DOI: 10.54254/2755-2721/2026.AD34360

Bidirectional DC Motor Drive Strategies Based on H-Bridge Topology

Jiayu Wang

Department of Information and Computing Science, Northeast Forestry University, Harbin, China
jiayuwang05@163.com

Abstract. Direct current (DC) motor drives are widely used in robotics, electric vehicles (EVs), and industrial automation because of their high torque capability, simple structure, and convenient speed regulation. In many modern applications, the drive system is required not only to adjust speed but also to realize bidirectional motion, rapid speed reversal, precise braking, and energy recovery. These functions require a converter that can reverse the motor terminal voltage and allow bidirectional current flow. The H-bridge topology is therefore widely adopted for four-quadrant DC motor drives. This paper reviews bidirectional DC motor drive strategies based on H-bridge configurations. The operating principle of four-quadrant operation is first explained from the relationship between torque, speed, and power flow. Then, two common pulse-width modulation (PWM) methods, namely bipolar PWM and unipolar PWM, are compared in terms of current ripple, switching losses, electromagnetic interference (EMI), transient response, and implementation complexity. Voltage-mode and current-mode control strategies are also discussed to show how different control structures influence torque response and disturbance rejection. Finally, several practical design issues, including dead time, current sensing, and protection, are considered. This review shows that no single method is optimal for all applications. A suitable H-bridge drive design should balance efficiency, dynamic performance, cost, and implementation difficulty according to the target application.

Keywords: H-bridge, DC motor drive, pulse-width modulation, four-quadrant operation, current-mode control

1. Introduction

Direct current (DC) motors are widely used in modern equipment, such as robots, automobiles, and automated systems [1]. With the development of these applications, the requirements placed on motor drive systems have become higher. A practical drive system should be able to regulate speed smoothly, reverse direction rapidly, provide braking torque, and recover energy when possible. These requirements are closely related to four-quadrant operation.

Four-quadrant operation means that the drive can control both the direction of motor speed and the direction of electromagnetic torque. In other words, the motor must be able to operate in forward motoring, reverse motoring, forward braking, and reverse braking modes. To achieve this behavior, the drive system needs to control both the polarity of the motor terminal voltage and the direction of

DOI: 10.54254/2755-2721/2026.AD34360

the armature current. The H-bridge converter provides a simple and effective solution because it can reverse the motor voltage and provide current paths in both directions [2].

This paper focuses on bidirectional DC motor drives based on the H-bridge topology. The discussion is organized around four main aspects: four-quadrant operating principles, H-bridge hardware structure, PWM modulation strategies, and control methods. The main performance criteria used for comparison are current ripple, switching losses, electromagnetic interference (EMI), transient response, and implementation complexity [3]. Since this paper is a literature-based review rather than an experimental study, the analysis is mainly based on existing research, waveform characteristics, and theoretical comparison.

2. H-bridge operation and four-quadrant capability

2.1. Four-quadrant operation of DC motor

Four-quadrant operation of a DC motor refers to the ability of the drive system to control both the rotational direction and the electromagnetic torque direction. The mechanical power of the motor can be expressed as:

$$P = T\omega \tag{1}$$

where P is mechanical power, T is electromagnetic torque, and ω is angular speed. When torque and speed have the same sign, the motor operates in motoring mode. This corresponds to the first quadrant for forward rotation and the third quadrant for reverse rotation. When torque and speed have opposite signs, the motor operates in braking or regenerative mode. This corresponds to the second and fourth quadrants [4].

As shown in Figure 1, the torque-speed plane can be divided into four operating regions. This bidirectional energy conversion capability is important in applications requiring rapid deceleration, precise speed control, and improved energy efficiency. Therefore, a suitable drive system must provide a reversible voltage at the motor terminals and allow current to flow in both directions.

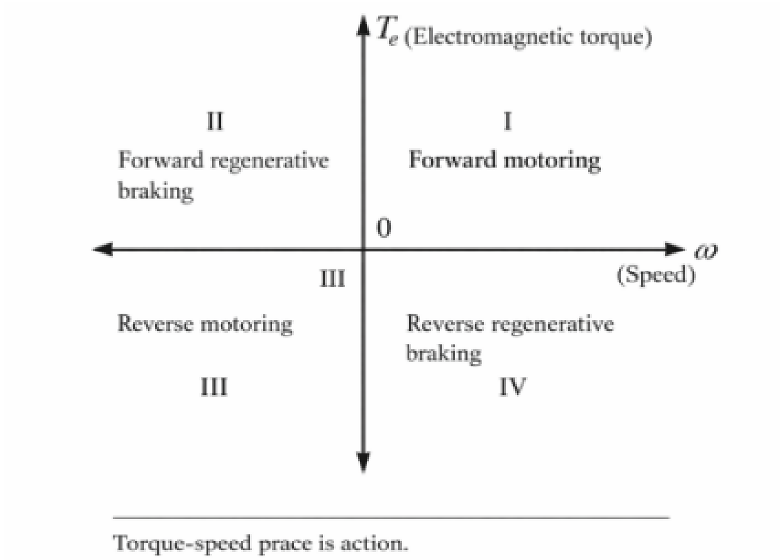

Figure 1. Torque-speed plane illustrating four-quadrant operation of a DC motor

DOI: 10.54254/2755-2721/2026.AD34360

2.2. Hardware requirements and H-bridge implementation

The four-quadrant operation discussed above requires bidirectional control of both voltage and current. An H-bridge converter consists of four switching devices arranged in a bridge structure. By controlling different diagonal switch pairs, the polarity of the voltage applied to the motor can be changed. This enables forward and reverse motor operation. In addition, the bridge and its freewheeling paths allow current to continue flowing when the motor inductance releases stored energy. These characteristics make the H-bridge suitable for bidirectional DC motor drive systems [5, 6].

In practical circuits, the switching devices may be metal-oxide-semiconductor field-effect transistors (MOSFETs) or insulated-gate bipolar transistors (IGBTs), depending on the required voltage, current, and switching frequency. Gate driving, dead-time insertion, and protection circuits are also required to ensure safe operation.

2.3. Operating modes of H-bridge drive

From the perspective of power flow, the four quadrants represent different directions of energy transfer. During motoring operation, electrical energy flows from the source to the motor and is converted into mechanical energy for the load. During braking or regenerative operation, mechanical energy from the load is converted back into electrical energy and may be returned to the source or dissipated in a braking element.

Therefore, a four-quadrant H-bridge drive must support power flow in both directions. This is the main difference between a simple one-direction motor driver and a bidirectional regenerative drive. The ability to reverse voltage polarity and maintain bidirectional current paths is the fundamental reason why the H-bridge is commonly used in four-quadrant DC motor applications.

3. Modulation and control strategies

3.1. Modulation strategies for H-bridge drives

3.1.1. Bipolar PWM

The modulation strategy of an H-bridge directly determines the voltage waveform applied to the motor. In bipolar pulse-width modulation (PWM), the output voltage of the bridge switches directly between +Vdc and -Vdc. This two-level waveform is simple to generate and can produce a strong voltage difference across the motor. As a result, bipolar PWM can provide fast current change and good transient response during rapid speed reversal or load variation.

However, the large voltage step also causes several disadvantages. The full DC bus voltage transition increases the rate of current change in the motor winding, which can lead to higher current ripple and torque pulsation [7]. Larger voltage transitions may also increase electromagnetic interference (EMI). In addition, frequent rail-to-rail switching can increase switching energy loss in the power devices [8]. Therefore, bipolar PWM is attractive for simple and low-cost systems, but its electrical performance is usually less favorable than unipolar PWM.

3.1.2. Unipolar PWM

In unipolar PWM, the two legs of the H-bridge are modulated separately. The motor terminal voltage can take three levels: +Vdc, 0, and -Vdc. Compared with bipolar PWM, the voltage step

DOI: 10.54254/2755-2721/2026.AD34360

applied to the motor is smaller. This reduces current ripple and helps to produce smoother torque [9]. The smaller voltage transition also helps reduce switching stress and EMI, which can improve the overall electrical performance of the drive.

The main disadvantage of unipolar PWM is its higher implementation complexity. It requires independent control signals for the two bridge legs and accurate dead-time management to avoid shoot-through. Nevertheless, most modern microcontrollers can generate complementary PWM signals with dead-time, so the practical difficulty is manageable. For applications that require lower ripple and higher efficiency, unipolar PWM is often preferred.

3.1.3. Comparison of bipolar and unipolar PWM

The key difference between bipolar and unipolar PWM is the size of the voltage step applied to the motor. Bipolar PWM switches directly between the positive and negative DC bus levels, while unipolar PWM introduces a zero-voltage level. This difference affects current ripple, switching losses, EMI, transient response, and implementation complexity. The comparison is summarized in Table 1.

Table 1. Performance comparison between bipolar and unipolar PWM

Performance metric	Bipolar PWM	Unipolar PWM
Voltage level	Two-level: +Vdc / -Vdc	Three-level: +Vdc / 0 / -Vdc
Voltage step	Large	Smaller
Current ripple	Higher	Lower
Switching loss	Higher	Lower
EMI	Higher	Lower
Transient response	Fast	Moderate
Implementation complexity	Low	Higher

As shown in Table 1, unipolar PWM generally provides better waveform quality, lower current ripple, and lower EMI. Bipolar PWM, however, has a simpler switching structure and is easier to implement. Therefore, the selection between the two methods depends on whether the design gives higher priority to electrical performance or implementation simplicity.

3.2. Control strategies for four-quadrant H-bridge DC motor drives

3.2.1. Voltage-mode control

In voltage-mode control, motor speed is regulated by adjusting the duty cycle of the PWM signal. The controller compares the reference speed with the measured speed and then changes the average output voltage of the H-bridge. This method has a simple structure, requires fewer sensors, and has a relatively low computational burden. Therefore, it is suitable for low-cost motor drive systems.

The limitation of voltage-mode control is that motor current is not directly regulated. Since electromagnetic torque is proportional to armature current, torque response depends on the natural electrical dynamics of the motor, such as armature inductance and back electromotive force (back EMF). During sudden load changes, speed reversal, or transitions between motoring and regenerative braking, the system may show larger overshoot and longer settling time [10].

DOI: 10.54254/2755-2721/2026.AD34360

3.2.2. Current-mode control

Current-mode control introduces an inner current loop in addition to the outer speed loop. Instead of only changing the applied voltage, the controller directly regulates armature current. Since motor torque is directly related to current, this method can improve torque response and disturbance rejection.

Compared with voltage-mode control, current-mode control usually provides lower overshoot and faster settling during dynamic operation [10]. This is particularly useful in four-quadrant drives, where the motor may frequently change between motoring and braking modes. However, current-mode control requires current sensing and more careful controller tuning. The additional hardware and control loops increase system complexity.

3.2.3. Comparative discussion

Voltage-mode and current-mode control mainly differ in how they treat armature current. Voltage-mode control adjusts the applied voltage and allows the current to follow according to motor characteristics. Current-mode control directly regulates the current, which gives better torque control. Table 2 summarizes the main differences between these two strategies.

Table 2. Comparison of voltage-mode and current-mode control strategies

Criterion	Voltage-mode control	Current-mode control
Control structure	Simple speed loop	Cascaded speed and current loops
Current regulation	Indirect	Direct
Transient response	Moderate	Improved
Overshoot	Larger	Reduced
Disturbance rejection	Limited	Enhanced
Implementation complexity	Low	Higher

As shown in Table 2, voltage-mode control is easier to implement, while current-mode control provides better dynamic performance. For applications with moderate performance requirements, voltage-mode control may be sufficient. For high-performance systems, current-mode control is more suitable because it can regulate torque more directly.

3.3. Integrated system-level discussion

Although modulation strategies and control architectures are often discussed separately, their interaction has a clear effect on the performance of four-quadrant H-bridge DC drives. The modulation method determines the voltage waveform applied to the motor, while the control architecture determines how current and torque are regulated.

For example, unipolar PWM produces smaller voltage steps and smoother motor current. When it is combined with current-mode control, the current loop can track the reference more easily, which helps reduce torque ripple and improve stability during dynamic operation. In contrast, bipolar PWM produces larger voltage transitions. This can improve response speed, but it also increases current ripple and places greater demand on the control loop during load changes or quadrant transitions.

DOI: 10.54254/2755-2721/2026.AD34360

Therefore, effective drive design should not optimize modulation and control independently. The final design should consider the combined influence of waveform quality, current regulation, transient response, system losses, and practical implementation difficulty.

4. Practical design considerations

In a practical four-quadrant DC motor drive design, engineers must balance performance, cost, and reliability. For high-performance applications such as EV traction drives and robotic actuators, unipolar PWM combined with current-mode control is often attractive because it provides smoother current, better torque control, and improved disturbance rejection. This combination is especially useful during regenerative braking and rapid speed reversal.

For low-cost or moderate-performance applications, voltage-mode control with a simpler PWM scheme may be more suitable. Although this solution may produce higher ripple and weaker dynamic performance, it reduces sensor requirements and simplifies the controller. This can be acceptable when the load changes slowly or when cost is the main design constraint.

Dead-time is another important issue. If two switches in the same bridge leg turn on at the same time, shoot-through may occur and damage the power devices. Therefore, a short dead-time must be inserted between complementary switching signals. However, excessive dead-time can distort the output voltage and affect current control accuracy. Current sensing and over-current protection are also necessary in reliable H-bridge systems, especially when the motor changes quickly between motoring and braking modes.

5. Conclusion

This paper has reviewed bidirectional DC motor drive strategies based on the H-bridge topology. The discussion started from the operating principle of four-quadrant DC motor drives, where the signs of torque and speed determine whether the motor operates in motoring or braking mode. This analysis shows why a four-quadrant drive must be able to reverse motor terminal voltage and support bidirectional current flow. The H-bridge converter is well-suited to this requirement because its bridge structure naturally provides reversible voltage polarity and multiple current paths. This paper then compared bipolar and unipolar PWM strategies. Bipolar PWM has the advantage of simple implementation and fast voltage reversal, which can support rapid transient response. However, because the motor voltage switches directly between +Vdc and -Vdc, the voltage step is large. This may increase current ripple, torque pulsation, switching losses, and EMI. Unipolar PWM introduces an additional zero-voltage level, reducing voltage steps and improving waveform quality. As a result, it usually provides lower current ripple, lower EMI, and better efficiency, although it requires more complex gate control.

Voltage-mode and current-mode control were also compared. Voltage-mode control is simple and low-cost, but it does not directly regulate armature current. Therefore, its torque response depends strongly on the motor's electrical dynamics. Current-mode control provides direct current regulation, which improves torque response, reduces overshoot, and strengthens disturbance rejection, but it requires current sensing and more careful controller tuning.

Overall, there is no universally best solution for all H-bridge DC motor drives. A high-performance system may prefer unipolar PWM with current-mode control, while a cost-sensitive system may choose a simpler voltage-mode structure. The most suitable design should be selected according to the required efficiency, transient response, reliability, and implementation cost.

DOI: 10.54254/2755-2721/2026.AD34360

References

[1] H. K. Bae and R. Krishnan. (1996) A study of current controllers and development of a novel current controller for high-performance SRM drives. IAS '96 Conference Record of the 1996 IEEE Industry Applications Conference, San Diego, CA, USA, vol. 1, pp. 68–75.
[2] N. Mohan et al. (2003) Restructuring of first courses in power electronics and electric drives that integrates digital control. IEEE Transactions on Power Electronics, vol. 18, no. 1, pp. 429–437.
[3] A. Ruderman. (2007) Three-phase multi-level PWM rectifier multi-carrier discontinuous voltage modulation strategy. 2007 European Conference on Power Electronics and Applications, Aalborg, Denmark, pp. 1–9.
[4] S. B., C. P. N., A. N., R. M., and Y. S. M. (2025) Design and implementation of four-quadrant DC drive. 2025 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE), Bangalore, India, pp. 1–5.
[5] M. Glinka and R. Marquardt. (2005) A new AC/AC multilevel converter family. IEEE Transactions on Industrial Electronics, vol. 52, no. 3, pp. 662–669.
[6] J. Fang, Z. Li, S. M. Goetz, S. Yang, and H. Wang. (2020) H-bridge MMCs with symmetrical half-bridge submodules. 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, pp. 2904–2908.
[7] J. C. A. Floriani. (2004) Generalized analysis of current ripple in a pulse-width modulation H-bridge converter with unipolar-bipolar switching. IEEE Power Electronics Letters, vol. 2, no. 3, pp. 83–86.
[8] R. W. Erickson and D. Maksimović. (2001) Fundamentals of Power Electronics, 2nd ed. Boston, MA, USA: Springer.
[9] J. Gottschlich and R. W. De Doncker. (2015) A programmable gate driver for power semiconductor switching loss characterization. 2015 IEEE 11th International Conference on Power Electronics and Drive Systems, Sydney, Australia, pp. 456–461.
[10] H. M. Usman, A. G. Haddad, H. Rehman, and S. Mukhopadhyay. (2019) Comparison of PI and FOPI-based voltage and current controlled DC motor drive system. 2019 International Aegean Conference on Electrical Machines and Power Electronics (ACEMP) and 2019 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Istanbul, Turkey, pp. 139-142.