TẠP CHÍ KHOA HỌC
TRƯỜNG ĐẠI HỌC QUY NHƠN

Khảo sát các chế độ làm việc của hệ thống chỉnh lưu PWM - động cơ điện một chiều kích từ độc lập

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TÓM TẮT

Trước đây, động cơ điện một chiều được cấp nguồn từ lưới thông qua thiết bị chỉnh lưu dùng thyristor. Tuy nhiên, các bộ biến đổi dùng thyristor truyền thống này có những nhược điểm như: Dòng điện đầu vào chứa nhiều sóng hài điều hòa bậc cao; Sự nhấp nhô đỉnh – đỉnh của điện áp đầu ra cao; Chỉ cho dòng điện đi theo một chiều dẫn đến không thể trả năng lượng dư thừa của ĐC về phía xoay chiều; Bộ chỉnh lưu PWM có thể khắc phục được những nhược điểm của các bộ chỉnh lưu, bộ biến đổi truyền thống dùng thyristor. Trong bài báo này, tác giả khảo sát các chế độ làm việc của hệ thống chỉnh lưu PWM – Động cơ điện một chiều kích từ độc lập (CLPWM – Đ) để thấy được những ưu điểm của hệ thống này so với hệ thống chỉnh lưu thyristor – Động cơ điện một chiều truyền thống (T - Đ).

Từ khóa: *Động cơ điện một chiều, chỉnh lưu thyristor, chỉnh lưu PWM, sóng hài bậc cao, điện áp đầu ra.*

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A survey of working models of direct current motor in PWM rectifier - separately excited direct current motor system

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ABSTRACT

Previously, direct current motors (DCMs) were powered from the alternating grid via thyristor rectifiers. However, these traditional thyristor converters have major disadvantagessuch as (1) input alternating currents contain a lot of high order harmonics, (2) peak-to-peak ripple in output direct voltage is high, and (3) output current can only flow in one direction. PWM rectifiers can overcome the disadvantages of conventional thyristor rectifiers or thyristor converters. This paper considers the working modes of DCM in PWM rectifier-DCM system in order that we can see the advantages of this rectifier system when it was compared to the traditional thyristor rectifier-DCM system.

Keywords: *Direct current motor, thyristor rectifier, PWM rectifier, high order harmonic, output voltage.*

1. INTRODUCTION

Direct current motors (DCMs) have the great advantage of being able to adjust the speed in a wider range and smoother than the AC motor. Therefore, these motors are still widely used in electrical equipment that needs to be adjusted speed with high precision and smoothness, such as motors for textile machines, printers, robots, electric cars, etc.

Previously, DCMs were powered by rectifiers using thyristors (T-D).[1,2] However, the traditional drive systems (T-D) have many disadvantages such as low voltage quality at the output of the rectifier, the generation of many high-order harmonics on the grid and difficulties in flowing energy from the DCM side to the grid when the regenerative braking occurs.

The PWM rectification method using IGBT[3-8] is expected to be able to replace traditional rectifiers using thyristors in controlling DCMs. In this paper, the authors examine different working modes of the PWM rectifier-DCM system (CLPWM-DCM) to see the advantages of this system compared to the traditional thyristor rectifier-DCM system (T-D).

The CLPWM-DCM system proposed in this paper can overcome the disadvantages of the drive systems T-D. For instance, the system does not cause many high-order harmonics on the grid; the peak-to-peak ripple of the system's output voltage is low; The PWM rectifier allows power to flow in two directions without any other supporting converters.

2. SURVEY OF WORKING MODES OF DCM

2.1. CLPWM – D drive system

Currently, there are different pulse width modulation (PWM) techniques.[9,10] Most of them require complex transformations and a large

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number of current and voltage sensors are used. In this paper, the author uses a PWM rectifier using the Sin-Triangle pulse width modulation method[11-13] to build and analyze the working modes of the DCM in the CLPWM-DCM drive system.

Compared with the PWM control techniques in references 8, 9, 10, the PWM rectifier control technique that the author uses does not use any sensors or any voltage estimator. Besides, this method does not require complicated transformations like space vector modulation[9] or PLL[10] controller, so the controller is not too complicated. This is suitable for designing an empirical system. The circuit diagram of the CLPWM-DCM system is shown in Figure 1.

In the article, the author does not go into a detailed analysis of the controller of the PWM rectifier but goes into the simulation and detailed analysis of the working modes of DCM in the CLPWM-DCM system. The control diagram of the PWM rectifier in the CLPWM-DCM system is also shown in Figure 2.

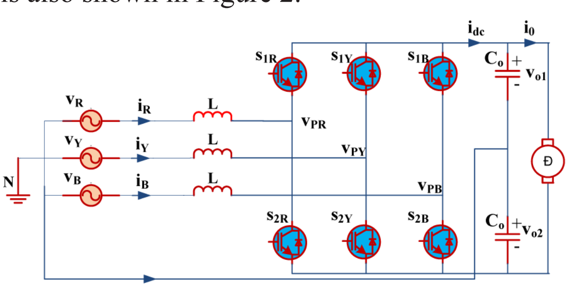

Figure 1. Circuit diagram of CLPWM-DCM system

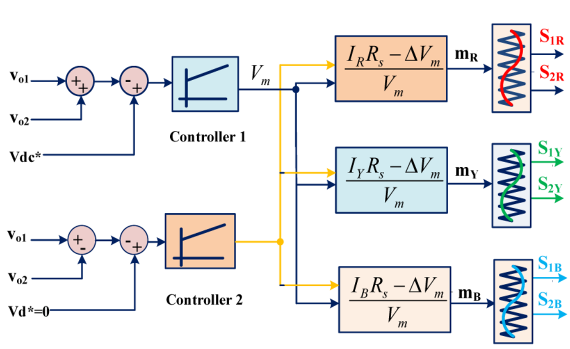

Figure 2. Control circuit diagram of PWM rectifier.[11,12]

2.2. Working modes of DCM

To see the advantages of the CLPWM-DCM system compared to the T-D system, the author analyzes the different working modes of the DCM in both systems. The examined DCM parameters are shown in Table 2. The rectifier used in the T-D system is a controlled 3-phase bridge thyristor rectifier. The circuit diagram of the T-D system is shown in Figure 3.

The simulation diagram of the working modes of the CLPWM-DCM system is shown in Figure 4. The parameters of the CLPWM-DCM system are shown in Table 1, and Table 2.

In the different working modes of DCM in the CLPWM-DCM system, the author uses the DCM starting method by changing the armature voltage,[14] so the starting current of the DC in all modes working (Figure 5, Figure 7, Figure 8, Figure 9, Figure 10, Figure 12 and Figure 15) is less variable, within the allowable limit to increase the service life and ensure the safety of the engine during the work process.

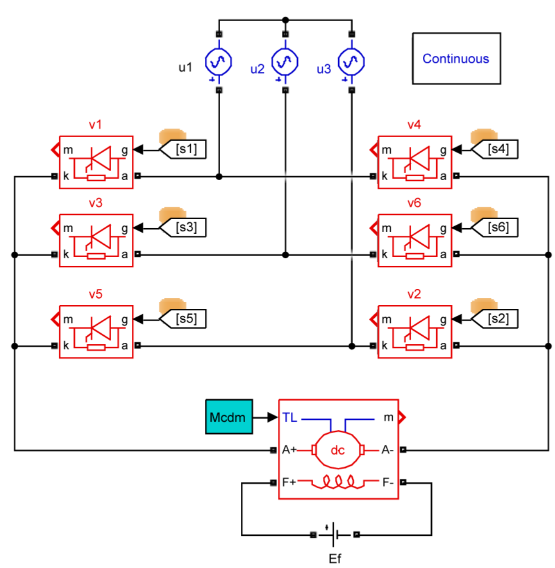

Figure 3. Circuit diagram of T-D drive system.

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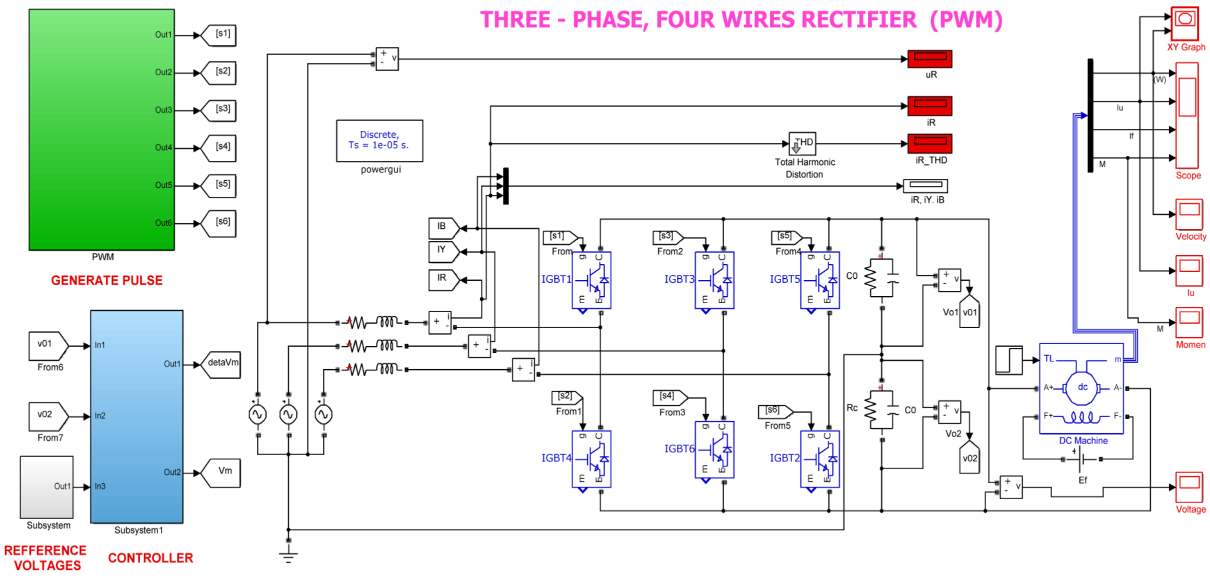

Figure 4. Simulation diagram of working modes of DCM in CLPWM–DCM system

Table 1. Parameters of PWM rectifier

No.	Symbol	Interpretation of the symbol	Parameter
1	f (Hz)	Frequency of the grid.	50
2	V_{Grid} (V)	The average phase voltage of the grid.	220
3	V_{o1}, V_{o2} (V)	The voltage value of two direct current (DC) buses.	120
4	L_c (mH)	Inductance L.	8.61
5	C_o (μF)	Capacitance C.	2200
6	R_S (Ω)	Current sensor gain.	1/10
7	F_c (kHz)	Carrier frequency.	11
8	R_c (Ω)	The resistance of the capacitor C_o.	11000

Table 2. Parameters of DCM

No.	Symbol	Interpretation of the symbol	Parameter
1	P (Hp)	Output Power	5
2	U_{udm} (V)	Input Voltage	240
3	ω_{dm} (Rad/s)	Angular speed	183
4	L_u (H)	Armature inductance	0.12
5	R_u (Ω)	Armature resistance	1.5
6	L_{kt} (H)	Field inductance	156
7	R_{kt} (Ω)	Field resistance	281.3
8	L_m (H)	Field-armature mutual inductance	1.10
9	U_{kt} (V)	Field Voltage	300

2.1.1. Motoring mode

When the motoring mode happens, the DCM speed is greater than 0 (Figure 5), the DCM Armature current is in the same direction as the electromotive force (E_d) of the rectifier, so the current is positive (Figure 5). Therefore, the torque-speed characteristic of DCM is in the first quadrant (Figure 6).

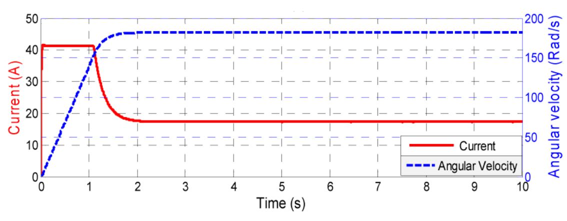

Figure 5. Current and speed of the motor in CLPWM-DCM system when the motoring mode happens

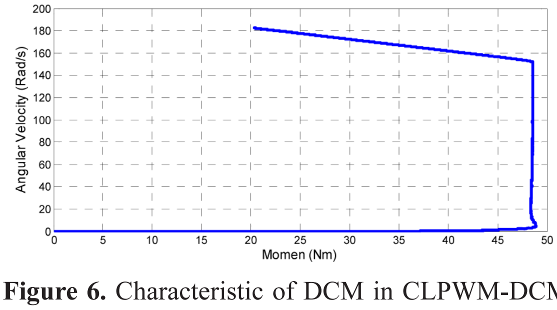

Figure 6. Characteristic of DCM in CLPWM-DCM system when the motoring mode happens

2.1.2. Regenerative Braking

At time t = 5(s), the voltage supplied to the DCM is rapidly reduced from the rated voltage

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Udm = 240V to 100V. If the DCM load is an inertial one, its speed at this time decreases slowly, not corresponding to the rate of voltage drop, so the DCM current now has a negative value.

Figure 7 shows that in a T-D drive system, the 3-phase bridge rectifier using thyristor only allows current to flow in one direction, so it cannot return excess energy from the DC (Direct current) side to the AC (Alternative current) side. This is the disadvantage of this drive system.

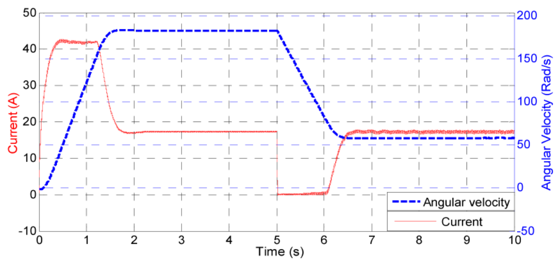

Figure 7. The DCM armature current and speed in T-D when the regenerative braking happens

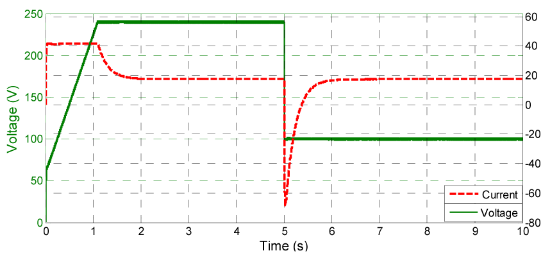

Figure 8. DCM armature current and speed in CLPWM-DCM system when the regenerative braking happens

Regarding the CLPWM-DCM system, the PWM rectifier allows current to flow in the opposite direction from the DC side to the AC side if there is excess energy on the DC side. So now, the excess energy on the DC side flows to the AC side as shown in Figure 8. This is the advantage of the CLPWM-DCM system over the T-D drive system.

The problem here is that the value of the regenerative braking current flowing from the DC side to the AC side is much larger than 2.5 times the DCM rated current (Figure 8). To overcome this problem, the author also calculates and gives a formula to determine the voltage drop rate so that the value of current when the regenerative braking happens is less than or equal to 2.5 times the DCM rated current as is shown in Formula (1).

$$Du = \frac{(KF)^2 K_h I_{udm} + KF\, M_c}{J} t + (K_h I_{udm} + I_{udm}) R_u \quad (1)$$

After determining the voltage drop rate so that the regenerative braking current does not exceed the allowable value as Formula (1), the regenerative braking process is simulated. The simulation results are shown in Figure 9. Specifically, when the DCM is working at rated load, at time t = 5s, we reduce the voltage supplied to the DCM from the rated voltage value to 100V with a voltage decreasing rate is calculated by Figure (1). If the load of the DCM is an inertial one, its speed at this time decreases slowly without corresponding to the voltage drop rate, so the DC current is negative. At this time, the PWM rectifier allows current to flow in the opposite direction, the excess energy on the DC side flows back to the AC side as shown in Figure 9. At this point, the regenerative braking happens, the operation of the DCM is in quadrant II (Figure 10). This is an advantage that the thyristor rectifier in the T-D systems does not have (Figure 7).

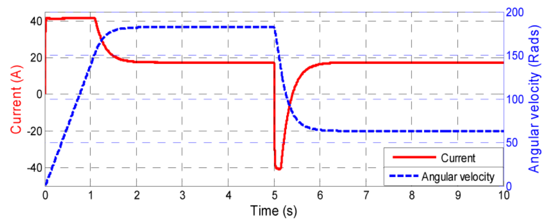

Figure 9. DCM current and speed in CLPWM-DCM system when the regenerative braking happens in case of the braking current is limited.

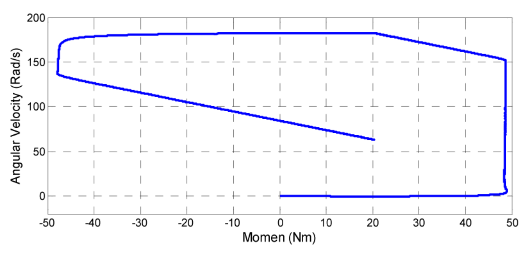

Figure 10. Characteristic of DCM in CLPWM-DCM system when the regenerative braking happens.

As the speed of the DCM gradually decreases, its armature current gradually increases. Until this current increases to greater than 0, the regenerative braking (in quadrant II) turns into the motoring mode (in quadrant I) (Figure 10).

Thanks to the voltage drop at the rate determined by Formula (1), the DCM current when the regenerative braking happens does not exceed the allowable current value as is the case shown in Figure 8. At this point, the current is less variable and is not exceed the allowable value ($2.5*I_{dm}$) as shown in Figure 9.

2.1.3. Reverse current braking

In order for reverse current braking to take place, at time t = 5(s), the voltage supplied to the DCM is rapidly reduced from the rated voltage Udm = 240 V to 15 V. If the DCM load is an inertial one, its speed at this time decreases slowly, not corresponding to the rate of voltage drop, so the DCM current would now have a negative value.

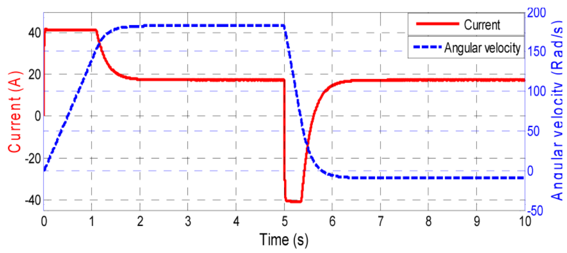

Figure 11. DCM current and speed in the CLPWM-DCM system when the reverse current braking happens.

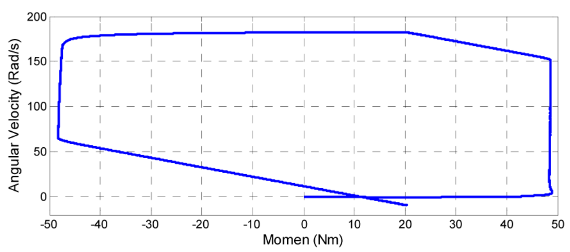

Figure 12. Characteristic of DCM in CLPWM-DCM system when the reverse current braking happens.

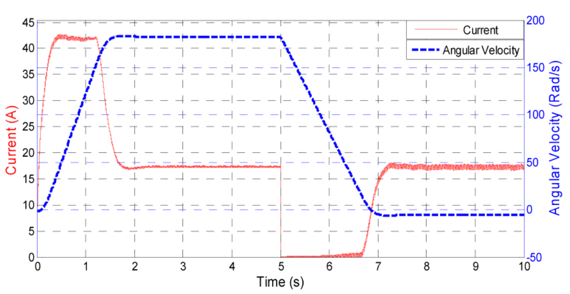

Figure 13. The DCM current and speed in T-D system when the reverse current braking happens.

At this time, the PWM rectifier allows current to flow in the opposite direction, the excess energy on the DC side would flows to the AC side as shown in Figure 11. At this point, the regenerative braking takes place, the operation of the DCM is in quadrant II (Figure 12). This is an advantage that thyristor-using rectifiers cannot do (Figure 13). The simulation results in Figure 11 also show that thanks to the voltage reduction at the rate calculated by Formula (1), the return current to the grid of the motor is not too large, not exceed the allowable value ($2.5*I_{dm}$).

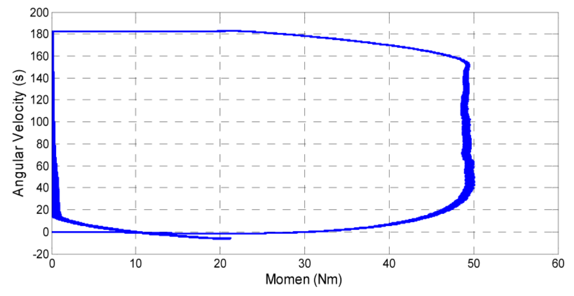

Figure 14. Characteristic of DCM in T-D system when the reverse current braking happens.

If the load is a potential load, under the influence of the load's gravity, the DC speed decreases gradually, so the DCM current gradually increases. Until the current has just increased to greater than 0, the torque is still smaller than the potential torque of the load, so the DCM speed continues to decrease. At this time, the torque-speed characteristic of the motor is in quadrant I (Figure 12).

When the speed drops to 0, because the DCM torque is still smaller than the load potential torque, the DCM speed starts to reverse and increase in the negative direction. The reverse current braking starts happening. The torque-speed characteristic of the motor is shown in Figure 12.

To see the advantages of the CLPWM-DCM system, we compare this system with the traditional T–D system. For the CLPWM-DCM system, the PWM rectifier can allow the current to flow in the opposite direction (Figure 11). So, at the time of voltage is dropped rapidly so

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that the reverse current braking happens, at first the regenerative braking takes place, returning energy to the grid (Figure 11).

The torque-speed characteristic of the DCM is shown in Figure 12. For the T-D system, the rectifier using thyristors cannot allow the current to flow in the opposite direction, so when reducing the voltage in order for the reverse current braking to happen, the DCM cannot return the excess energy to the grid (Figure 13). This leads to a waste of excess energy when dropping voltage in order the reverse current braking to arise. The characteristic of the motor when the reverse current braking happens is shown in Figure 14.

2.1.4. Dynamic Braking

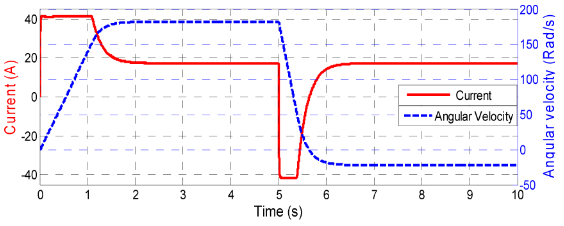

Figure 15. DCM current and speed in CLPWM-DCM when the dynamic braking arises.

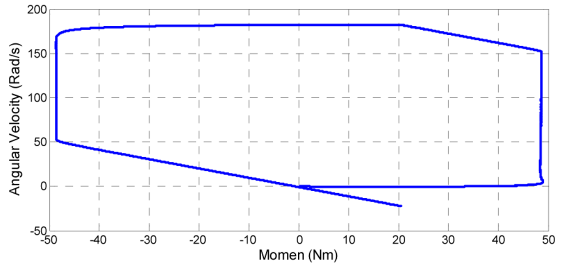

Figure 16. Characteristic of DCM in CLPWM-DCM system when the dynamic braking happens.

At time t = 5(s), the voltage supplied to the DCM is rapidly reduced from the rated voltage to 0V with the voltage reduction rate as (1). If the DCM load is an inertial one, its speed at this time decreases slowly, not corresponding to the rate of voltage drop, so the DCM current now is negative.

At this time, the PWM rectifier allows current to flow in the opposite direction, the excess energy on the DC side flows to the AC side as shown in Figure 15. At this point, the regenerative braking takes place, the operation of the DCM is in quadrant II (Figure 16). This is an advantage that thyristor-using rectifiers cannot have.

Under the influence of the load gravity, the DCM speed decreases gradually to 0 (Rad/s). When the speed is 0(rad/s), the armature current would be 0(A). When the current is zero, the DCM torque is also zero. At this time, the torque is less than the load potential torque, so the DCM reverses rotation and accelerates in the opposite direction. At this time, the dynamic braking happens, the operation of DCM is in quadrant IV and the characteristic of the motor is shown (Figure 16).

When the DCM speed increases (in the negative direction), the DCM current would also increase, so the DCM torque would rise. When the DCM torque and load torque are equal, the motor works stably in quadrant IV (dynamic braking happens) as shown in Figure 16.

To see the advantages of the CLPWM-DCM system, this system is compared with the traditional T-D system. For the CLPWM-DCM system, the PWM rectifier is able to allow the armature current to flow in the opposite direction (Figure 15). Therefore, when we reduce the armature voltage in order for the dynamic braking to happen, regenerative braking at first arise, allow energy to flow to the AC side (Figure 15).

The characteristic of the DC in the CLPWM-DCM system is shown in Figure 16. For the T-D system, the current in the thyristor rectifier cannot flow in the opposite direction. Therefore, when the voltage is reduced in order for dynamic braking to take place, the rectifier does not allow the excess energy to flow to the AC side (Figure 17). This leads to a waste of energy on the DC side when reducing DCM armature voltage to allow the dynamic braking to happen. The characteristic of the motor when the dynamic braking happens is shown in Figure 18. This is the disadvantage of the T-D system compared with the CLPWM-DCM one.

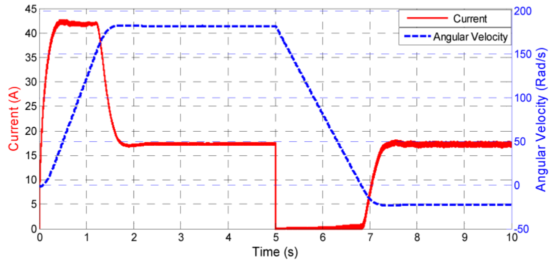

Figure 17. DCM current and speed in T-D system when the dynamic braking happens.

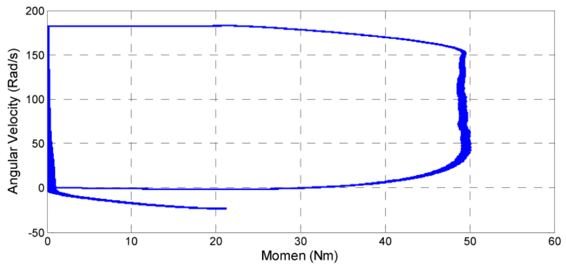

Figure 18. Characteristic of DCM in the T-D system when the dynamic braking happens.

2.2. Quality analysis of DC voltage

To see the advantages of the CLPWM-DCM system compared to the T-D system, the peak-to-peak ripples of the DC voltage at the output of the PWM rectifier and the 3-phase bridge rectifier using thyristors in the T-D system is simulated, compared and analyzed.

Figure 20 shows the peak-to-peak ripple of the DC voltage at the output of the PWM rectifier in a CLPWM-DCM system is about 3(V), approximately 1.25% of the average value of the DC voltage.

Meanwhile, the peak-to-peak ripple of the DC voltage at the output of the 3-phase bridge rectifier using thyristors in the T-D system in the case of the best output voltage quality of this system ($\alpha = 0^o$) is about 38(V) (Figure 19), approximately 15% of the average DC voltage. Therefore, it can be said that the output voltage quality of the PWM rectifier in the CLPWM-D system is better than the output voltage quality of the thyristor rectifier in the T-D system. This helps the motor in the CLPWM system to work more quietly, reducing the losses in the system.

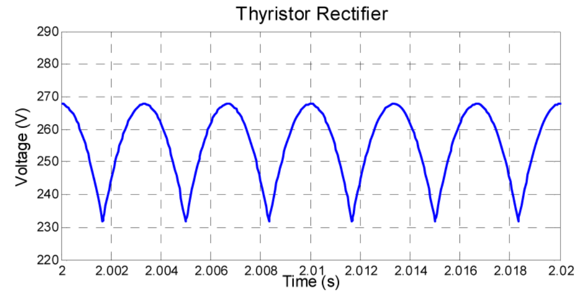

Figure 19. The quality of DC voltage at the output of the 3-phase bridge rectifier with the firing angle $\alpha = 0^o$ in T-D system.

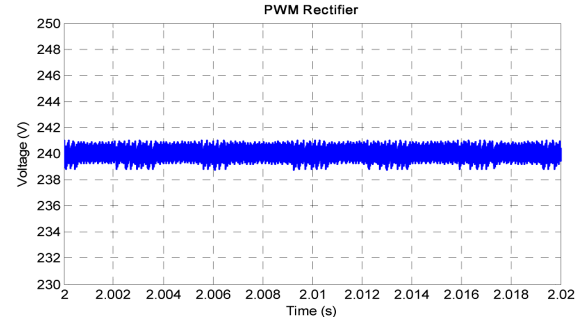

Figure 20. DC voltage quality at output of PWM rectifier in CLPWM system-DCM (zoomed).

To analyze the influence of inductor L and capacitor C on the quality of DC voltage supplied to the DCM in the T-D system, the author simulates the T-D system when adding 2 elements L and C to the system (Figure 21). The values of these two elements L and C in the CLPWM-DCM system and the T-D system are the same (See Table 1). The obtained results show that the peak-to-peak ripple of output voltage in the T-D system is significantly reduced, but the transient time of the system is very large, about 3.5 seconds (Figure 22). This transient time is approximately 3 times larger than that of the CLPWM-DCM system (Figure 23). So, the practical applicability of the T-D system when connecting inductors L and capacitor C is very limited, especially cannot be used in systems that need fast adjustment speeds such as robots, textile machines or electric cars, etc.

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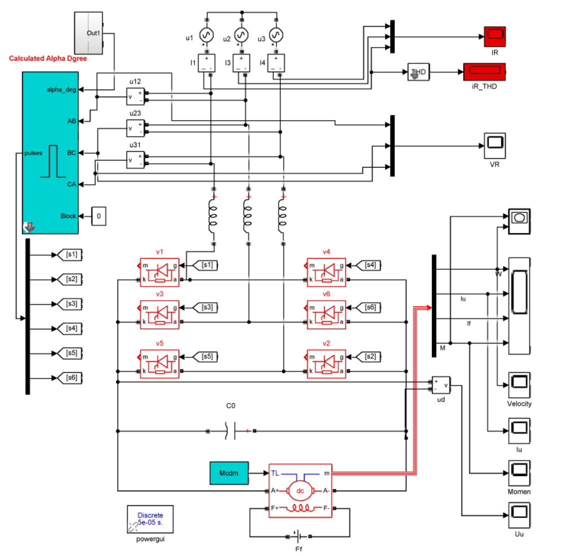

Figure 21. T-D system when adding inductor L and capacitor C.

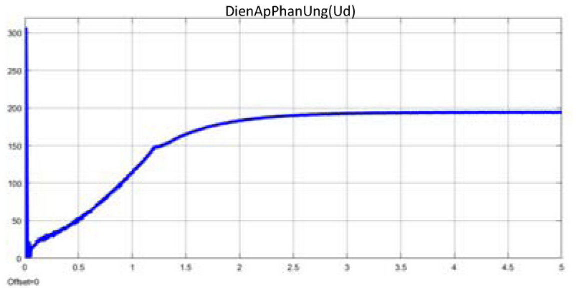

Figure 22. DC voltage in the T-D system when L and C are added.

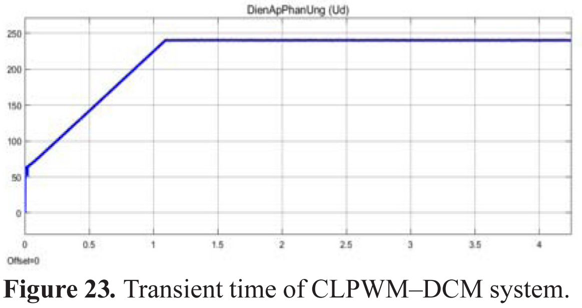

Figure 23. Transient time of CLPWM–DCM system.

2.3. Analysis of high order harmonics

To see the distortion of the alternating current in front of the rectifier in the T-D and in the CLPWM-DCM system, the author uses the fast Fourier analysis tool in Matlab software to analyze the spectrum of the AC current. In this way, alternating current form in front of the rectifier and the total harmonic distortion (THD) of this current were obtained.

Figure 24 and Figure 25 show the alternating current at the input of the rectifier in the T-D system with a non-sine form. From these two figures, it can be seen that the larger the firing angle α is, the greater the distortion of the input current and the larger the current harmonics (THD). For example, When α = 0^o, THD = 31.11% (Figure 24); When α = 90^o, THD = 33.09% (Figure 25).

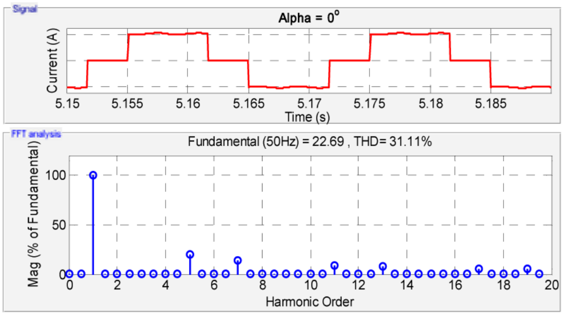

Figure 24. Current and THD of current with firing angle α = 0^o in T-D system.

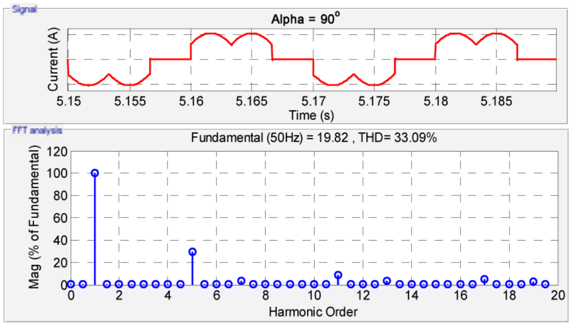

Figure 25. Current and THD of current with firing angle α = 90^o in T-D system.

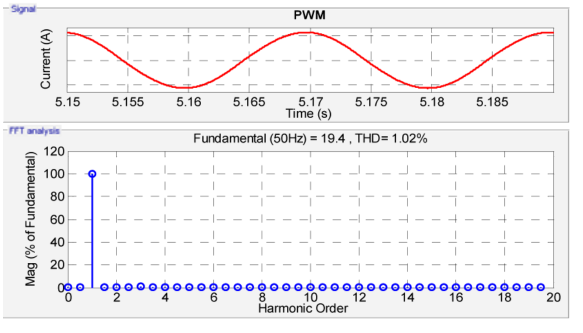

Figure 26. Current and THD of current in CLPWM-DCM system.

Figure 27 shows the simulation results of the current form and the total harmonic distortion THD of the alternating current in front of the PWM rectifier, THD = 1.02%. Comparing the simulation results in Figure 27 with Figure 25 and Figure 26, it can be seen that the PWM rectifier in the CLPWM-DCM system does not distort the AC current at the input of the rectifier as much as in the case of the rectifier using thyristor in the T-D system. In other words, this input AC current has an almost ideal sine form, and the THD of the current is very small with 1.02%.

To analyze the influence of the inductor L and capacitor C on the current distortion at the input of the rectifier in the T-D system, the author conducts a simulation of the T-D system when adding two L and L elements into this system (Figure 21). The values of these two elements L and C in the T-D system and those in the CLPWM-DCM system was the same (See Table 1). The obtained results show that when adding the inductor L to the T-D system, the total harmonic distortion of the system is reduced, from 31.11% (Figure 24) to 23.14% (Figure 27). However, the THD of current in T-D system is 23.14%, which is still much larger than that in the CLPWM-DCM system, THD = 1.02% (Figure 26).

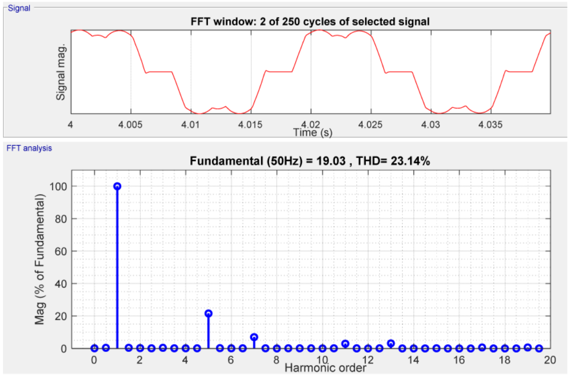

Figure 27. Current and THD of current with firing angle $\alpha = 0^o$ in T-D system.

In addition, when we add L and C elements into the T-D system, the DC voltage value feeding to the DCM is significantly reduced, dropping from 514(V) (voltage corresponding to the firing angle $\alpha = 0^o$ to 190(V) (Figure 22). Actually, the voltage feeding to the DCM has significantly reduced because of a voltage drop on the additional reductor L in the system. Therefore, adding an inductor L with a large inductance value to the T-D system helps reduce the amount of high-order harmonics returned to the system's grid, but not significantly. In addition, the voltage drop on the inductor is too large, making the system no longer optimal, so it is not prioritized.

3. CONCLUSION

The simulation, comparison and analysis results in the paper show that the T-D drive system still has many disadvantages. In addition, the article also shows that the CLPWM-DCM drive system has many advantages and can overcome many disadvantages of the traditional T-D system. For instance, it does not distort the alternating current in front of the rectifier; The total harmonic distortion of the input current in front of the rectifier is low; The peak-to-peak ripple of the rectifier output voltage is low; It is possible to allow current to flow in two directions, enabling the exchange of energy between the DC side and the AC side easily. However, the CLPWM-DCM drive system also has the disadvantage that the design and control of the system are relatively complicated.

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