuzzy Logic System (STFLS) for an induction motor controlled by an improved Modified Direct Torque Control (MDTC) approach. Indeed, Conventional Super-twisting Sliding Mode Speed Controller (CSTSMSC) is chosen as an alternative solution for attenuating the chattering phenomenon brought on by the discontinuous control law of the First Order Sliding Mode Speed Control

(FOSMSC) and maintaining its advantages like simplicity, robustness and accuracy. Moreover, the STSMSC is a type of a second order sliding mode control technique that needs only the information about the sliding surface, not its time derivative. However, the choice parameters of the CSTSMSC existing in the control law effects the tracking accuracy, the overshoot and the amplitude of the chattering. Therefore, an STSMSC based on an STFLS (STFLS-STSMSC) is proposed for online tuning of these parameters in transient and steady state operations. In fact, the STFLS is considered as an intelligent supervisor to adjust these parameter values according to the system state, which consequently provides excellent performance consisting in a higher robustnessrate under disturbances and uncertainties, tracking with excellent accuracy and reduced chattering in steady state and transient operations. Numerous simulation and HIL co-simulation results are presented to demonstrate the effectiveness of the suggested STFLS-STSMSC based MDTC implemented on a Xilinx FPGA Zynq 7000 SoC ZC702 (Krim & Mimouni, 2023).

Machine learning (ML) based methods are used to estimate rotor mechanical speed of brushless direct current (BLDC) motors. Training performances of approaches such as Artificial Neural Network, k-Nearest Neighbor, and Random Forest in the ML-based speed estimator are tested using the datas obtained from the direct torque control (DTC) drive system of BLDC motor in simulation and it is seen that the ANN approach has the highest accuracy. In addition, a novel extended Kalman filter (EKF)-based estimator is proposed for the estimation of back-EMFs of BLDC motor. A hybrid estimation method is proposed by using the developed ML- based speed estimator with the proposed EKF-based estimator and its estimation performance is tested in simulation on DTC drive system (İnan et al., 2023).

Direct Torque Control (DTC) of Induction Motors (IMs) is popular in motor drive applications because of its robust and simple control structure. The IM winding can be controlled on both sides using dual inverter technique which more effective for Electric Vehicle (EV) with a greater number of voltage vectors. However, the battery performance of the dual inverter will deteriorate unevenly on both sides, resulting in fluctuating voltages for the EV system. This will lead to the generation of distorted stator currents and a significant droop in the stator flux, which in turn can increase the total harmonic distortion (THD) in the system. Additionally, the performance of torque may not be able to regulate effectively. This paper examines the effect of unstable voltage on voltage vector mapping performance with tilted angles and proposes new sector definitions based on voltage ratio conditions. Moreover, the proposed sector for each predefined voltage ratio is tested under three-speed conditions. The proposed technique effectiveness is validated through hardware experiments using a dSPACE 1104 controller and retuning the stator current for proper waveform. This approach improves the stator current waveform, improves stator flux droop, enhances torque regulation and minimizes the THD in the DTC system (Aihsan et al., 2023).

In this research we suggest using a circuit to reduce voltage and current harmonics thereby reducing ripples in motor torque using direct torque control. From this research we will look at the efficiency of BLDC motors before and after being given ripple suppression.

2. Literature Studies

2.1. Direct Torque Control

Direct torque control (DTC) is a method used to control torque and speed in a motor with variable frequency drive (vfd). This method is a calculation that includes an estimate of the motor flux and torque based on the voltage and current on the stator. In a stator, the flux is estimated based on the stator voltage while the torque is estimated from the stator flux estimator and the motor current (Mukti, 2014). The electro-magnetic torque of the brushless DC machine (BLDC) synchronously rotates which can be written with the equation:

$$Te = \frac{3}{2}\frac{p}{2}(\varphi\beta i\alpha - \varphi\alpha i\beta) \qquad (2.1)$$

Te = Electromagnetic Torque (Nm)
i = Current (amperes)
φ = Stator Flux
P = Pole
3/2 = Abc to alpha beta constant

DTC consists of several main parts including inverter, stator flux, torque estimator and switching table. The switching table for BLDC motors can be seen in the table below of the continuous security disturbances in the system.

Table 1. Table Switching DTC

Torque τ	Flux ϕ	Sector I	II	III	IV	V	VI
1	1	V_1 (100001)	V_2 (001001)	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)
	0	$\mathbf{V_2}$ **(001001)**	$\mathbf{V_3}$ **(011000)**	$\mathbf{V_4}$ **(010010)**	$\mathbf{V_5}$ **(000110)**	$\mathbf{V_6}$ **(100100)**	$\mathbf{V_1}$ **(100001)**
	-1	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)	V_1 (100001)	V_2 (001001)
0	1	V_1 (100001)	V_2 (001001)	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)
	0	$\mathbf{V_0}$ **(000000)**	$\mathbf{V_0}$ **(000000)**	$\mathbf{V_0}$ **(000000)**	$\mathbf{V_0}$ **(000000)**	$\mathbf{V_0}$ **(000000)**	$\mathbf{V_0}$ **(000000)**
	-1	V_3 (011000)	V_4 (010010)	V_5 (000110)	V_6 (100100)	V_1 (100001)	V_2 (001001)

The Table 1 above can be presented with an inverter which becomes a switch on the BLDC motor drive with the DTC method depicted in the figure below.

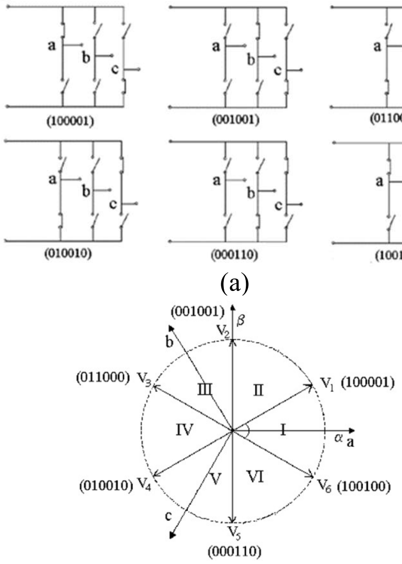

Figure 1. (a) and (b) Nonzero-voltage chambers in BLDC motors

In the BLDC motor drive, there are only 2 phases that transmit an angle of 120°, except during the turnover period. Figure 1 (a) shows the six digits required to represent the status of the inverter switch where one digit represents to switch the status of the inverter switch. The space vector on the inverter is presented as switching signals (100 001), (001 001), (011 000), (010 010), (000110), and (100 100). The numbers represent the status of the upper and lower switching signals for 2 alternating phases. For the number (000 000) denotes the zero voltage chamber (Liu et al., 2005).

BLDC motors have a trapezoidal ideal back-EMF with a flat top with an angle of 120°, one side of the current sensor on the dc link can be used to estimate torque by knowing the sectors of the hall-effect torque sensor. Placing the sensor on a non-sinusoide surface on the permanent magnet of the motor can achieve a more accurate estimate of torque (Montazeri & Khaburi, 2010).

2.2. BLDC MOTOR

BLDC motor is an AC synchronous motor with permanent magnets on the rotor (moving parts) and windings on the stator (stationary part). These permanent magnets create rotor fluxes and stator windings that are energized giving rise to electromagnet poles. The magnetic field generated by the rotor rotates at the same frequency. BLDC motors even though they include AC synchronous electric motors but are still referred to as BLDC because in its implementation, BLDC still uses a DC source as the main source which is then converted into AC voltage using a 3-phase inverter (Welekar and Apte, 2014).

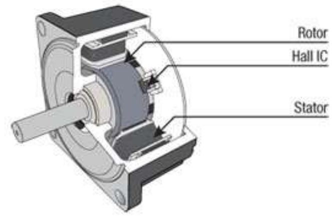

Figure 2. BLDC Motor

These three hall effect sensors are used to obtain 6 different timing combinations, this combination is used for the commutation process where the motor will detect an angle every 60° to produce three signals to create switching pulses so that the magnet will change or regulate the commutation of the power flowing on the stator.

2.3. Torque Ripple On BLDC Motor

Ripple torque is the main factor that affects the performance of a motor, the cause of a ripple on a permanent magnet in this case BLDC is cogging, harmonic flux magnets and errors in current delimitation. Cogging is the torque generated by the shaft when the rotor rotates against the stator, cogging is also an inherent characteristic of the motor. Electromagnetic torque can be expressed by the formula below (Liang et al., 2020).

$$T_e = T_{e0} + \Delta T_e \qquad (2.2)$$

BLDC motor is a motor with electronic commutation through the change of the power electronic switch. The result of the commutation gives rise to electromagnetic torque, the electro-magnetic torque produced contains ripples in the form of waves. This torque ripple produces noise that can reduce motor performance and complicate speed control characteristics, especially at speed (Arunkumar & Thangavel, 2015).

2.4. Torque Ripple Suppression

The torque ripples contained in the BLDC motor will limit torque performance. Torque ripples can arise by three main factors such as motor construction, motor performance and control of the motor (Salah et al., 2011). There are several techniques to suppress and minimize torque ripples in BLDC motors based on experts including:

a) Modifying PWM Control

The BLDC motor moves every 60°, the magnetic field circulates unevenly and jumps every 60° resulting in uneven torque. Based on the results of the study, reducing torque ripples when the BLDC motor commutes can use PWM on PWM mode (Meng et al., 2009). Another method of reducing torque ripples can be by controlling the turnover time by strategizing the time where the interval of switching from the incoming and outgoing phases can be equated with proper PWM control (Basu et al., 2009).

b) Bus DC Voltage Control

The torque ripple in the BLDC motor can be reduced by varying the input voltage. The varied input voltage can reduce the current ripples occurring within the conduction region (Ki-Yong Nam et al., 2006).
Another method to reduce torque ripples by using multistage DC inverters for low-inductance BLDC motors. This multistage DC inverter can compress and dredge ripples for BLDC motor drive (Gui-Jia Su & Adams, 2001).

c) Torque Control Techniques

The torque control technique for BLDC motors can be through the events, namely direct torque control (DTC) and torque control method. The electromagnetic torque in PMSM (BLDC) is proportional to the angle between the stator and rotor fluxes, so a high dynamic response can be achieved using DTC, with low frequency compared to PWM control (Zhu et al., 2005).

The above methods and techniques are some techniques for torque ripple reduction that can reduce the performance of the BLDC motor.

3. The System

3.1. BLDC Motor Speed Control System Using Direct Torque Control Method

The block diagram scheme for the BLDC motor speed control system using the direct torque control method can be seen in the picture below.

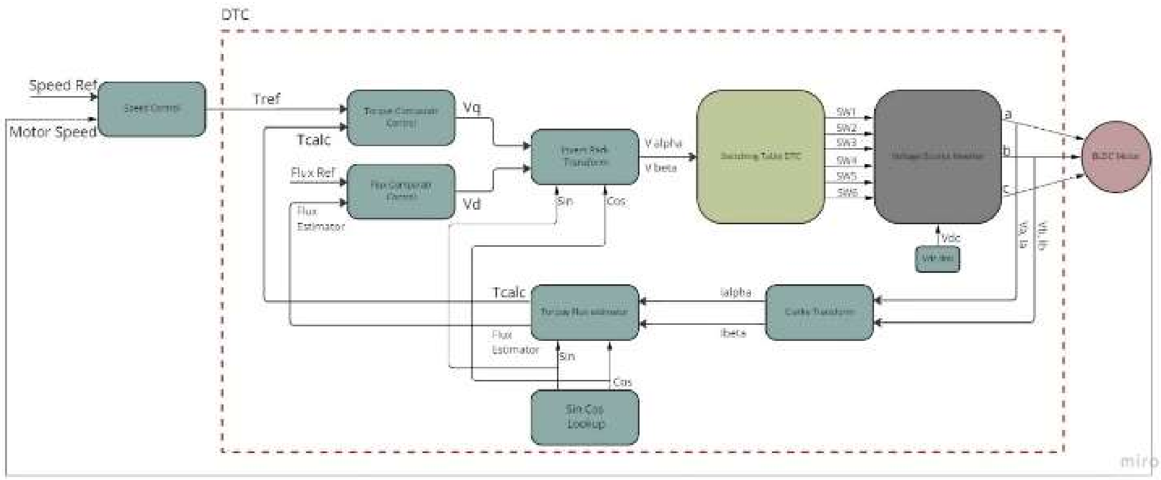

Figure 3. DTC Block Diagram

Reference torque and reference flux are determined as a reference in the calculation of torque and flux before entering the table switching direct torque control as a switch for the inverter.

The result of flux and Iq, Id generates torque by using the torque formula.

$$Te = \frac{3}{2}\frac{p}{2}(\varphi\beta i\alpha - \varphi\alpha i\beta)$$

Te	= Electromagnetic Torque (Nm)
i	= Current (amperes)
φ	= Stator Flux
P	= Pole
3/2	= Abc to alpha beta constant

To calculate a flux using a formula

$$\psi_\alpha = Ls.i_\alpha + \psi_m.cos\theta \quad (3.4)$$

$$\psi_\beta = Ls.i_\beta + \psi_m.sin\theta \quad (3.5)$$

$$\psi = \sqrt{\psi_\alpha^2 + \psi_\beta^2} \quad (3.6)$$

ψ_α	= Flux rotor along the axis α (Weber)
ψ_β	= Flux rotor along the axis β (Weber)
ψ	= Flux rotor (Weber)
i_α	= Motor current α-axis (amperes)
i_β	= βMotor current -axis (amperes)

3.2. System Specification

The BLDC motor speed control system using the direct torque control method has several components that must be inputted specifications according to the original specifications in the market so that the simulation results can be close to real conditions. The component that can be inputted specifications is the BLDC motor.

1. BLDC Motor Specification

The BLDC motor used is a BLDC with a capacity of 5 KW or 7 HP, so that the maximum output of the simulation is 5 KW or 7 HP. Bldc motor specifications can be seen in the table below:

Table 2. BLDC Motor Specifications

Quantities	Specification
Voltage	72 Volt
Power	5 KW
Effiiency	91%
Resistor Phasa	12 mΩ
Induktor Phasa	154 uH
Speed	2000-6000 RPM
Weight	11 Kg
Length Width	126 mm, 206 mm
Pole	4

The value in the Table 2 above is the specification of a motor with a golden brand with an axial capacity of 5 KW.

2. Input Voltage Specification

A BLDC motor is a motor with a voltage input in the form of a direct voltage (DC) which is converted into a three-phase voltage by an inverter because the BLDC motor has a three-phase voltage on the stator connected to a permanent magnet. Based on the specifications, the voltage of the BLDC 5 KW motor is 72 Volts, so that the circuit is supplied with a unidirectional source (DC) with a value of 72 Volts.

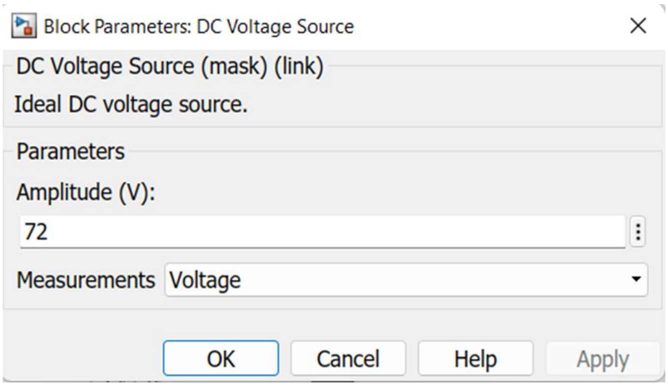

Figure 4. Voltage Input Specification

The direct torque control scheme is the calculation and estimation of the output of the motor and its reference. In the DTC subsystem, there are two subsystems, namely speed regulators and flux and torque calculations. The inputs of the main subsystems of DTC are three-phase stator voltage (Vabc), three-phase current (Iabc), input DC voltage, reference speed (Wref), motor output speed (Wm) and reference flux.

The output of this direct torque control scheme is the reference voltage (Vref), angle voltage d and q (VdVq), torque and flux. Reference voltage is a calculation of torque and flux using PID, the voltage will enter to block space vector modulation (SVM) or space vector pulse width modulation (SVPWM) which is a table switching process to produce pulses and is connected to the inverter as an input voltage regulator to the BLDC motor.

There is one subsystem to measure the output value on the motor such as speed, torque, output power, and efficiency of the motor. The output power of the motor is obtained from the values of magnetic electric torque (N.m) and the resulting speed (RPM).

3.3. Design Simulation System

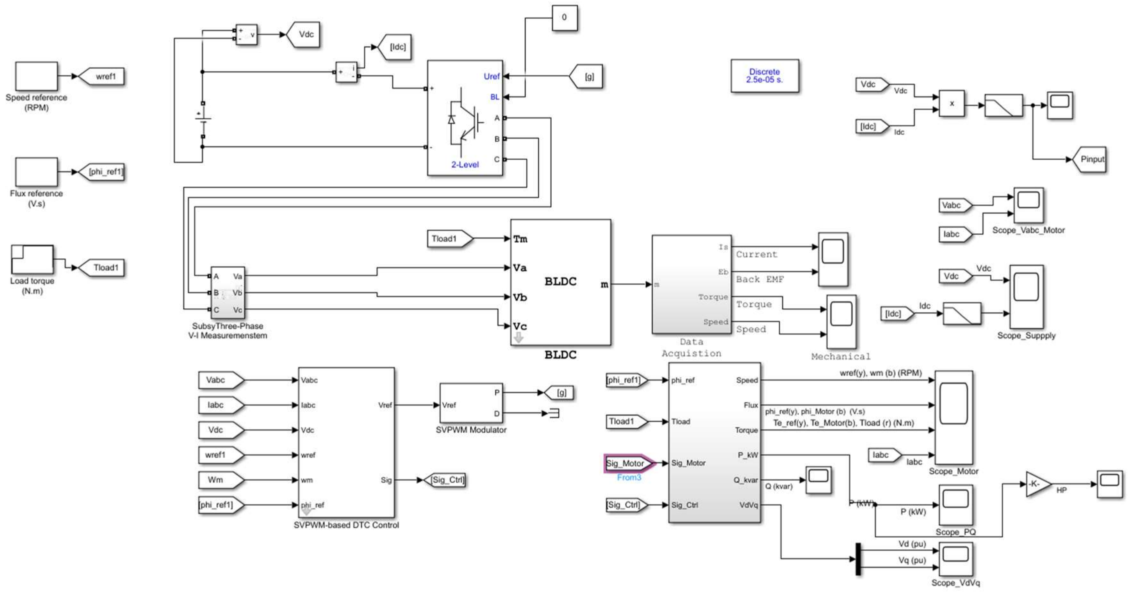

Figure 5. DTC Schematic

The simulation system for BLDC motor speed control using the direct torque control method is designed using the Simulink matlab application. All components are taken from the base workspace located in simulink or mathworks.

The overall design of the system shows the systems and subsystems connected in the simulation circuit.

$$P_{out} = Te \times \omega \qquad (3.1)$$
$$P_{out} = Te \times \left(Nr \times \frac{2\pi}{60}\right) \qquad (3.2)$$

Pout = Output power (Watt)
Te = Electromagnetic Torque (N.m)
ω = Speed (rad/s)
Nr = Speed (RPM)

The efficiency of a motor can be calculated if it has the values of input power and output power. So that efficiency is a comparison of the power output of the motor used against its total power output.

$$\eta = \frac{Pout}{Pin} \qquad (3.3)$$

η = Efficiency
$Pout$ = Output Power (Watts)
Pin = Input Power (Watts)

4. Result

The data analyzed are the results of simulations before and after ripple suppression is given. There are three conditions, namely the condition of the no load motor, the condition of the motor with constant torque but increasing speed, and the condition of the motor with torque changing but constant speed.

a) No-load Condition

The condition of the no-load motor is that we do not give a load to the motor so that in the simulation the load torque is given a value of zero. The torque value of the motor cannot be equal to zero but it has a very small value.

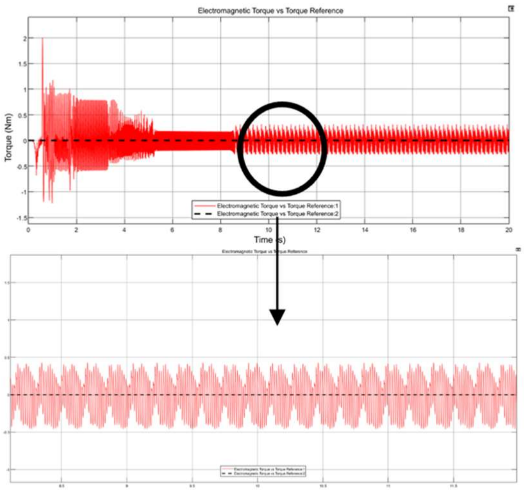

Figure 6. Torque Graph Before Ripple Suppression

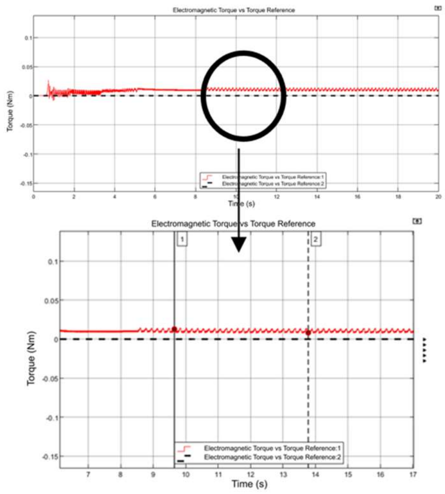

Figure 7. Torque Graph After Giving Ripple Suppression

Based on the torque graph before and after ripple suppression is given, the difference in the values of the two can be seen in the table below.

Table 3. No-load Condition Result

Torque Reference (Nm)	Motor Torque (Before)	Motor Torque (After)
0	0.01	0.009

The speed under no-load conditions is given a reference speed of 6000 RPM, so the results when the motor before and after are given ripple suppression are as follows.

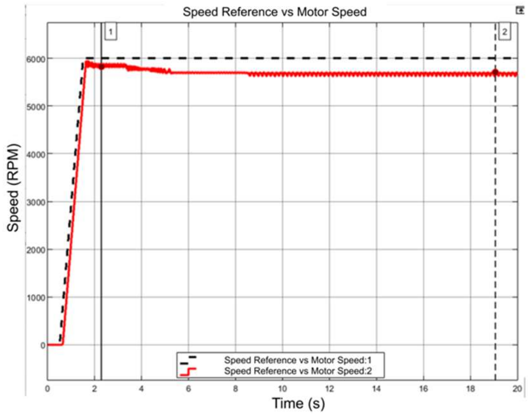

Figure 8. Speed Graph Before Ripple Suppression Is Given

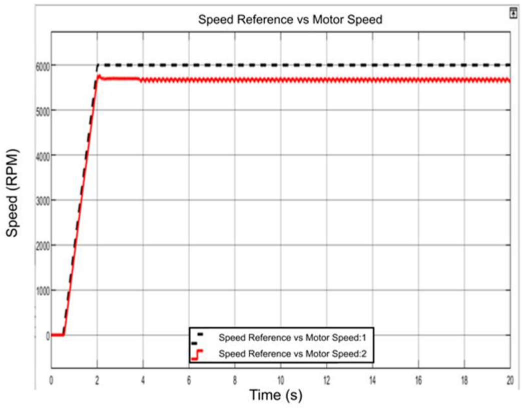

Figure 9. Speed Graph After Applying Ripple Suppression

From the two charts above, the value of the speed before and after the ripple suppression is obtained as follows.

Table 4. Speed Data of No-load Motor Condition

Reference Speed (RPM)	Motor Speed (Before)	Motor Speed (After)
6000	5707	5712

The value of speed and torque generally has an effect on the output power, the difference between the output power before and after being given ripple suppression is as follows.

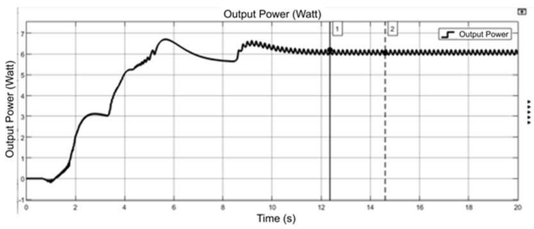

Figure 10. Graph of Output Power Before Giving Ripple Supression

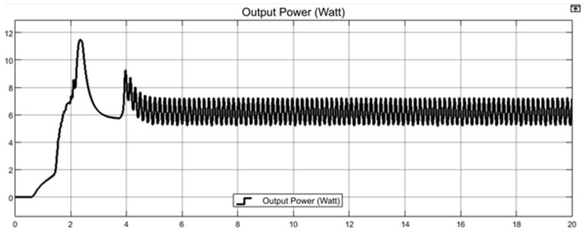

Figure 11. Graph of Output Power After Giving Ripple Suppression

From both graphs of output power at no-load it is seen that the graph before given ripple suppression has a faster transient value, this can happen due to the influence of ripple on torque and speed. So that from the conditions after the transient, the following speed data is obtained.

Table 5. Power Out Put Data of No-Load Condition

Output Power (watts) (before)	Output Power (watts) (After)
6.12	6.14

The input power in the simulation was obtained at 612.8 Watts with a voltage of 72 volts and a current of 8.54 Amperes. From the input power and output power data, the efficiency values before and after ripple suppression are given as follows.

Table 6. Efficiency of No-Load Condition

Effisiensi (Before)	Effisiensi (After)
0.99%	1.01%

b) Constant Torque and Increased Speed Condition

The condition of the motor is constant torque with the speed changing, in this condition then the motor speed value will try to approach the given reference speed value. The torque given is a constant of 3 Nm with a speed change of 0-4000 RPM for 20 seconds.

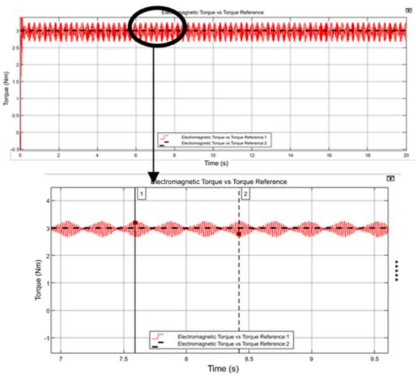

Figure 12. Torque Graph Before Ripple Suppression

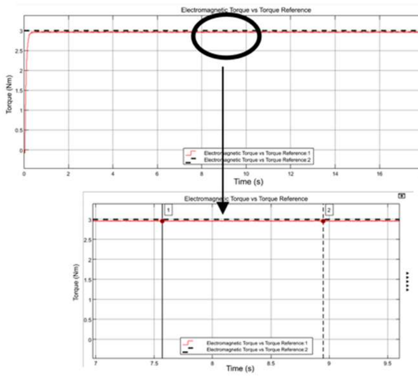

Figure 13. Torque Graph After Giving Ripple Suppression

Based on the torque graph before and after ripple suppression is given, the difference in the values of the two can be seen in the table below.

Table 7. Torque Data of Constant Torque and Increased Speed Condition

Reference Torque (Nm)	Motor Torque (Before)	Motor Torque (After)
3	2.98	2.95

The current speed of this condition is given a reference speed of 0-4000 RPM for 20 seconds, so that the results when the motor before and after are given ripple suppression are as follows.

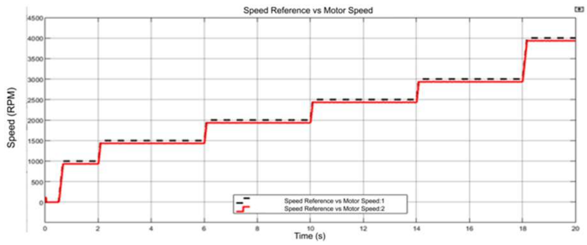

Figure 14. Speed Graph Before Giving Ripple Suppression

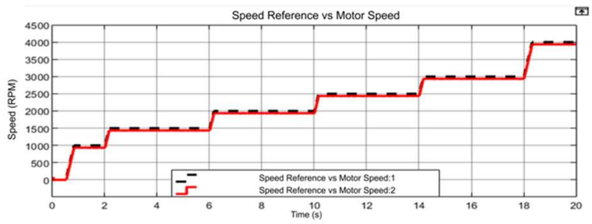

Figure 15. Speed Graph After Giving Ripple Suppression

The chart above does not show a noticeable difference because the RPM increase is only slightly. From the two charts above, the value of the speed before and after the ripple suppression is obtained as follows.

Table 8. Motor Speed Data of Constant Torque Speed Change Condition

Time (seconds)	Reference Speed (RPM)	Motor Speed (Before)	Motor Speed (After)
0 - 0.5	0	0	0
0.5 - 2	1000	931	932.7
2 - 6	1500	1434	1433
6 – 10	2000	1930	1933
10 – 14	2500	2432	2433
14 – 18	3000	2942	2946
18 - 20	4000	3931	3933

The value of speed and torque generally has an effect on the output power, the difference between the output power before and after being given ripple suppression is as follows.

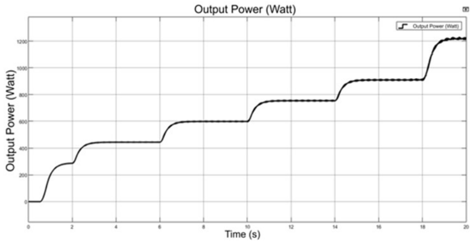

Figure 16. Graph of Output Power Before Giving Ripple Supression

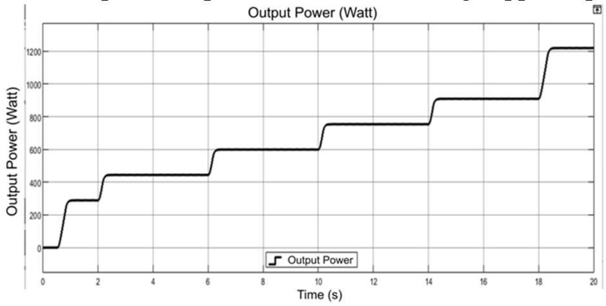

Figure 17. Graph of Output Power After Giving Ripple Suppression

From both output power charts on this condition, it can be seen the chart before given ripple suppression has ripple. So that from this condition, output power data for 20 seconds is obtained as follows.

Table 9. Output Power Data of Constant Torque Speed Changed Condition

Time (seconds)	Output Power (watts) (before)	Output Power (watts) (after)
0- 0.5	0	0
0.5 - 2	257.3	289.1
2 - 6	447	444.2
6 – 10	599.1	599
10 – 14	758.7	754.2
14 – 18	910.5	909
18 - 20	1206	1219

The input power in the simulation was obtained at 1303.2 Watts with a voltage of 72 Volts and a current of 18.1 Amperes. From the input power and output power data, the efficiency values before and after ripple suppression are given as follows.

Table 10. Efficiency Value of Condition Constant Torque Speed Change Condition

Time (seconds)	Efficiency (before)	Efficiency (after)
0 - 0.5	0	0
0.5 - 2	21.89%	24.6%
2 - 6	34.31%	34.1%
6 – 10	45.98%	45.97%
10 – 14	58.21%	57.86%
14 – 18	69.89%	69.77%
18 - 20	92.25%	93.57%

c) Changing Torque and Constant Speed Condition

The condition of the torque motor changes at a constant speed, generally when the motor is given a continuously increasing load torque, the speed value will continue to decrease. However, with the torque response of the DTC system so that the speed can be controlled so that it can still follow the reference speed. The reference speed is worth a constant of 4000 RPM with torque growing from 2-5 Nm for 20 seconds.

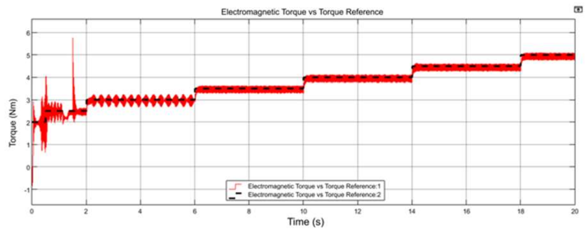

Figure 18. Torque Graph Before Ripple Suppression

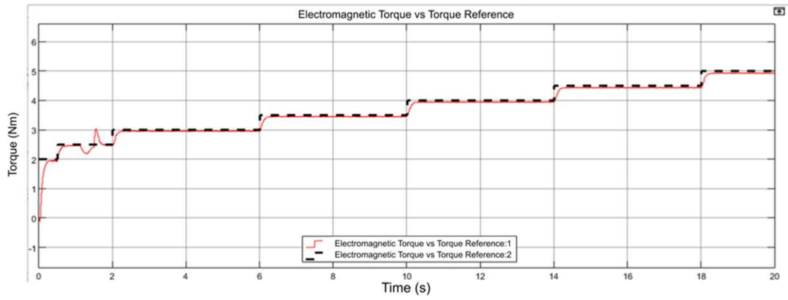

Figure 19. Torque Graph After Giving Ripple Suppression

Based on the torque graph before and after ripple suppression is given, the difference in the values of the two can be seen in the table below.

Table 11. Torque Motor Data of Torque Changing Constant Speed Condition

Time (seconds)	Reference Torque (Nm)	Motor Torque (Before) (Nm)	Motor Torque (After) (Nm)
0, - 0.5	2	2.01	1.93
0.5 - 2	2.5	2.3	2.21
2 - 6	3	2.95	2.96
6 – 10	3.5	3.44	3.45
10 – 14	4	3.95	3.95
14 – 18	4.5	4.43	4.46
18 - 20	5	4.92	4.95

The current speed of this condition is given a reference speed of 4000 RPM for 20 seconds, so that the results when the motor before and after are given ripple suppression are as follows.

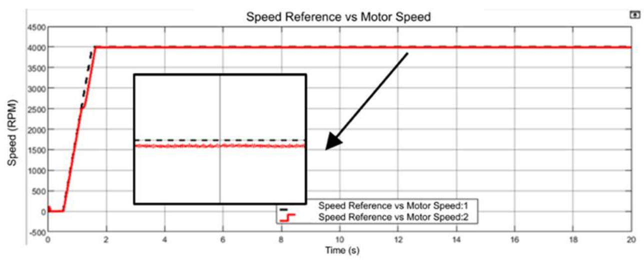

Figure 20. Speed Graph Before Ripple Suppression Is Given

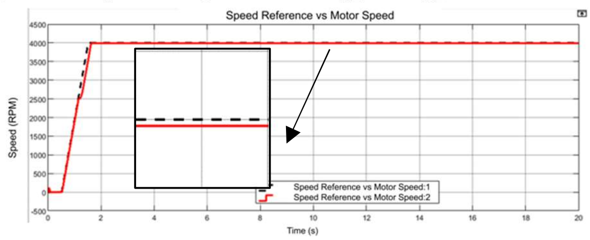

Figure 21. Speed Graph After Giving Ripple Suppression

The chart above does not show a noticeable difference because the RPM increase is only slightly. From the two charts above, the value of the speed before and after the ripple suppression is obtained as follows.

Table 12. Motor Speed Data of Torque Change Constant Speed Condition

Time (seconds)	Reference Speed (RPM)	Motor Speed (Before)	Motor Speed (After)
0 - 0.5	0	0	0
0.5 - 2	4000	2595	2593
2 - 6	4000	3993	3995
6 – 10	4000	3990	3992
10 – 14	4000	3989	3989
14 – 18	4000	3990	3992
18 - 20	4000	3991	3993

The value of speed and torque generally has an effect on the output power, the difference between the output power before and after being given ripple suppression is as follows.

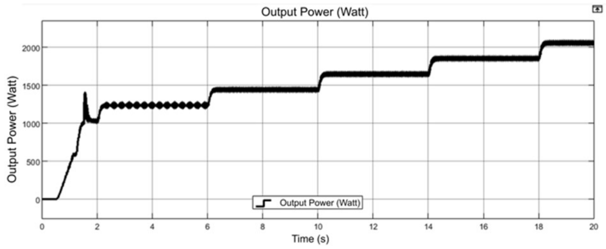

Figure 22. Graph of Output Power Before Giving Ripple Supression

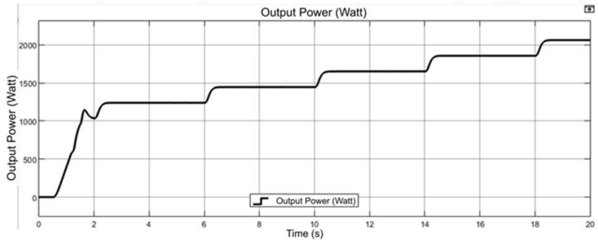

Figure 23. Graph of Output Power After Giving Ripple Suppression

From both output power charts on this condition, it can be seen the chart before given ripple suppression has ripple. So that from this condition, output power data for 20 seconds is obtained as follows.

Table 13. Power Output Data of Torque Change Constant Speed Condition

Time (seconds)	Output Power (watts) (before)	Output Power (watts) (after)
0- 0.5	0.0166	0
0.5 - 2	624.7	616
2 - 6	1232.9	1239
6 – 10	1436.6	1445
10 – 14	1649.18	1651
14 – 18	1850.05	1857
18 - 20	2055.2	2062

Input Power in the simulation results has different values along with the addition of torque to the motor, so that the motor efficiency values obtained from input power and output power can be seen in the table below.

Table 14. Motor Efficiency Value of Torque Changing Constant Speed Condition

Time (seconds)	Efficiency (before)	Efficiency (after)
0- 0.5	0	0
0.5 - 2	52.89%	52.15%
2 - 6	70.89%	71.24%
6 – 10	73.78%	74.21%
10 – 14	75.92%	76.01%
14 – 18	76.98%	77.23%
18 - 20	80.31%	81.34%

5. Conclusion

BLDC motors can be run using the DTC method which is commonly used in induction motors. The simulation results of all three conditions when before being given Ripple Suppression for torque has an unstable value and affects the value of speed and output power of the motor. The application of ripple suppression to torque can improve output stability and can reduce losses in the motor that is being driven. From the research results, it can be seen that the efficiency of BLDC motors increases by 2 to 3 percent at starting time and increases by around 1.5 percent at steady state.

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