《高阶会员专属视频》-第34期

安川电机发表的速度搜寻技术，适用于永磁同步与感应电机，让电机在有初始速度下能无缝接续启动

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An Estimation Method of Rotational Direction and Speed for Free-Running AC Machines Without Speed and Voltage Sensor

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***Abstract*—This paper presents an estimation method of rotational direction and speed for free-running ac machines driven by an inverter without speed and voltage sensor. The method has four estimation modes, and it utilizes only the measured phase current of machines. The performance of the proposed method is verified through the experiments for both permanent-magnet synchronous motor and asynchronous machines.**

***Index Terms*—AC machines, estimation of rotational direction and speed, free running, without speed and voltage sensor.**

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I. Introduction

RECENTLY, fan and turbine systems driven by variable speed ac drives have been popular owing to the trend of energy saving for global environment protection. In such system, sometimes ac machines rotate by external torque such as water flow or wind power without being energized by inverters. In those cases, overvoltage or overcurrent faults can occur if the rotating motor and inverter voltage are out of phase. In order to avoid trips, rotating speed and direction of the machine are required to synchronize an inverter with the machine. However, most of the systems are speed sensorless drives. Therefore, speed estimation is required. For example, the inertia of the fan systems is 50–300 times bigger than that of the ac machines, and it does not stop for a few minutes up to several tens of minutes during free running of the machines. Even with such

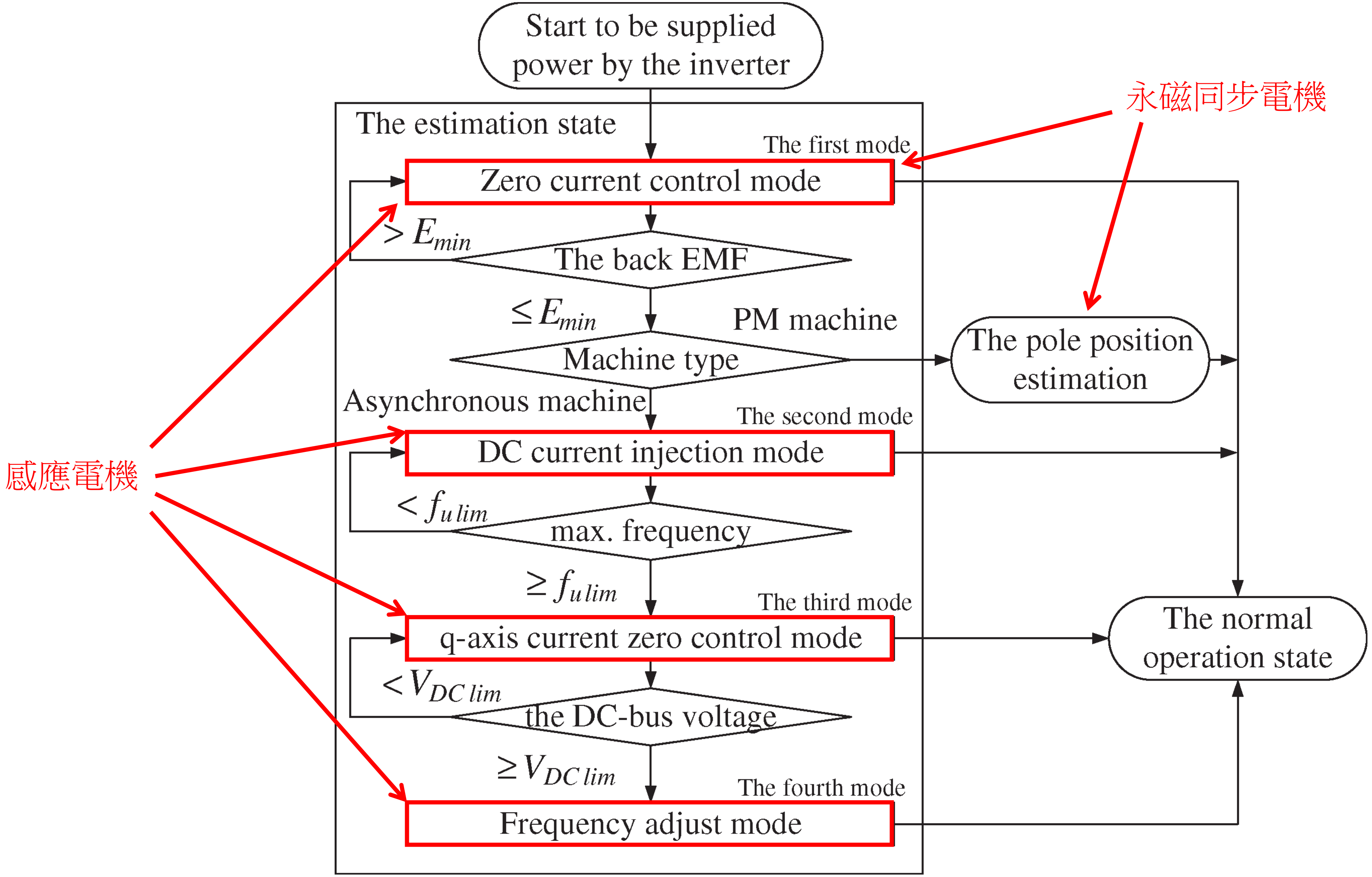

Fig. 1. Flowchart of the estimation mode shift sequence.

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The first mode is most suitable for estimating PMSM machines or asynchronous machines with a long rotor time constant. In this mode, the rotational direction and speed can be estimated by the back EMF. The first mode detects the back EMF by controlling the motor current to zero. The first mode is called the zero-current control mode. When the back EMF is less than the setting value $E_{\min}$, the speed and the rotational direction cannot be correctly estimated by the first mode. In case of the asynchronous machine, the back EMF reduces even though the machine rotates. Therefore, asynchronous machine needs the estimation mode that is not based on the back EMF. The mode shifts from the first mode to the second mode. Since the back EMF is generated whenever PMSM rotates, it is standstill or low speed. In this case, the method shifts into the pole-position estimation state. The pole position or initial pole-position method of the PMSM is proposed by a high-frequency injection method [5]. However, the magnetic pole-position detection might be disturbed if the rotor were not standstill. In that case, power devices on the P side (or N side) of the inverter are turned on at the same time. Then, the PMSM machine is stopped by a short-circuited current. The method shifts from the pole-position state to the normal operation state. Thus, the estimation method for PMSM machine is applied only in the first mode.

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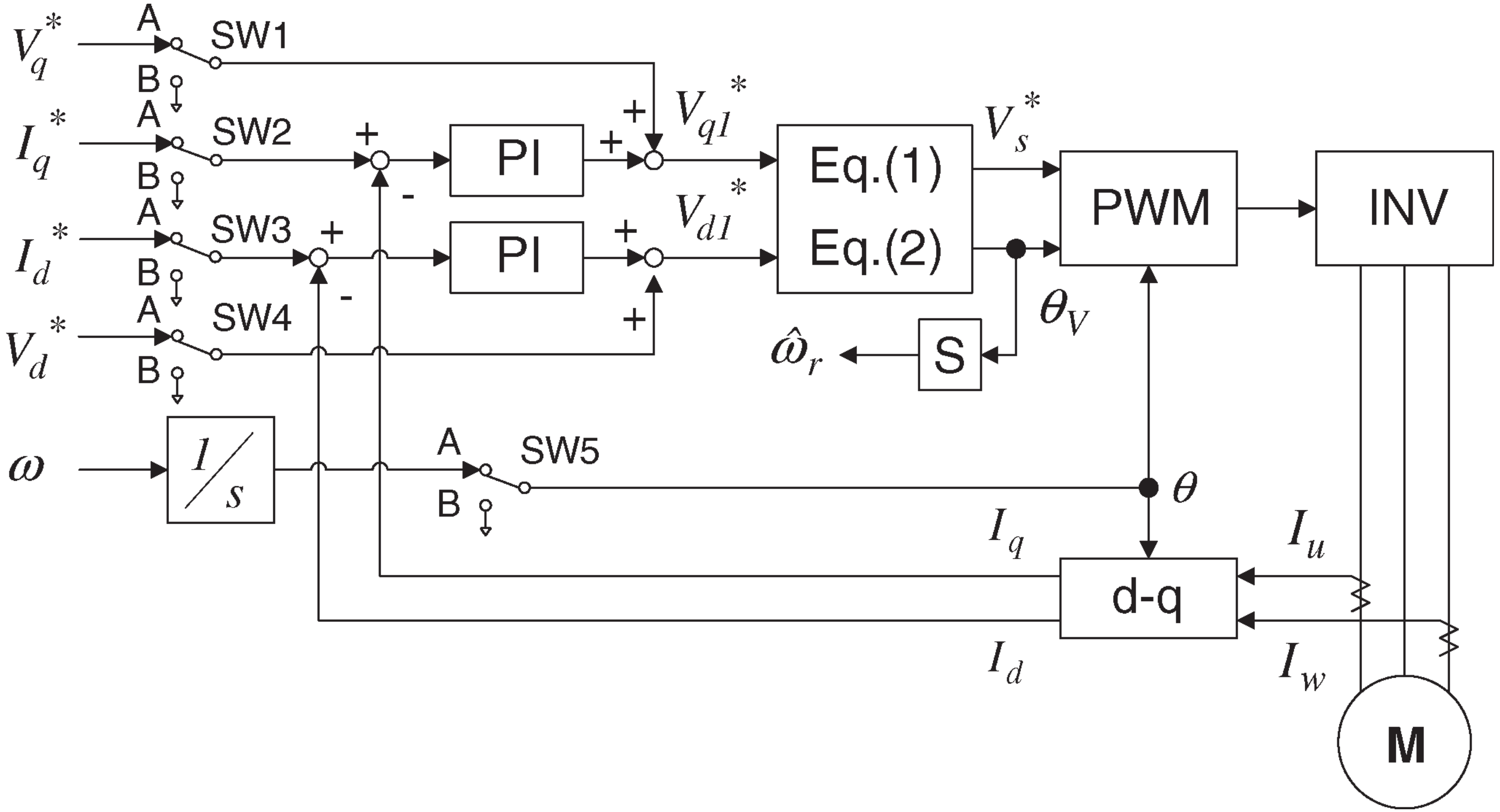

Fig. 2. Block diagram of the zero-current control mode.

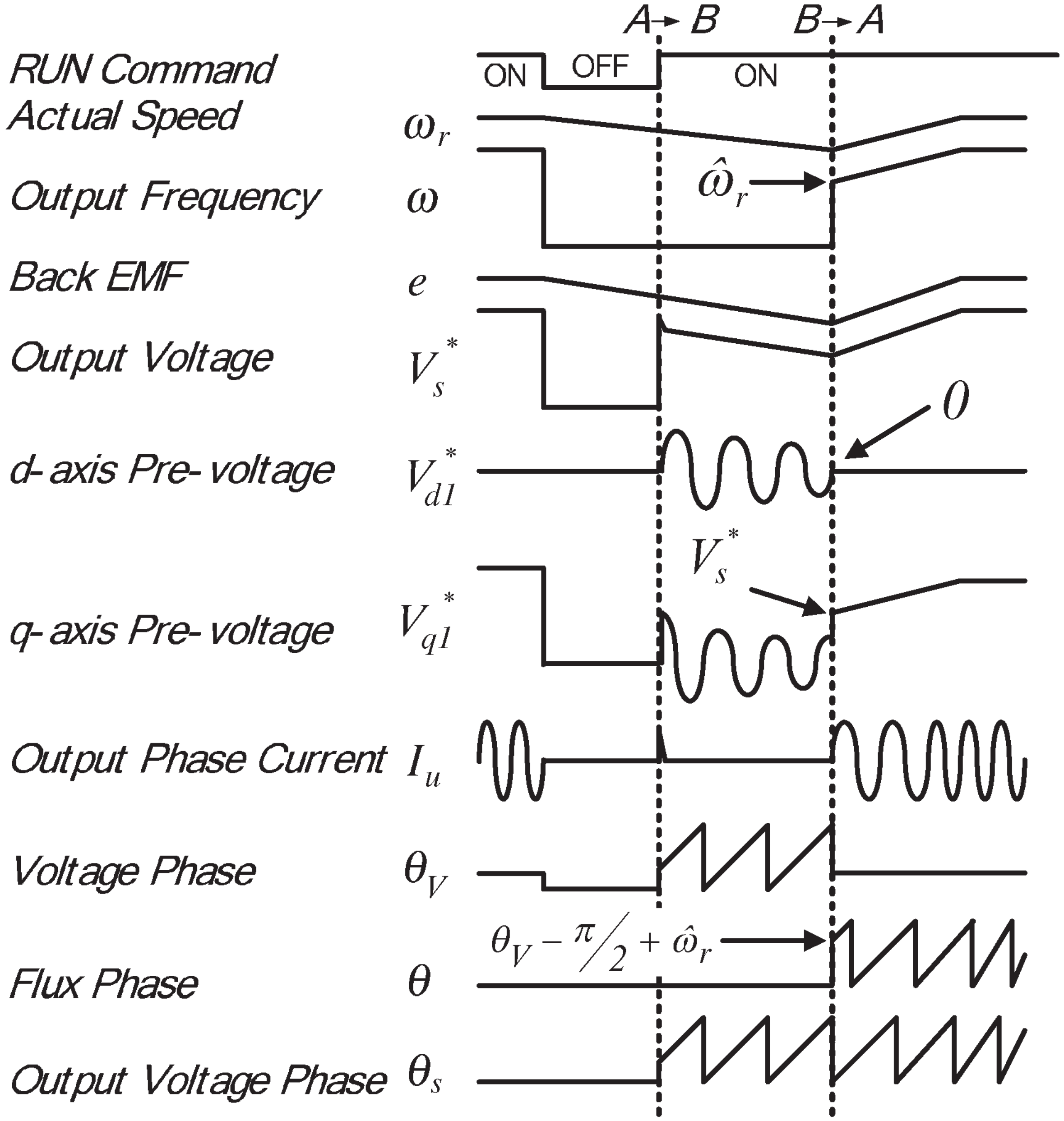

Fig. 3. Timing chart of the zero-current control mode for PMSM.

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A. Zero-Current Control Mode for PMSM Machine

Fig. 2 shows the block diagram of the zero-current control mode. Fig. 3 shows the timing chart of the zero-current control mode for PMSM machine. The mode starts with turning on all switches from A side to B side; the d-axis current command I_d^*, the q-axis current command I_q^*, the d-axis prevoltage command V_d^*, the q-axis prevoltage command V_q^*, and the flux phase θ are set to zero. If the machine is rotating, the current induced by the back EMF flows during the zero control mode. The amplitude and phase of inverter output voltage will be synchronized with

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that of the back EMF if the output current is zero. The output voltage command V_s^* and the voltage phase θ_V are shown in (1) using the d-axis voltage command V_{d1}^* and the q-axis voltage command V_{q1}^*

$$V_s^* = \sqrt{V_{d1}^{*2} + V_{q1}^{*2}} \tag{1}$$

$$\theta_V = \tan^{-1} \frac{V_{q1}^*}{V_{d1}^*}. \tag{2}$$

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Fig. 4(a) shows the locus of the output voltage vector and the variations of the d-axis voltage command V_{d1}^* and the q-axis voltage command V_{q1}^* when the machine is rotating in forward direction; Fig. 4(b) shows the case of the reverse direction.

The output voltage phase θ_V contains the information of the rotational direction and the speed. Therefore, the estimated speed $\hat{\omega}_r$ of the machine is calculated from the output voltage phase θ_V as follows:

$$\hat{\omega}_r = \frac{d\theta_V}{dt}. \tag{3}$$

The polarity of the estimated speed $\hat{\omega}_r$ of the machine is plus when the machine is rotating forward. The method shifts from the estimated state to the normal operation state when the

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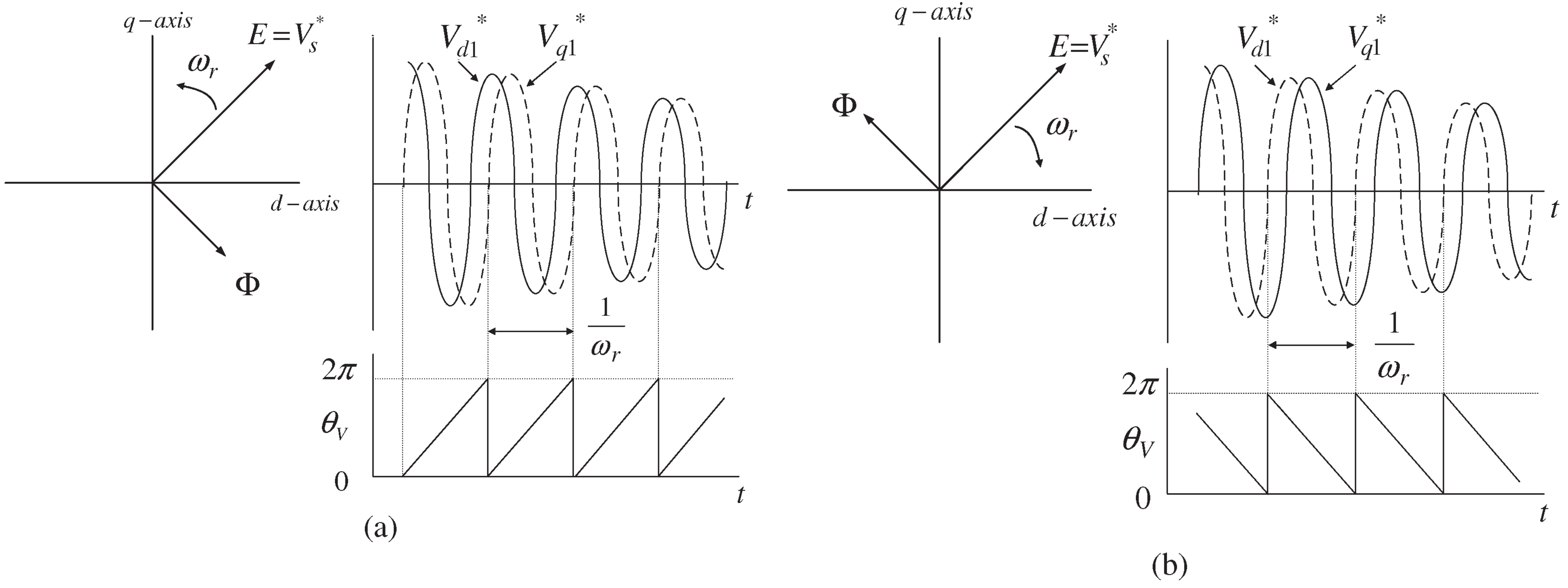

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method is able to detect them. The amplitude, phase, rotational direction, and frequency of the inverter output voltage are used as an initial condition of the normal operation. The d-axis prevoltage command V_d^* and the q-axis prevoltage command V_q^* are set, respectively, depending on the next equations

$$V_d^* = 0 \tag{4}$$

$$V_q^* = \begin{cases} V_s^* & \text{(forward)} \\ -V_s^* & \text{(reverse).} \end{cases} \tag{5}$$

The output frequency ω is set the same as the estimated speed in (3)

$$\omega = \hat{\omega}_r. \tag{6}$$

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The d-axis is fixed to the u-phase of the stator in the estimated state. However, the d–q-axes should be rotated in the normal operation state. Therefore, the flux phase θ should be set as follows:

$$\theta = \begin{cases} \theta_V - \frac{\pi}{2} + \hat{\omega}_r \cdot T_s & \text{(forward)} \\ \theta_V + \frac{\pi}{2} - \hat{\omega}_r \cdot T_s & \text{(reverse)} \end{cases} \tag{7}$$

where T_s is the sampling time of the current control.

After the estimated state is over, all switches are turned on from B side to A side. Then, the machine starts accelerating or decelerating according to the speed command.

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B. Zero-Current Control Mode for Asynchronous Machine

Naturally, the estimation principle of the speed and the rotational direction of the zero-current control mode for asynchronous machine is the same as that of the PMSM machine. Therefore, the same block diagram is used, as shown in Fig. 2. However, the residual flux of the asynchronous machine weakens according to the rotor time constant. The difference between the PMSM machine mode and asynchronous machine in the mode appears in the q-axis voltage amplitude. Therefore, the timing chart changes as shown in Fig. 5. Due to the decay of rotor flux, estimated q-axis voltage is smaller than normal voltage to frequency (V/F) level. Therefore, the q-axis prevoltage command V_q^* is needed to increase up to the voltage referred to the normal V/F level according to output frequency ω. Then, the machine accelerates or decelerates according to the speed command.

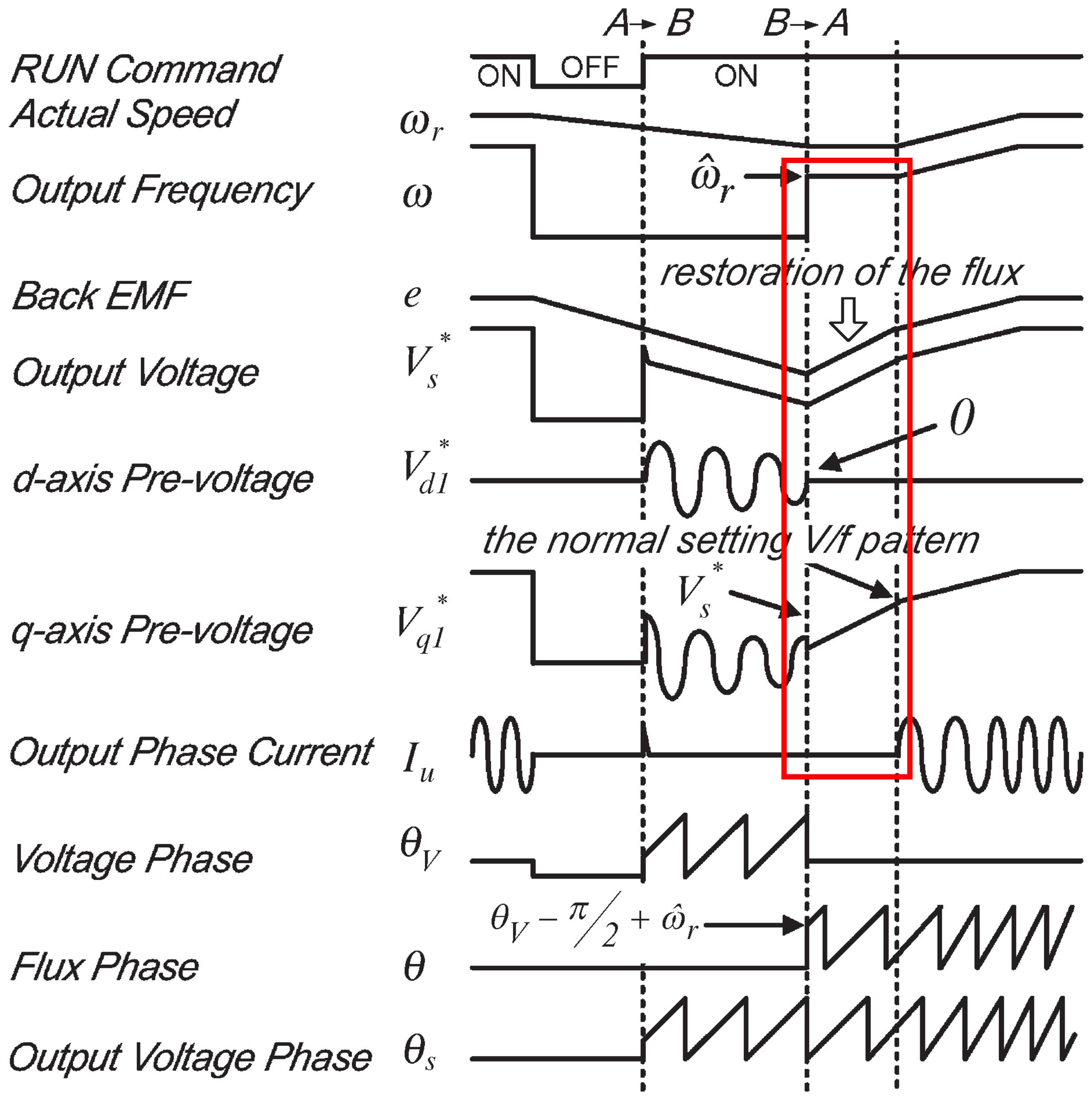

Fig. 5. Timing chart of the zero-current control mode for asynchronous machine.

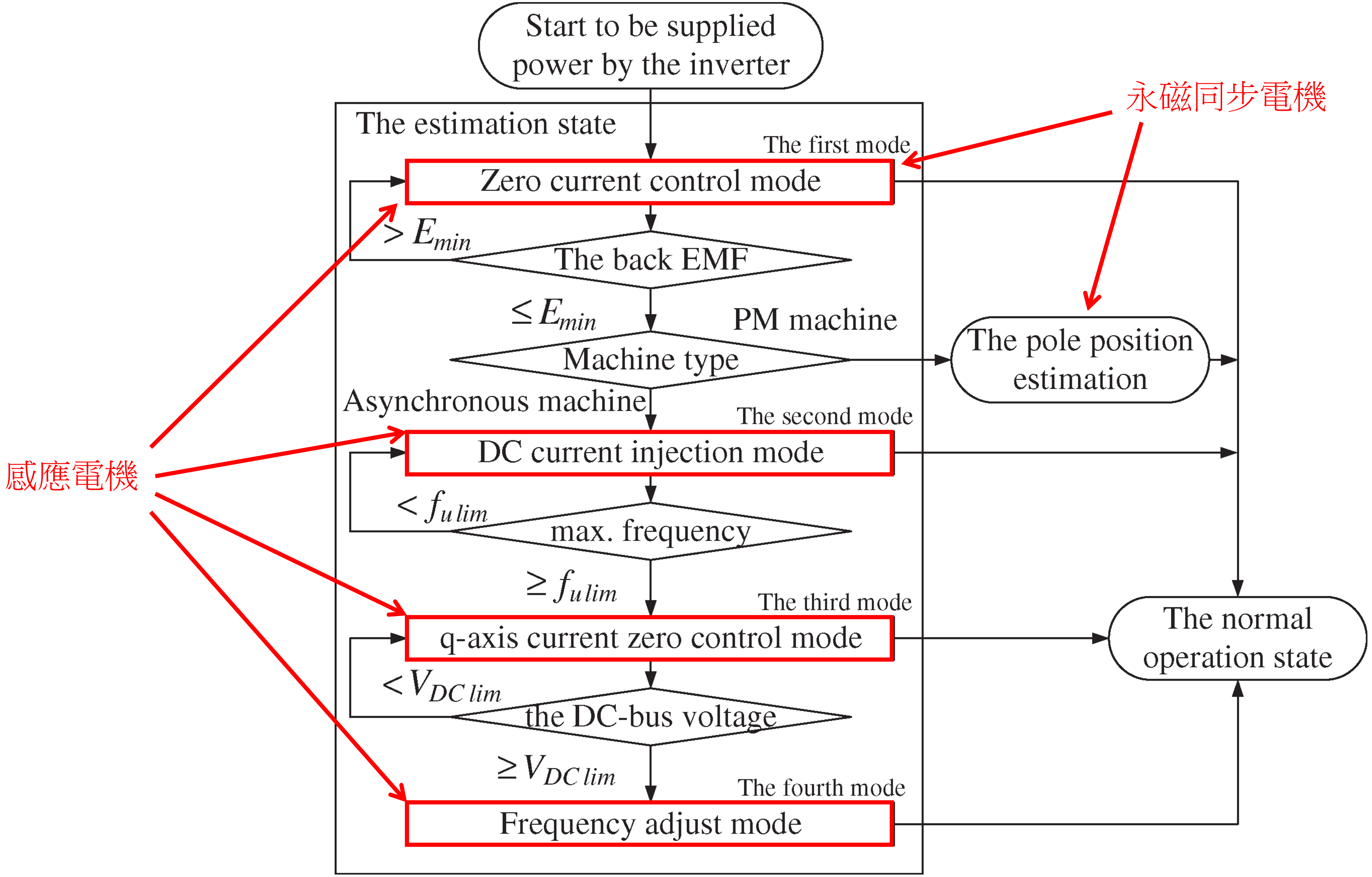

Fig. 1. Flowchart of the estimation mode shift sequence.

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C. DC Current Injection Mode

Figs. 6 and 7 show the block diagram and the timing chart of the dc injection mode. It starts with turning on all switches from A side to B side, then the d-axis voltage command V_d^*, the q-axis voltage command V_{q1}^*, and the flux phase θ are set to zero. The d-axis is fixed to the u-phase. It is important to control only the d-axis current because the speed information is detected from the variations of the q-axis current. When the dc current is injected to the machine, the primary flux is excited. If the machine is rotating, the q-axis current will flow by the generated back EMF in the rotor. The frequency of the q-axis current corresponds to the speed of the machine. The speed of the machine can be estimated by detecting the frequency of the q-axis current.

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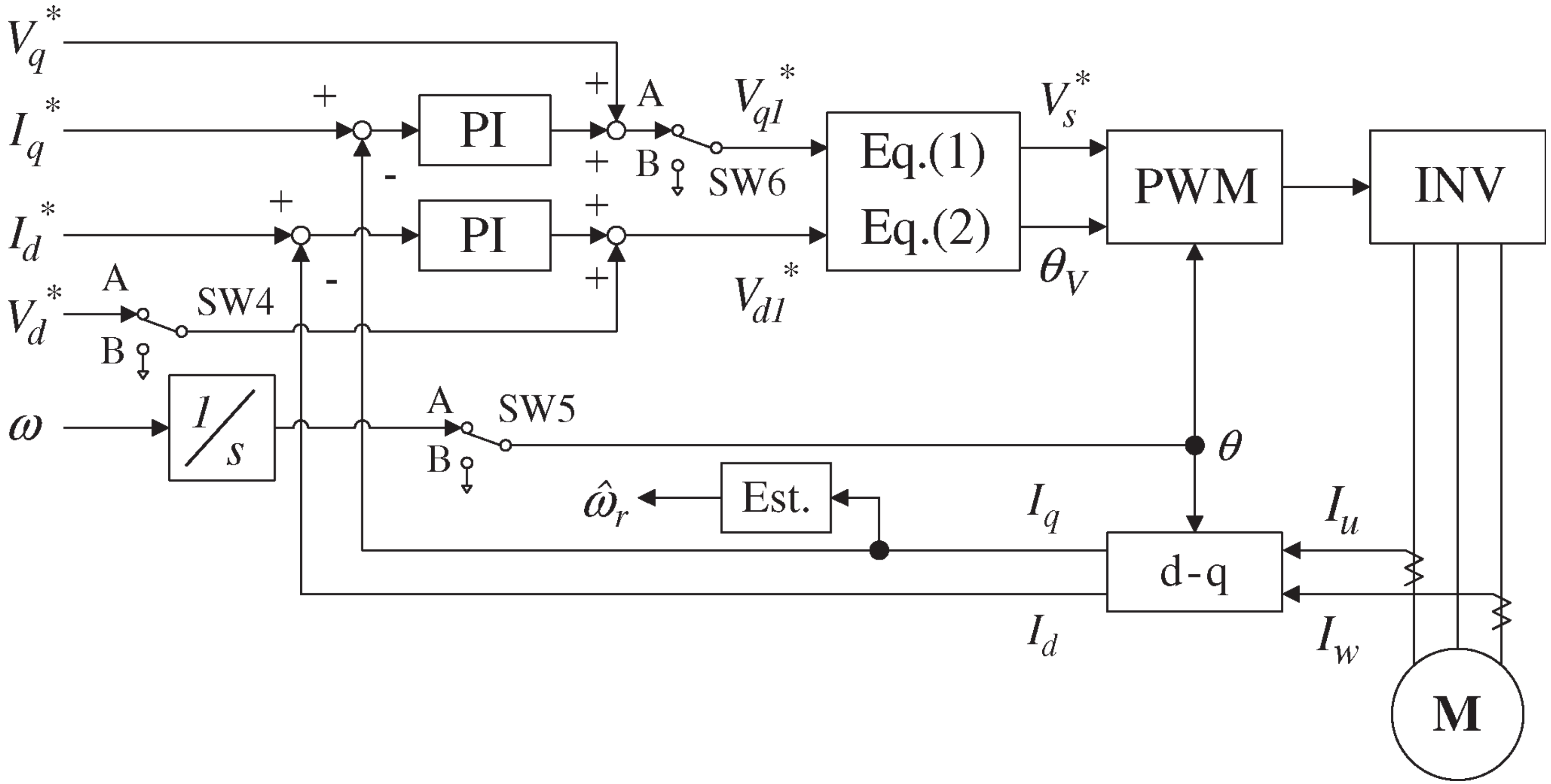

Fig. 6. Block diagram of the dc current injection mode.

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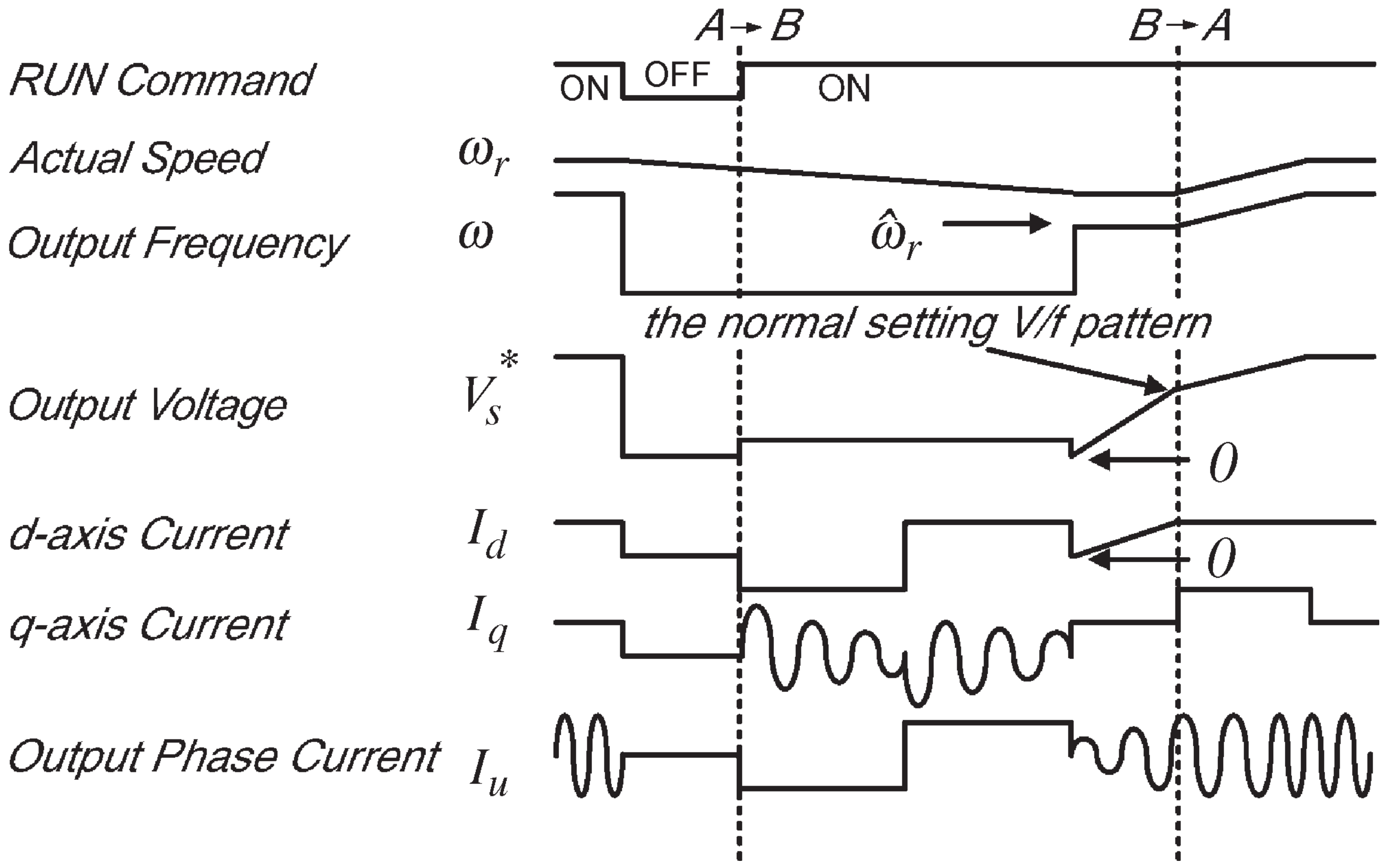

Fig. 7. Timing chart of the dc current injection mode.

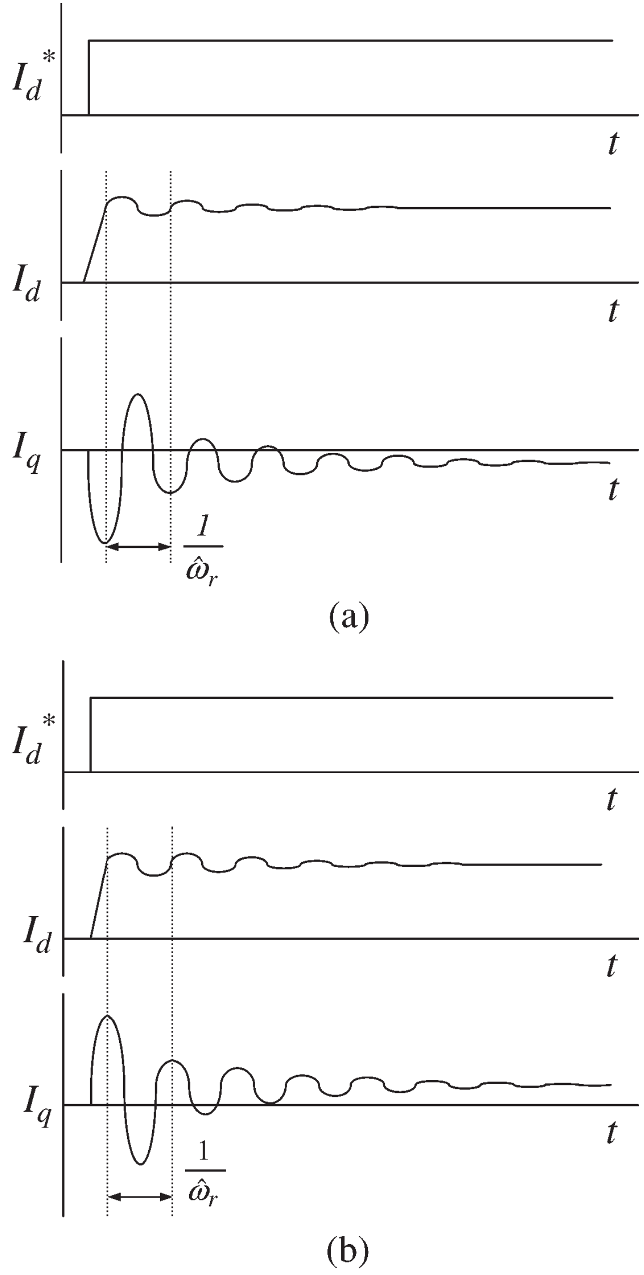

Fig. 8. d-axis current and the q-axis current waves of the injected dc current of the machine. (a) Forward direction. (b) Reverse direction.

Fig. 8(a) shows the d-axis current and the q-axis current waveforms of the injected dc current of the machine when the machine is rotating in forward direction, and Fig. 8(b) shows the case of the reverse direction. The phase of the oscillating component in the q-axis current lags compared to that in the d-axis current, or the q-axis current starts from the minus direction when the machine is rotating in forward direction. The phase of the oscillating component in the q-axis current goes ahead of that in the d-axis current, or the q-axis current starts from the plus direction. However, the phase of the exited flux is affected by the phase of the small residual flux in the machine as

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D. *q*-Axis Current Zero Control Mode

Figs. 12 and 13 show the block diagram and the timing chart of the q-axis current zero control mode. It starts with turning on all switches from A side to B side; the d-axis prevoltage command V_d^* and the frequency ω are set to zero. The d-axis current command I_d^* is set to the exciting current, and PI controller is used for the current control. When the machine is rotating, then the q-axis current I_q is induced by the back EMF. The dc-bus voltage V_{dc} rises because the q-axis current flows from the machine to the inverter. Although it is easy to control the q-axis current so that the dc-bus voltage does not rise, the q-axis current I_q must not be controlled because it contains the important speed information. If the machine is rotating forward, the q-axis current I_q flows into the minus direction by the back EMF. This principle is explained by using Figs. 14 and 15.

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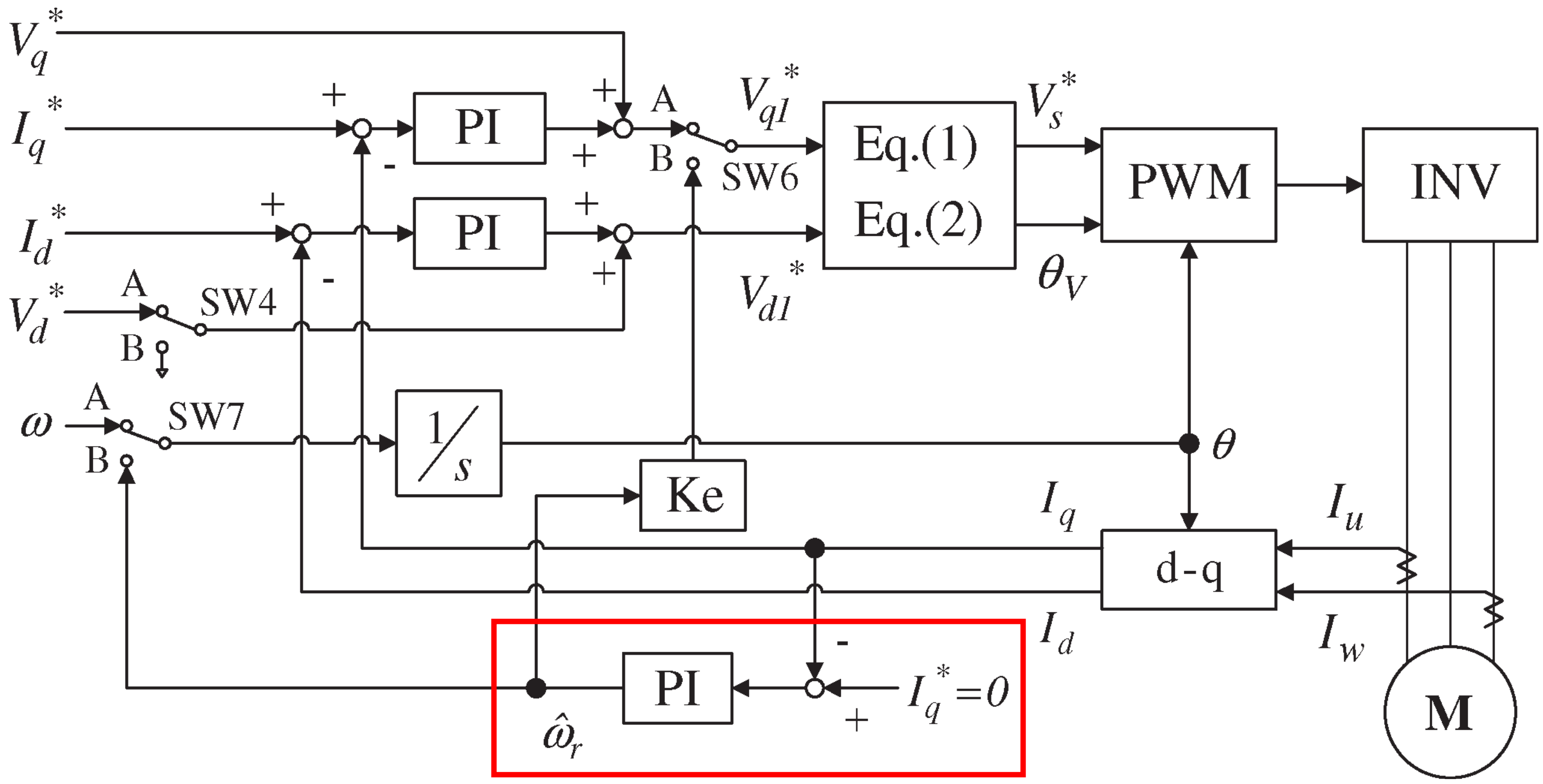

Fig. 12. Block diagram of the *q*-axis current zero control mode.

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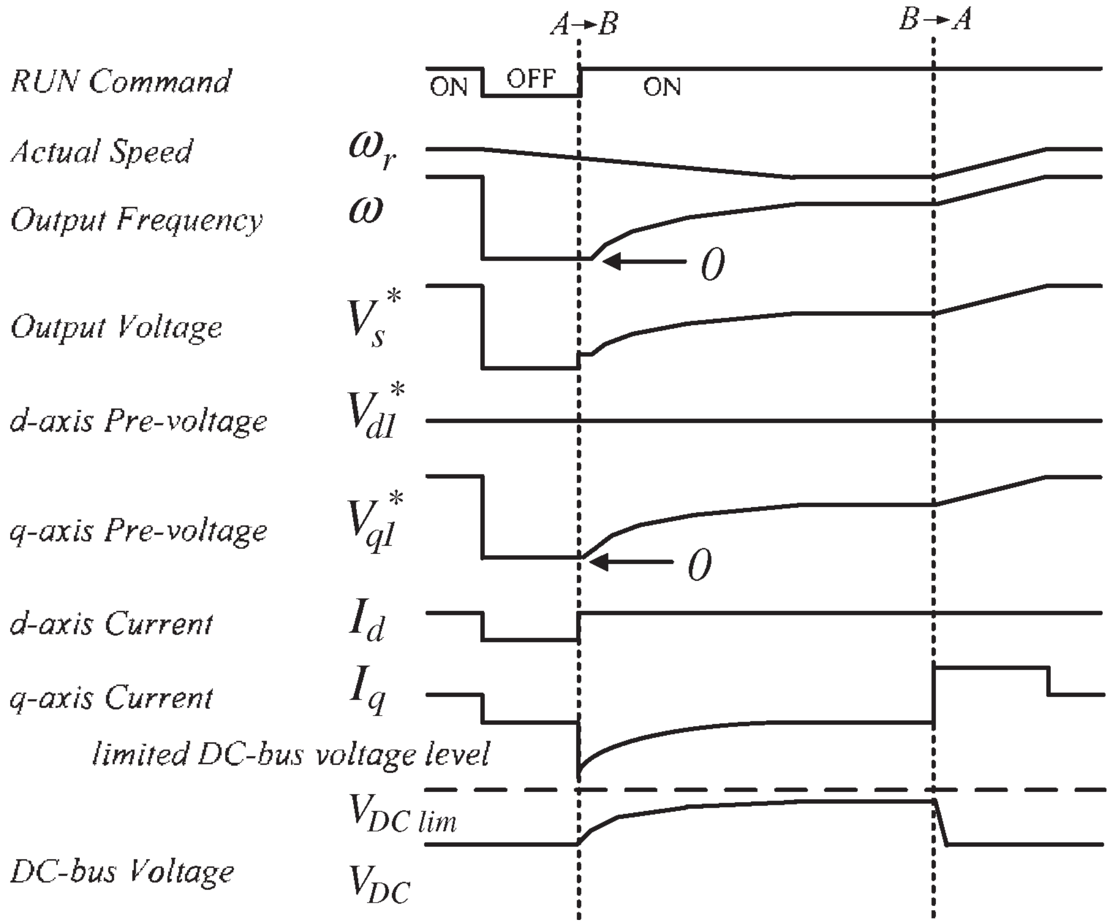

Fig. 13. Timing chart of the *q*-axis current zero control mode.

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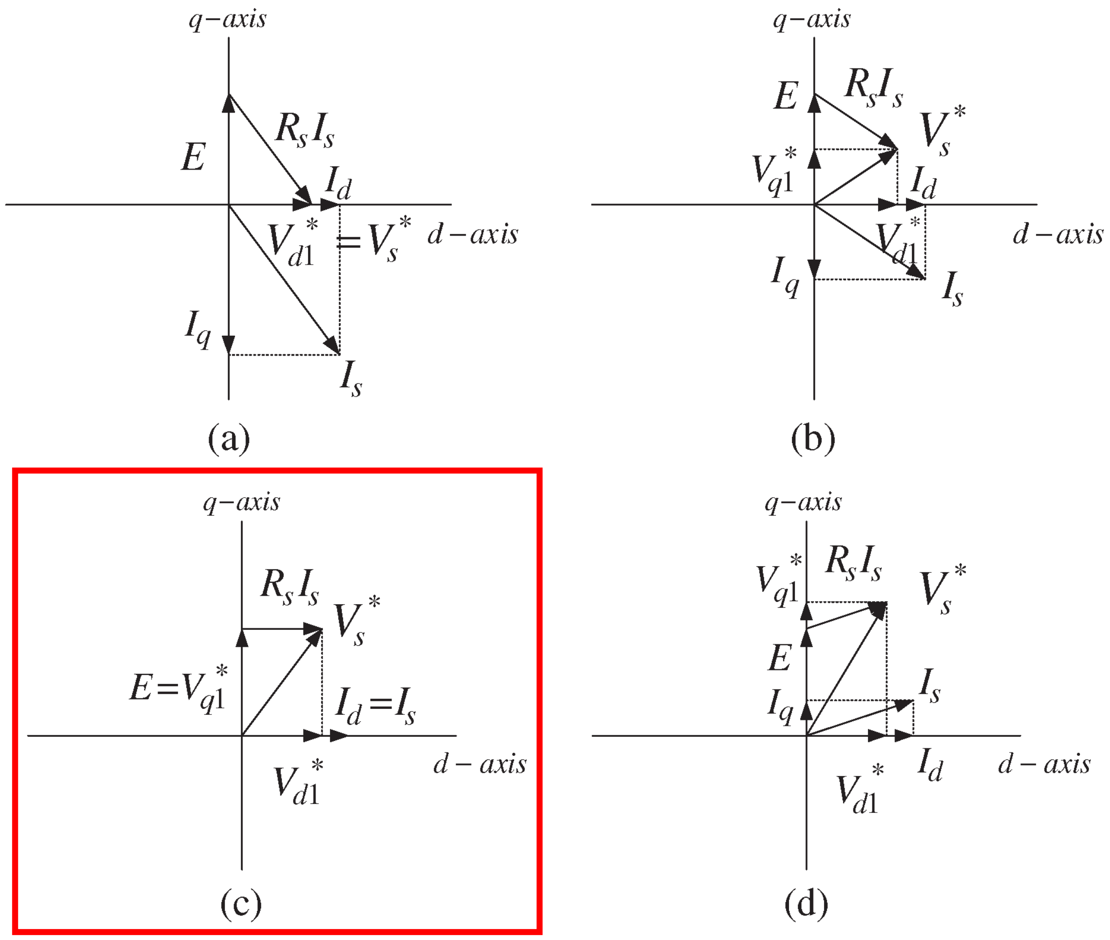

Fig. 15. Voltage and the current vector diagram. (a) $\omega = 0$. (b) $\omega < \hat{\omega}_r$. (c) $\omega = \hat{\omega}_r$. (d) $\omega > \hat{\omega}_r$.

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E. Frequency-Adjust Mode

Figs. 16 and 17 show the block diagram and the timing chart of the frequency-adjust mode. It starts with switching all switches from A side to B side, and the d-axis voltage command V_{d1}^* is set to zero. The frequency adjustor is set to the maximum frequency of the machine. The voltage adjustor increases the q-axis voltage command V_{q1}^* from zero to the maximum value according to the rotor time constant of the machine.

The estimation principle can be explained with Fig. 14. The amplitude of the output current I_s is determined by slip S that is the difference between the output frequency ω and the actual

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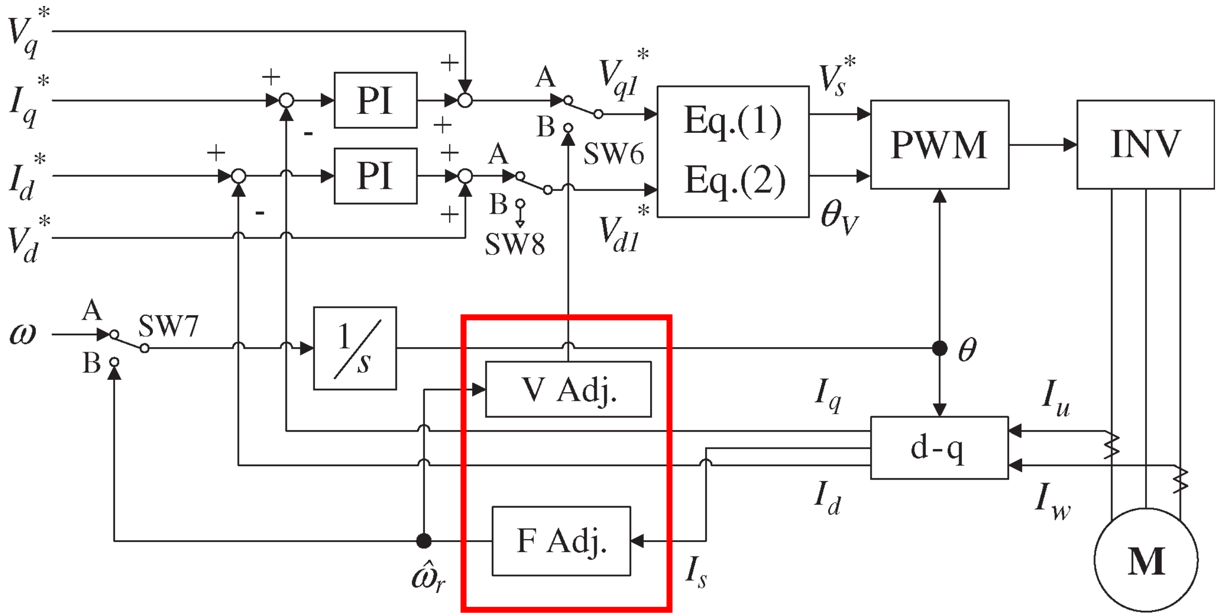

Fig. 16. Block diagram of the frequency-adjust mode.

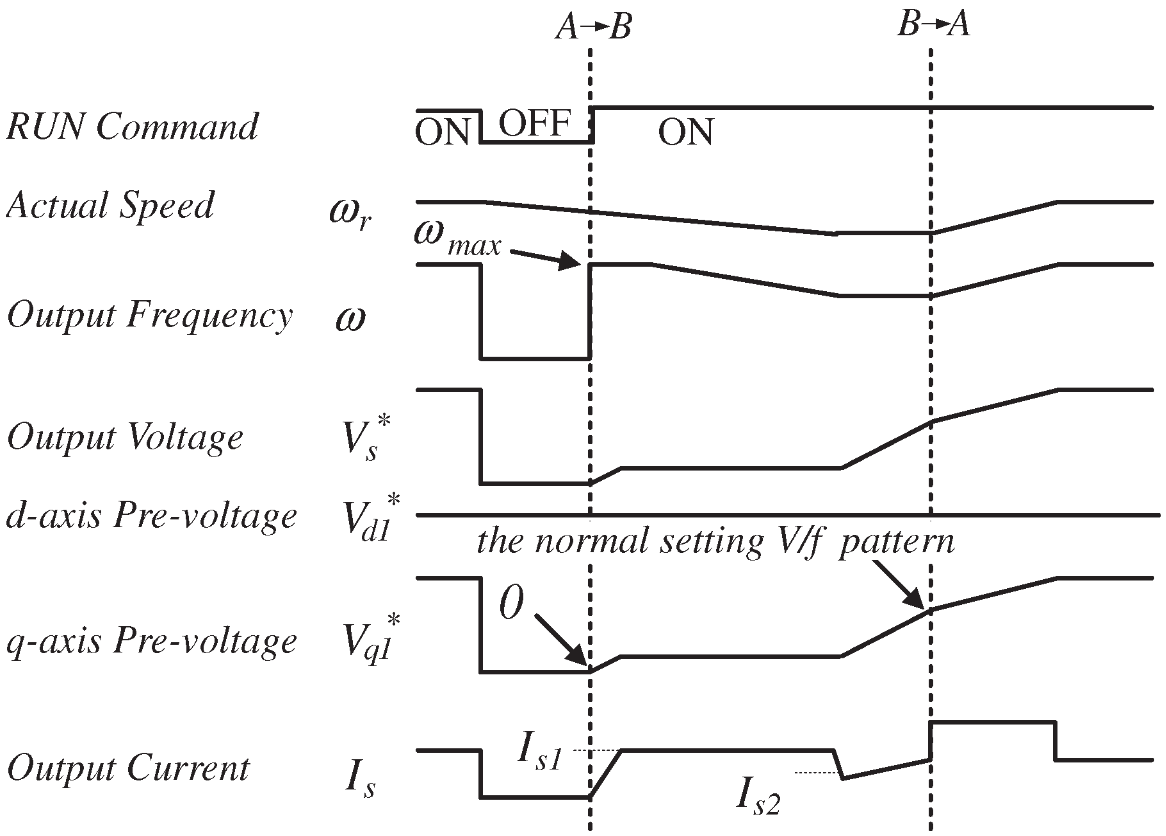

Fig. 17. Timing chart of the frequency-adjust mode.

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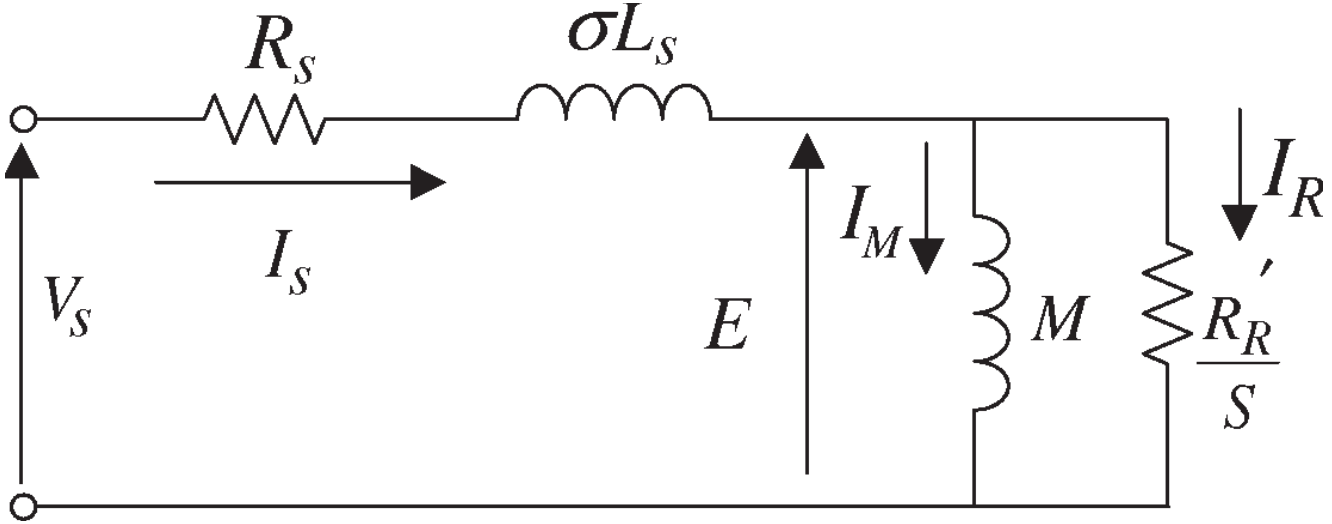

Fig. 14. Equivalent circuit of the asynchronous machine.

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speed ω_r. When the machine is standstill (i.e., the slip $S = 1$), then the output current can be obtained as follows:

$$I_s = \frac{1}{\sqrt{(R_s + R'_R)^2 + \omega^2 \sigma L_s^2}} V_s. \tag{8}$$

In this case, current to the mutual inductance is negligible. When the machine rotate at synchronous speed (i.e., the slip $S = 0$), then the output current can be obtained as follows:

$$I_s = \frac{1}{\sqrt{R_s^2 + (\omega \sigma L_s + \omega M)^2}} V_s. \tag{9}$$

In this case, the output current I_s does not flow to the rotor resistance and (9) is the amplitude of the exciting current or the no-load current.

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chine or the overload fault of the inverter might occur. If the output current I_s is larger than the setting level I_{s1} before the q-axis voltage command V_{q1}^* reaches the maximum, the q-axis voltage command V_{q1}^* is held. The level I_{s1} is set to 15%–25% bigger than the exciting current level. This level is suitable for precise speed estimation preventing torque shock. Then, the q-axis voltage command V_{q1}^* is held while the frequency adjustor reduces the frequency ω. When the current increases further, the frequency command is held and the voltage command V_{q1}^* is reduced. After then, the q-axis voltage command V_{q1}^* is held, while the frequency adjustor reduces frequency ω again. The output current I_s is getting closer to the exciting current level if the output frequency corresponds to the speed of the machine.