Improving the torque direct control method of the asynchronous motor in the converter using the active rectifier

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Abstract. The frequency converter study has shown that controlled rectifiers, also known as active rectifiers, have many advantages over uncontrolled rectifiers (diode bridges). The frequency converter with an active rectifier ensures that the input current is sinusoidal, the power factor is 1, the DC voltage constant at the output, the energy exchange according to bidirectional is between the load and grid. The voltage oriented control for the active rectifier will measure the grid voltage and use current control circuits or instantaneous power control circuits. The paper analyses the advantages of using the method of controlling the current in the rectifier circuit when working with the three-phase motor load. The torque direct control method of the motor is enhanced by selecting a new switch table of the voltage vector. The combining power, an active rectifier circuit, inverter, motor, and load create a complete electric drive system with improved working efficiency. The research results were verified by Matlab&Simulink software.

1. Introduction

Currently, the diode rectifier and thyristor rectifier are commonly used. These rectifiers have advantages such as very low initial investment, operation, maintenance, repair. At the same time, the diode and thyristor valves are capable of working with high currents and voltages, so they are used a lot in applications requiring very large capacity. However, the main disadvantages of these rectifiers are their nonlinearity and distortion of the current and voltage of the grid. In frequency converters with diode rectifiers, the power is only transmitted in one direction. When using the thyristor, there are many circuit diagrams in practice to ensure a two-way power transmission. However, the diagram is cumbersome, there is low efficiency and it is difficult to control [1-3]. Currently, active rectifiers using fully controlled switching valves (IGBT) are being developed and applied in practice. These rectifiers control the charging current for the capacitor, so the DC voltage at the output of the rectifier can be controlled. This is the advantage of an active rectifier [4-6].

Active rectifiers, using the voltage oriented control (VOC) method, will estimate the grid voltage and then control the current. This method has advantages such as a fixed switching frequency in order to design a simple input filter block, which takes advantage of the PWM modulation method [7]. The combination of an active rectifier with the inverter and the speed control of a three-phase AC motor will ensure energy is exchanged in two directions between the grid and the load. During operation, the
induction motor can work at all four quadrants of the coordinate system. Direct torque control (DTC) has a fast torque response, low torque ripple, and stable switching frequency so the motor is stable at low speed or when the torque is changed [8, 9]. The basic DTC control method uses a six-sector switch table that has disadvantages such as a torque controller, which is a delay relay (two positions), so it has a large torque error and the torque amplitude fluctuates when the torque load changes [9, 10]. This paper will study the switching table with twelve new vectors. The controller ensures a faster response when torque fluctuates, the amplitude is kept at the required level, and the control process is more accurate. Combining the method of active rectifier control with the inverter and direct torque control will improve the quality of electric drive systems in practice.

2. Methods

2.1. Direct current control method of an active rectifier
The direct current control (DCC) structure is based on the conversion between the fixed coordinate system $\alpha-\beta$ and the rotating coordinate system $d-q$. The measured values in the natural coordinate system $abc$ are first converted to the fixed coordinate system $\alpha-\beta$, then converted to the rotating coordinate system $d-q$ as shown in figure 1. This method ensures a stable output DC voltage and high static efficiency through internal current control circuits. In figure 2, the load is an inverter and a three-phase ac motor; PI – Regulators of current along the $d - q$ axis and direct voltage regulators (DC); PWM – IGBT control pulse generator; L – Line inductance has the function of not giving input short circuit and is the booster unit; CM&LVE – Current measurement & line voltage estimation.

![Figure 1. Structure of PWM rectifier according to DC](image)

In the coordinate system $d-q$ the grid voltage is calculated as follows:

$$u_{Ld} = Ri_{Ld} + L \frac{di_{Ld}}{dt} + u_{sd} - \omega Li_{Lq}$$

$$u_{Lq} = Ri_{Lq} + L \frac{di_{Lq}}{dt} + u_{sq} + \omega Li_{Ld}$$

Assuming the input resistance is extremely small compared to the input inductance, the minimalist formula becomes:

$$u_{Ld} = L \frac{di_{Ld}}{dt} + u_{sd} - \omega Li_{Lq}$$

$$u_{Lq} = L \frac{di_{Lq}}{dt} + u_{sq} + \omega Li_{Ld}$$

The $i_{qref}$ current is set to 0 to always ensure the input power factor is 1 and will result in the formula:
The $i_{\text{dref}}$ current at the DC voltage regulator output (PI) is then compared with the converted current value by converting coordinates (abc) to ($\alpha$ - $\beta$) and (d - q). The error of comparison is the input of the controller. In the control structure, the current value $i_{\text{qref}}$ is constant. The goal is that the tracking control requires an integral stage to eliminate static errors. So select the current regulator with the PI structure to eliminate noise and eliminate static errors. Also, when dividing the current in two d - q axes, there will be a mutual inductance phenomenon between the axes. To eliminate these cross components we use a decoupled controller as shown in Figure 2.

The PI regulator in the voltage loop works to keep the $U_{\text{dc}}$ voltage constant on capacitor C according to the set value, that is, control the flow of active power flowing to the capacitor C. Always ensure the output voltage of the rectifier is equal to the $U_{\text{dcref}}$ set value when the load changes.

![Figure 2. Current and dc-link voltage controller](image)

### 2.2. Method of direct control of torque

The DTC torque control method is widely used in the industry. With advantages such as very small torque response time and high reliability, formulas can be used to estimate rotor speed without using a speed sensor. Torque control is a control that ensures the amplitude of the stator flux vector and the torque is kept within the permissible range. The error between the two calculation steps depends on the sampling frequency. The basic DTC control method using a switch table having six sectors (figure 3) only creates two control areas: increasing and decreasing torque, so the controller response will be slow as the torque of the load changes continuously.

During DTC control the vector of the output voltage of the autonomous inverter is calculated based on the switching algorithm which is constructed based on table 1. The output signals of the relay regulators and the number of the sector in which the vector of flux linkage of the stator is located flow into the switching table. In table 1 the following symbols represent:

- $FI$ – increase in flux linkage of the stator;
- $FD$ – decrease in flux linkage of the stator;
- $MI$ – increase in the moment of the motor;
- $M$ – the moment of the motor corresponds to the given value;
- $MD$ – decrease in the moment of the motor.

Control of moment in motor AC within the DTC system is unstable as the size of flux linkage of the stator and the moment constantly changes in the range which is defined by insensitive regulators. Also, the range of pulsations depends on the frequency of switching the autonomous inverter. Based on the provision of a vector of flux linkage of the stator, reduction or increase in torque voltage vector corresponds to table 1. If on the switching period the size of the moment goes beyond a tolerance zone, then the chosen vector of the voltage of the autonomous inverter is replaced with another. Thus,
the DTC system doesn't allow providing a constant value of moment for the motor AC, and that is a disadvantage.

**Table 1.** The switching table of the switch table with six sectors

| dΨ  | dM  | N1 | N2 | N3 | N4 | N5 | N6 |
|-----|-----|----|----|----|----|----|----|
| MI  | V2  | V3 | V4 | V5 | V6 | V1 |
| FI  | V0  | V7 | V0 | V7 | V0 | V7 |
| MD  | V6  | V1 | V2 | V3 | V4 | V5 |
| MI  | V3  | V4 | V5 | V6 | V1 | V2 |
| FD  | V7  | V0 | V7 | V0 | V7 | V0 |
| MD  | V5  | V6 | V1 | V2 | V3 | V4 |

**Figure 3.** Splitting the phase plane into six direct sectors

The main way modification of the DTC system is to change its switching table, which the structure changes in two ways:
- Change of types of regulators;
- Change in quantity of sectors of a phase plane.

The maximum effect is reached by the use of both ways in a complex. It is advisable to carry out the transition to the 12 sectors splitting the phase plane. We will consider these ways of modification of the DTC systems.

When splitting the phase plane into 12 sectors the size of each sector is 30°. The 12th sector splitting the phase plane is shown in fig 4. When adjusting the torque, the actual value of the motor torque can vary widely. To estimate the magnitude of the torque in Fig. 5, the following regions are selected:
- I – zone of the sharp increase of the torque;
- D – zone of the sharp decrease of the torque;
- SI – zones of the slight increase of the torque;
- SD – zones of the slight decrease of the torque.

The change of moment is shown in fig. 5.
Whereby $\text{Md}$ – the operating value of moment on the motor shaft; $\text{Md}^*$ – given moment value and $\text{Mb}$ - a tolerance zone of the regulator of the moment.

Communication between $\text{Mb}$ and $\text{M}$ is caused by the following. In the table of the switching with 12 sectors, if the value of $|\text{M} - \text{Mb}|$ is rather high, the moment needs to be changed to quickly bring the system to a stable state. In the opposite state, when $|\text{M} - \text{Mb}|$ it is relatively little for the stabilization of the system because it only requires a small change. Therefore there has to be an accurate difference between the required value of the moment. Thus in the DTC system in a contour regulation of the moment, it is necessary to use 4-level regulators. The output signal of a 4-level regulator which depends on the number of misalignment is explained as follows:

$\text{dM} = 2$, if $\Delta \text{M} > \text{M}_d - \text{M}_d$
$\text{dM} = 1$, if $0.5(\text{M}_d - \text{M}_d) < \Delta \text{M} < \text{M}_d$
$\text{dM} = 0$, if $\Delta \text{M} < 0.5(\text{M}_d - \text{M}_d)$
$\text{dM} = -1$, if $\text{M}_d - 0.5|\Delta \text{M}| < \text{M} < \text{M}_d$
$\text{dM} = -2$, if $\Delta \text{M} < \text{M}_d - \text{M}_d$

For the reasons given above it is visible that the regulator of the moment represents a four-position relay tolerance zone. Relay setting borders ($\text{dM}_1$, $\text{dM}_2$, $-\text{dM}_2$, $-\text{dM}_1$) correspond to tasks on the small and sharp reduction of the moment as well as the sharp and small increase of moment. Thus, the amplitude of the moment is maintained at the required level, and the control accuracy is increased. The switching table for the 12 sectors plane and the 4 positions regulator is shown in table 2.

### Table 2. The switching table of switchboards with 12 sectors

| $\text{dP}$ | $\text{dM}$ | $\text{N}_1$ | $\text{N}_2$ | $\text{N}_3$ | $\text{N}_4$ | $\text{N}_5$ | $\text{N}_6$ | $\text{N}_7$ | $\text{N}_8$ | $\text{N}_9$ | $\text{N}_{10}$ | $\text{N}_{11}$ | $\text{N}_{12}$ |
|-----------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $\text{FI}$ | $\text{MSI} = 2$ | $\text{V}_2$ | $\text{V}_3$ | $\text{V}_4$ | $\text{V}_5$ | $\text{V}_6$ | $\text{V}_7$ | $\text{V}_8$ | $\text{V}_9$ | $\text{V}_10$ | $\text{V}_11$ | $\text{V}_12$ |
| $\text{MSD} = -1$ | $\text{V}_3$ | $\text{V}_4$ | $\text{V}_5$ | $\text{V}_6$ | $\text{V}_7$ | $\text{V}_8$ | $\text{V}_9$ | $\text{V}_10$ | $\text{V}_11$ | $\text{V}_12$ |
| $\text{MD} = -2$ | $\text{V}_4$ | $\text{V}_5$ | $\text{V}_6$ | $\text{V}_7$ | $\text{V}_8$ | $\text{V}_9$ | $\text{V}_10$ | $\text{V}_11$ | $\text{V}_12$ |

2.3. Results and analysis

Parameter of induction motor: $\text{P} = 2.2$ (kW), $\text{U} = 220/380$ (V), $\text{f} = 50$ (Hz), $\text{Rs} = 6.367$ (Ω), $\text{n} = 1436$ (rpm), $\text{Ls} = 0.002981$ (H), $\text{J} = 0.05$ (kg·m²). Based on the motor parameters, we will calculate the parameters for IGBT active rectifier circuit: supply voltage $\text{U}_{\text{m}} = 220$ (V), frequency $\text{f} = 50$ (Hz), DC filter capacitor $\text{C} = 3900$ (μF), input inductance $\text{L} = 0.005$ (H), required DC output voltage $\text{V}_{\text{dc}} = 690$ (V).
Where: 1 – three-phase source; 2, 6 – AC current and voltage sensors; 3 – inductance; 4 – active rectifier circuit (IGBT); 5 – voltage inverting circuit (IGBT); 7 – asynchronous motor; 8 – active rectifier control unit by DCC method; 9 – direct torque control unit (DTC); 10 – DC voltage sensor; Mc – load torque.

To study the working quality of the electric drive system, in the beginning, the motor speed and torque increased. When the system is working stably, the load torque suddenly reverses. These are the two most strict changes when the asynchronous motor works as shown in figure 7 and figure 8.

**Figure 7.** Set motor speed

**Figure 8.** Set load torque

The simulation results are as follows:

**Figure 9.** AC input voltage

**Figure 10.** Input current (same phase angle with voltage)

Figures 9 and 10 show the grid current in the standard sine form and it has a phase angle equal to the phase angle of the voltage at the input of the active rectifier.

**Figure 11.** DC output voltage ($U_{dc} = 690V$)

**Figure 12.** Grid current with reverse load torque at $t = 0.15s$ (Mc = -16 N.m)

Figure 11 shows that at the output of the positive rectifier, the DC voltage is equal to the preset voltage value ($U_{dc} = 690V$). Demonstrate that the control system for the active rectifier works well and meets the requirements.
Figure 13. Current harmonics at active rectifier input (TDH=1.82%)

Figure 13 shows the grid current harmonics are very small and the total harmonic distortion of the current THD = 1.82%. Figure 14 shows at time t = 0.15s, the reactive load torque Mc = -16 N.m, the asynchronous motor works in the generator mode. Active power (p<0) will be returned to the grid through the inverter and rectifier circuit.

Figure 14. Active power of the rectifier input

Figure 15. Power factor

Figure 15 shows that when the system is working, the power factor is approximately equal to 1, ensuring the efficiency of the active rectifier. When the motor operates in the regenerative braking state, the energy returns to the grid and cosφ ≈ -1. Figure 16 shows that the speed of the motor always follows the preset speed value (n = ± 1000 rpm). This proves that the control system has been designed to meet the requirements of the drive system.

Figure 16. The rotation speed of the motor

Figure 17. Electromagnetic torque of a motor with switch table having six sectors

From the results in Figures 17 and 18, the electromagnetic torque of the motor will change rapidly when there is a change of load torque and always follow the load torque to ensure Mc = Md. However, in the 12 sectors method, there is good torque and less undulating.

Figure 18. Electromagnetic torque of a motor with switch table having twelve sectors
Figures 19 and 20 shows that the method of using twelve sectors switch table has a circular motor magnetic flux trajectory than the six sectors method. This shows that the stator current by the method of twelve sectors with small harmonic content.

3. Conclusion
Theoretical analysis and the results obtained from simulation show that the frequency converter with an active rectifier has more advantages than the inverter with a rectifier diode. The energy is exchanged in two directions when braking occurs, there is a high power factor, there is a sine-grid current and the harmonic content is reduced. The direct torque control method using a switch table has twelve sectors to ensure that the rotation speed is always tracking to the set value, the electromagnetic torque responds quickly to changes of load torque, and the magnetic torque has lower adjustment. This research aims at improving the DTC control method in a 4Q frequency converter by using the new voltage switch table (twelve sectors) to ensure the high quality of the actual electric drive control system.

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