Practical tables for tolerance assessment of adjustable speed drives under voltage sag

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Abstract
The tolerance of adjustable speed drive (ASD) under voltage sag is important for users to select equipment and take mitigation methods. However, it is not easy for users to obtain the tolerance information of ASD. To address this issue, this paper proposes practical tables for tolerance assessment of ASD under voltage sag, providing a simpler and faster way for an approximate understanding of the tolerance of ASD. First, this paper proposes a calculation method for three trip characteristics to describe the tolerance of ASD. Second, this paper presents a voltage tolerance curve (VTC) assessment model based on the three trip characteristics, and the coordinate of the “knee point” of VTC can be assessed straightforwardly. Furthermore, the practical tables for tolerance assessment of ASD are formed based on the studies mentioned above. Users can obtain the tolerance of ASDs by looking up the table when they know several key parameters. Simulations tests verify the effectiveness of the calculation method and practical tables.

1 | INTRODUCTION

Voltage sag may lead to abnormal operation of sensitive equipment in the industrial process, bringing huge economic losses to industrial users [1–3]. Adjustable speed drive (ASD) is the indispensable but sensitive equipment in industrial processes, which may trip the process under voltage sags [4]. However, there is limited information about the tolerance of ASD from manufacturers [5]. Utilities and the users are interested in a simpler and faster method for an approximate understanding of the tolerance of ASD under voltage sag, when purchasing ASDs or mitigation equipment against voltage sag.

The voltage tolerance curve (VTC) [6] is used to quantify the tolerance of ASD usually. There are two typical ways to obtain VTCs under voltage sags.

The first way is the experimental test. IEEE Std. 1668–2017 [7] and IEC 61000-4-11 [8] recommend tolerance testing methods. The test results show that there are two major causes of ASD shutdown under voltage sag [9,10]: (i) the low DC voltage triggering the low-voltage protection (LVP) during the voltage sag, (ii) the inrush current triggering the overcurrent protection (OCP) at the ending of sag. DC voltage and current are affected by voltage sag type, residual voltage, duration, capacitor capacity and load rate [9–14]. The other parameters, such as point on wave (POW) and phase angle jump (PAJ) have little influence on the behaviour of ASD [9]. Nevertheless, there are limited types or brands of ASDs that have been tested, due to the high cost of experimental tests. There is no tolerance information of most untested ASDs.

The other way is to get the tolerance information by simulations [15–17], to avoid high-cost experimental tests. The detailed models consist of open-loop V–Hz controlled, closed-loop V–Hz controlled and vector controlled drives [18, 19]. Although simulation can avoid the expensive cost, the modelling process is extraordinarily complicated. Thus, it is difficult for most industrial users to establish the simulation model of ASD and complete the simulation test, due to the lack of professional knowledge and skills.

Because of the limitations of the two methods mentioned above, it is difficult for users to get the tolerance information of ASD directly. In fact, it is possible to propose a simpler and faster method for an approximate understanding of the tolerance of ASD, from the knowledge of the response mechanism of ASD under voltage sag.

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To address this issue, this paper proposes an effective method to obtain VTC to help users understand the tolerance of ASD easily and quickly. The novelties and main contributions of this paper are as follows.

1. This paper proposes three trip characteristics, including one threshold duration and two threshold voltages for triggering LVP and OCP respectively. And the calculation method for trip characteristics is proposed by studying the response mechanical of ASD under voltage sag.
2. This paper proposes an assessment model to get the approximate VTC by the “knee points”. The “knee points” under different types of voltage sags can be obtained based on the three trip characteristics.
3. This paper establishes practical lookup tables to help users quickly understand the tolerance of ASD. The “knee points” of ASD under different typical parameters are presented in the practical lookup table. With the help of the practical lookup table, users can obtain the tolerance of ASDs by looking up the table when they know the related parameters.

The paper is organized as follows. Section 2 introduces the structure of ASD and its integrated protection function. The calculation method for trip characteristics of ASD is proposed in Section 3, based on the response mechanism of ASD under voltage sag. The response mechanism of ASD can be divided into three parts, including the response characteristics in the pre-event segment, during-event segment and post-event segment of voltage sag. In Section 4, a VTC assessment model and related practical tables for tolerance assessment of ASD under voltage sag are presented. Simulations tests are conducted in Section 5 to verify the effectiveness of the assessment model and the table. Finally, conclusions are summarized in Section 6.

2 STRUCTURE AND PROTECTION OF ASD

ASD is the most common power electronic equipment in the industrial process. The circuit structure of ASD and its integrated protection are introduced briefly here.

2.1 Structure of ASD

The structure of a typical ASD is shown in Figure 1 [15]. The main circuit of ASD consists of a rectifier, a DC-link and an inverter. The rectifier is composed of diodes, and each phase bridge contains two diodes. The inductor $L$ in the DC-link is used to smooth DC current. The capacitor $C$ in DC-link is used for energy storage to reduce DC voltage fluctuations. Each phase bridge arm of the inverter contains two insulated gate bipolar transistors (IGBTs) and two feedback diodes. The role of the inverter is to convert DC voltage into AC voltage with adjustable magnitude and frequency.

2.2 The protection of ASD

The main protections of ASD include over-voltage protection, low-voltage protection, overcurrent protection, overload protection, etc. The low-voltage protection and overcurrent protection often trip ASD during the voltage sag.

(i) Low-voltage protection: The function of LVP is to prevent ASD from running abnormally or being damaged when DC voltage is too low. LVP is often triggered by faults on the AC side, such as voltage interruptions or voltage sags.

(ii) Overcurrent protection: The function of OCP is to prevent the jump-value of current exceeding the allowable DC current of ASD. This allowable current is related to the margin of power electronic devices such as diodes. OCP mainly trips ASD when the current rise rate is great and the current is greater than the setting value, which may pose a threat to ASD.

3 THE CALCULATION METHOD FOR TRIP CHARACTERISTICS

The single-event characteristics of voltage sag include residual voltage, duration, POW, PAJ and the type of voltage sag. Experimental results show that the behaviour of ASD is mainly affected by residual voltage, duration and the type of voltage sag.

(i) Influence of the voltage sag type on ASD: ASD is three-phase equipment, so the influence of voltage sag type should be considered. As shown in Figure 2, IEEE Std.1668–2017 classifies the common voltage sag types into Type I, Type II and Type III. The effects of voltage sag due to single-phase faults can be ridden through by the rectifier.
with a correct DC voltage and overcurrent trip levels [20]. Therefore, this paper focuses on the states of ASD under Type II and Type III sags.

(ii) Influence of the residual voltage and duration on ASD: The residual voltage and duration decide whether the protections of ASDs are triggered. When the duration of voltage sag is longer than the threshold duration $t_T$ and the residual voltage is lower than a certain magnitude, ASD trips. Considering LVP, when the residual voltage is lower than the threshold voltage $U_V$, DC voltage would drop below the setting value $U_S$ of LVP and ASD trips. Considering OCP, DC current depends on the residual voltage. When residual voltage is lower than $U_I$, the maximum value of DC current at the end of voltage sag would be higher than the setting value $I_S$ of OCP and ASD trips.

Thus, there are three trip characteristics to describe the voltage sag tolerance of ASD. They are $t_T$, $U_V$ and $U_I$. The three trip characteristics are inherent attributes of ASD; they are only related to the parameters of ASD itself, they do not depend on the characteristics of voltage sag. This section proposes a calculation method to calculate the three trip characteristics, based on the response mechanical of ASD under voltage sag. The related analysis considers three segments of the voltage sag event, including the pre-event segment, during-event segment and post-event segment.

### 3.1 Overview of trip characteristics calculation

The calculation flowchart is shown in Figure 3 for the three trip characteristics. The behaviours of ASD in different segments of voltage sag events are analysed in Sections 3.2, 3.3 and 3.4. The normal operation of ASD depends on DC voltage and current. Thus, the three trip characteristics can be obtained by analysing the influence of residual voltage and duration of voltage sag on DC voltage and current. In Figure 3, the blocks for calculating three trip characteristics are highlighted in purple. $u_{dc}(t)$ is the base for calculating $t_T$, and the detailed method for calculating $u_{dc}(t)$ is presented in the pre-event segment; $U_V$ and $U_I$ are calculated in the during-event segment; $U_I$ is calculated in the post-event segment.

### 3.2 Pre-event segment

The calculation methods of current and voltage of rectifier circuit and inverter circuit in steady state are presented in the published research [21]. When ASD works normally, the DC circuit provides the inverter with high-frequency square wave current. Therefore, when studying the DC-link, the inverter and the load can be equivalent to a linear resistance $R_L$ [22]. $R_L$ is defined as the Thevenin equivalent resistance of the inverter/load connected to the DC-link.

\[
R_L = \frac{U_{dc0}^2}{P} \tag{1}
\]

where $U_{dc0}$ is the RMS value of the DC voltage before sag, and $P$ is the power of the load.

The effect of DC-link inductor $L$ on DC voltage is much less than that of capacitor $C$, when ASD works normally. Therefore, the influence of the inductor on DC voltage can be ignored.

Due to three-phase voltage symmetry and half-wave symmetry, it is representative to analyse the working state of the circuit for $1/6$ cycles. According to the state of charge and discharge of the capacitor, the circuit working states include two modes (A) and (B). In mode (A), one diode in each of the upper and lower bridge arms is turned on. The energy exchange is between the power source, capacitor, induction motor and load. In mode (B), all the diodes are in the off-state and the load is supplied with the required energy by the capacitor. The two modes (A) and (B) appear alternatively according to the change of the input AC voltage.

Figure 4 shows the equivalent circuit of the two modes and the voltage/current waveforms of DC-link. The zero point of the time-axis coordinate is the abscissa of the intersection point $K$ of the positive half-cycle voltage $u_{ab}$ and the DC voltage $u_{dc}$. At $t = 0$, the diode starts to conduct. Assumed the initial phase angle of $u_{ab}$ is $\delta$, there is:

\[
u_{ab}(0) = U_{dc0} = U_p \sin(\delta) \tag{2}\]

$U_{dc0}$ is the DC voltage when the diode is conducting, and $U_p$ is the peak value of the rated input voltage.
In mode (A), the capacitor $C$ is in the charged state. For Segment $K-G$ in Figure 4, the current and voltage satisfy Equations (3)–(5).

$$u_{ab} = U_p \sin(\omega t + \delta) = u_{dc0} + \frac{1}{C} \int_0^t i_c dt \quad (3)$$

$$i_c = C \frac{d u_{dc}}{dt} = U_p C \omega \cos(\omega t + \delta) \quad (4)$$

$$i_{dc} = i_c + i_L = U_p C \omega \cos(\omega t + \delta) + \frac{U_p}{R_L} \sin(\omega t + \delta) \quad (5)$$

When the diode is conducting, $u_{ab}$ continues to rise, the capacitor is charged, and $u_{dc}$ rises with $u_{ab}$. During charging, the current $i_{dc}$ keeps decreasing. The diode is off when reaching Point N ($\dot{u}_{dc}$ decreases to 0). That is, the diode is conducting from $\omega t = 0$ to $\omega t = \phi$. The relationship between the initial phase angle $\delta$ and the continuous conduction angle $\phi$ of the diode is as follows.

$$\tan(\delta + \phi) = -R_I \omega C \quad (6)$$

When $\omega t > \phi$, the diode is off. The circuit works in mode (B), the AC input current drops to zero, and only capacitor $C$ supplies power to load. During the cut-off period of the diode, $u_{dc}$ decreases exponentially. The $u_{dc}$ drops to $U_{dc0}$, when $\omega \cdot t = \pi / 3$.

$$u_{dc}(t) = \frac{\pi}{3\omega} \left( \frac{U_p}{\sin(\delta + \phi)} e^{-\frac{\delta + \phi}{R_I C}} - \frac{\pi - \phi}{3R_I C} \right) \quad (7)$$

On the basis of Equations (6) and (7), the following equation can be obtained.

$$\sin(\delta) = \frac{R_I \omega C}{\sqrt{1 + (R_I \omega C)^2}} e^{-\frac{\delta + \phi}{3R_I C}} \quad (8)$$

From Equations (2) to (8), the simplified solution of DC voltage can be expressed as follows:

$$u_{dc}(t) = \begin{cases} 
U_p \sin(\omega t + \delta) & \frac{\delta + \phi}{R_I C} < t \leq \frac{\phi}{\omega} + \frac{\delta}{\omega} \\
U_p \sin(\omega t + \phi) e^{-\frac{\delta + \phi}{3R_I C}} & \frac{\phi}{\omega} + \frac{\delta}{\omega} < t \leq \frac{(\phi + \delta)}{\omega} \end{cases} \quad (9)$$

From Equations (6) and (8), the initial conduction angle $\delta$ and continuous conduction $\phi$ can be obtained. Then the DC-side voltage waveform can be obtained by Equation (9). $u_{dc}$ is important for analyzing the performance of ASD under voltage sag, which is used in Section 3.3.

### 3.3 During-event segment

During voltage sag, ASD may trip because LVP is triggered when DC voltage is too low. The rectifier stops conducting due to the input voltage is lower than the DC voltage at the starting of voltage sag. The capacitor starts to discharge. All the energy of the load comes from the energy stored in the capacitor, during the continuous discharge of the capacitor.

Assumed that the size of the capacitor is $C$, the load size is $P$. Before ASD trips, it can be considered that the load power is $P$. Assumed that the voltage sag occurs at $t_b$, and the energy storage of the capacitor at time $t$ can be expressed as Equation (10).

$$\frac{1}{2} C u_{dc}^2(t) = \frac{1}{2} C u_{dc}^2(t_b) - \int_{t_b}^t P dt \quad (10)$$

#### 3.3.1 Threshold duration

ASD trips due to DC voltage drops below the setting value $U_S$ of LVP, during the voltage sag. Assumed the DC voltage drops to $U_S$ at time $t_T$, the relationship between $t_T$ and $U_S$ is as follows.

$$t_T = \frac{C (u_{dc}^2(t_b) - U_S^2)}{2P} \quad (11)$$

From Equations (6), (8), (9) and (11), $t_T$ of ASD can be obtained. Define $\varepsilon$ as the ratio of the capacitor to load power.

$$\varepsilon = \frac{C}{2P} \quad (12)$$

Substitute Equation (12) into Equation (11), and then it can be simplified to Equation (13).

$$t_T = \varepsilon (u_{dc}^2(t_b) - U_S^2) \quad (13)$$

ASD fails only when the residual voltage is lower than anyone of the two threshold voltages and the duration is greater than threshold duration $t_T$, but the residual voltage does not affect the value of $t_T$. It is obvious from Equations (9) and (13) that $t_T$ is affected by the ratio $\varepsilon$ and POW $\omega t_b + \delta$, in addition to the setting value $U_S$. Figure 5 shows the varying curve of $t_T$ calculated from the parametric equation with POW and $\varepsilon$.  

![Figure 5: Effect of POWs and $t$ on the threshold duration of ASD](image-url)
θ and the line voltage of Phase C-A. The value of the smaller the angle is deduced as follows.

\[
\theta = 2\arctan \left( \frac{\sqrt{3}K_{\Delta U} \left( \sqrt{4(U_{\text{dc-min}}^{\text{II}})^2 - 3U_{p}^2} - U_p \right)}{4U_p + K_{\Delta U} \left( \sqrt{4(U_{\text{dc-min}}^{\text{II}})^2 - 3U_{p}^2} - U_p \right)} \right)
\]

(16)

In order to increase the calculation accuracy, a correction coefficient \( K_{\Delta U} \) is considered in Equation (16). \( K_{\Delta U} \) is equal to the ratio of \( U_{\text{Lp-sag}}^{\text{II}} \) to \( U_{\text{dc-min}}^{\text{II}} \). According to the law of conservation of energy in capacitors, there is Equation (17).

\[
\frac{C}{2} \left( (K_{\Delta U}U_{\text{dc-min}}^{\text{II}})^2 - (U_{\text{dc-min}}^{\text{II}})^2 \right) = P \cdot \Delta T
\]

(17)

where \( \Delta T \) is the discharge time during voltage sag which is shown in Figure 6. Both \( K_{\Delta U} \) and \( \Delta T \) are unknown in (17). However, \( \Delta T \) has the typical value, which is 5.4–8 ms under different residual voltages, this paper chooses the intermediate value (6.7 ms) of \( \Delta T \) for the further calculation, which is represented in Equation (18). It is worth to note that \( \Delta T \) can be selected flexibly according to the characteristics of ASD in practice.

\[
K_{\Delta U}=\sqrt{\frac{0.0134P}{C(U_{\text{dc-min}}^{\text{II}})^2 + 1}}
\]

(18)

According to the above equation, \( K_{\Delta U} \) can be obtained. The value of \( K_{\Delta U} \) is mainly affected by the capacitor size and load size.

As shown in Figure 6, when the peak value of input line voltage drops to \( U_{\text{Lp-sag}} \), the minimum DC voltage is \( U_{\text{dc-min}}^{\text{II}} \). The relationship between \( U_{\text{Lp-sag}} \) and \( U_{\text{dc-min}}^{\text{II}} \) can be characterized as follows.

\[
\left\{ \begin{array}{l}
U_{\text{dc-min}}^{\text{II}} = \sqrt{\left( U_{\text{Lp-sag}} \right)^2 - \frac{2P\Delta T}{C}} \\
\Delta T = \left( 0.5 - \frac{\theta-\arctan(U_{\text{Lp-sag}}/U_{\text{dc-min}}^{\text{II}})}{\pi} \right) \frac{T}{2}
\end{array} \right.
\]

(19)

LVP is triggered, when the minimum DC voltage reaches the protection setting value \( U_S \). In this case, the peak of the input line voltage \( U_{\text{Lp-sag}} \) is equal to the threshold line voltage \( U_{L-th} \). Therefore, it can be seen from Equation (19) that \( U_{L-th} \) can be calculated according to the following formula.

\[
U_{L-th} = \sqrt{\left( U_S \right)^2 + \frac{2P\Delta T}{C}}
\]

(20)

Generally, residual voltage describes the dropping of phase voltage. \( U_{L-th} \) is line voltage, which should be transformed to phase voltage.

For the example in Figure 7, it is assumed that Phase A is the dropped phase and phase C is the non-dropped phase. The
Assumed the voltage recovers at the instant of voltage recovery. DC current can reach the maximum value, when the initial conditions are \( u_{dc}|_{t=0} = U \) and \( C(d\phi_{dc}/dt)|_{t=0} = 0 \). Based on the initial conditions, \( a_1 \) and \( a_2 \) in Equation (23) can be solved, and \( u_{dc} \) can be expressed as:

\[
u_{dc} = -e^{-\frac{R_d}{2L}} \times U \times \left[ \cos(\omega_{sag} t) + \frac{R_d \sin(\omega_{sag} t)}{2L\omega_{sag}} \right] + U_{RE} - i_l R_d
\]

\[
\Delta U = U_{RE} - U
\]

Substitute Equation (25) into the second equation in Equation (22) and ignore the effect of load current, the DC current \( i_{dc} \) is as follows.

\[
i_{dc} = \sqrt{\frac{4C}{4L - CR_d^2}} e^{-\frac{R_d}{2L}} \Delta U \sin(\omega_{sag} t)
\]

Take the derivative of Equation (27) as 0, DC current reaches the maximum value \( I_{dc-max} \) at \( t_m \).

\[
\omega_{sag, max} = \arctan \left( \frac{2L\omega_{sag}}{R_d} \right)
\]

3.4.1 Maximum current

Assumed the voltage recovers at \( t = 0 \), the approximate solution of the DC current is as follows.

\[
\begin{align*}
\sqrt{3}U_p \sin(\omega t) &= L \frac{di_{dc}}{dt} + i_{dc} R_d + u_{dc} \\
i_{dc} &= C \frac{\frac{dU_p}{dt}}{R_d} + i_l
\end{align*}
\]

where \( R_d \) is DC-link resistance, and its value is usually less than 1 \( \Omega \). \( i_l \) is the load current.

Since the charging time of the capacitor after the sag is much shorter than the fundamental cycle of the power system, the input voltage \( \sqrt{3}U_p \sin(\omega t) \) of ASD can be regarded as constant voltage \( U_{RE} \). Therefore, the solution of Equation (22) is as follows.

\[
u_{dc} = e^{-\frac{R_d}{2L}} \left[ A_1 \cos(\omega_{sag} t) \right] + U_{RE} - i_l R_d
\]

3.4.2 Threshold voltage of OCP

Generally, the lower DC voltage, the higher DC current at the ending of the event, the more possible to trigger OCP. Transform the setting value \( I_s \) of OCP to a voltage value \( U_{SI} \) through Equation (29). Let \( I_{dc-max}(U_{SI}) \) equals to setting value \( I_s \) of OCP, the solution of \( U_{SI} \) can be obtained as follows.

\[
U_{SI} = \left[ U_{RE} - I_s \sqrt{\frac{(R_d + 2L\omega_{sag})(4L - CR_d^2)}{8L\omega_{sag}}} \right] \times \left( \frac{R_d}{\omega_{sag}} \arctan \sqrt{\frac{2L\omega_{sag}}{R_d}} \right)
\]

\( U_{SI} \) is defined as an intermediate variable for calculating threshold voltage \( U_t \). If the DC voltage drops to \( U_{SI} \), the
maximum value of DC current reaches $I_s$ when the voltage recovers, resulting in OCP being triggered.

The calculation method of the threshold voltage of OCP is similar to that of LVP. The threshold voltage $U_{IV-III}$ of OCP in the case of Type III voltage sag is as follows.

$$U_{IV-III} = \sqrt{\frac{2P(\pi - \varphi)}{9\omega C}} + \frac{U_{S}}{3}$$  \quad (31)$$

In the case of Type II voltage sag, the threshold voltage $U_{IV-II}$ of OCP is obtained as follows.

$$\begin{align*}
\theta_i &= 2\arctan \left( \frac{\sqrt{3}K_{12} \left( \sqrt{4(U_{S})^2 - M^2} - U_p \right)}{4U_p + K_{12} \left( \sqrt{4(U_{S})^2 - M^2} - U_p \right)} \right) \\
\Delta T_2 &= \left( 0.5 - \frac{\arctan \left( \frac{U_{S0}}{U_{p0}} \right)}{\pi} \right) \frac{T}{2} \\
U_{IV-II} &= \sqrt{(U_{S})^2 + \frac{2\Delta T_2}{C}} \\
\alpha_i &= \arctan \left( \frac{-U_{p0} - 2U_{p-II}}{\sqrt{3}U_{p0}} \right), \quad \alpha_i \in \left[ \frac{2\pi}{3}, \frac{5\pi}{6} \right] \\
U_{VI-II} &= \frac{U_{IV-II} - U_p \sin(\theta_i + 2\pi/3)}{\sin \alpha}
\end{align*}$$

4 | THE PROPOSED PRACTICAL TABLE

The three trip characteristics could be used for VTC assessment. The typical VTC of ASD is roughly rectangular, based on the test results in [9], shown in Figure 8.

There is a “knee point” to determine the curve. This section proposes a VTC assessment model, the key is to obtain the “knee points” of VTCs under different types of voltage sags based on equipment parameters by considering LVP and OCP. The “knee points” corresponding to different parameters can form a practical table for tolerance assessment of ASD under voltage sag. Users can quickly obtain the tolerance of ASD under voltage sag by looking up the table.

4.1 | The upper and lower limit VTCs for ASD

The load rate of ASD is related to its efficiency closely. It is most suitable for ASD to operate in high efficiency when the power of ASD is equal to that of the motor. However, when the two powers are different, the power of ASD should be close and slightly higher than that of the motor.

The load rate of the motor is generally 0.7–1, which is the best working condition of the motor. So the load rate of ASD is generally about 0.6–0.9. On this basis, this paper considers a certain margin. It is considered that the upper limit of VTC of ASD can be obtained at full load rate and the lower limit of VTC can be obtained at half load rate. As shown in Figure 9, the two curves can be obtained based on the following four key parameters.

(i) Two magnitudes: the magnitudes of the “knee points” on VTC of 100% rated power ($U_{100Pn}$) and VTC of 50% rated power ($U_{50Pn}$).

(ii) Two durations: the durations of the “knee points” on VTC of 100% rated power ($t_{max1}$) and VTC of 50% rated power ($t_{max2}$).

4.2 | Create practical lookup table

It is the key to calculate $U_{100Pn}$, $U_{50Pn}$, $t_{max1}$ and $t_{max2}$, to get VTC of ASD. The flowchart of VTC assessment model is shown in Figure 10. First, five parameters ($C$, $L$, $U_S$, $I_s$ and $P_s$) are known, which are the input of the model. Generally, these parameters can be got from the manufacturer. Considering the two load rates, the threshold duration $t_T$ is calculated based on Equation (11). Then calculate the threshold voltages of ASD. There are different equations for calculation under Type III and Type II voltage sag. $U_{IV-III}$ and $U_{IV-II}$ can be calculated by Equations (15) and (21), respectively. $U_{IV-III}$ and $U_{IV-II}$ can be calculated by Equations (31) and (32), respectively. In the case of Type III sag, the tripping voltage is $U_{trip} = \max (U_{IV-III}, U_{IV-II})$. In the case of Type II sag, the tripping voltage is $U_{trip} = \max (U_{IV-II}, U_{IV-II})$. Finally, the coordinate of “knee point” is ($t_T$, $U_{trip}$).

However, VTC assessment model may be complex and inconvenient for users. The “knee points” of ASD under
different typical parameters are calculated and presented in the practical lookup table of VTC for ASD, using the proposed model. Table 1 and Table 2 are two examples. Table 1 can be applied to Example 1-ASD with protection setting value $U_S$ of 0.6 p.u. and $I_S/P_n$ of 30 A/kW. Table 2 can be applied to Example 2-ASD with protection setting value $U_S$ of 0.65 p.u. and $I_S/P_n$ of 30 A/kW. The practical lookup tables, for the ASDs with the other parameters, can also be calculated based on the assessment model. $I_S/P_n$ is selected instead of $I_S$ in Tables 1 and 2 to increase the generality of the table, because there are many ASDs with different power levels. However, due to the limited space, only two examples are given here.

The lookup table can help users to obtain the upper and lower limit VTCs. For Example 1-ASD, the information of VTCs can be found in Table 1. For example, When $L/P_n$ is 25 $\mu$H/kW and $C/P_n$ is 160 $\mu$F/kW, the coordinates of the “knee points” corresponding to the upper and lower limit VTC for Type III sag are (0.741, 13.1) and (0.715, 27.0). The coordinates of the “knee points” corresponding to the upper and lower limit VTC for Type II sag are (0.652, 13.1) and (0.513, 27.0).

VTCs are obtained by experimental tests usually, so it is difficult for users to obtain the tolerance information when purchasing ASDs, which is the barrier for users to select ASD. With the help of the practical lookup table, users can obtain the tolerance of ASDs by looking up the table when they know the five parameters: $C, L, P_n, U_S, I_S$.

## 5 CASE STUDY

The simulation platform of ASD tolerance test under voltage sag, is modelled in PSCAD/EMTDC based on [18]. The simulation results are used to verify the validity of the calculation method for trip characteristics and the proposed practical table. The parameters of ASD and load motor in the simulation model are listed in Table 3.

The case study has two parts, presented in Sections 5.1 and 5.2 respectively. The first part is to verify the correctness of the calculation method for trip characteristics. The second part

| $U_S$ = 0.6 (p.u.) | $I_S/P_n$ = 30 (A/kW) |
|-------------------|---------------------|
| $U_{100P_n}/t_{max1}$ | $U_{50P_n}/t_{max2}$ | $C/P_n$ ($\mu$F/kW) | $I_S/P_n$ | |
| (p.u./ms) | (p.u./ms) | | | |
| $L/P_n$ ($\mu$H/kW) | 140 | 150 | 160 | 170 | Sag type |
| 25 | 0.736/11.7 | 0.739/12.6 | 0.741/13.1 | 0.743/14.4 | Type III |
| | 0.708/23.9 | 0.712/25.7 | 0.715/27.0 | 0.718/29.5 | |
| 30 | 0.721/11.7 | 0.723/12.6 | 0.726/13.1 | 0.729/14.4 | |
| | 0.691/23.9 | 0.695/25.7 | 0.699/27.0 | 0.702/29.5 | |
| 35 | 0.706/11.7 | 0.709/12.6 | 0.712/13.1 | 0.715/14.4 | |
| | 0.676/23.9 | 0.681/25.7 | 0.684/27.0 | 0.689/29.5 | |
| 40 | 0.693/11.7 | 0.696/12.6 | 0.700/13.1 | 0.702/14.4 | |
| | 0.662/23.9 | 0.667/25.7 | 0.671/27.0 | 0.676/29.5 | |
| $L/P_n$ ($\mu$H/kW) | 140 | 150 | 160 | 170 | Sag type |
| 25 | 0.665/11.7 | 0.658/12.6 | 0.652/13.1 | 0.647/14.4 | Type II |
| | 0.514/23.9 | 0.513/25.7 | 0.513/27.0 | 0.513/29.5 | |
| 30 | 0.637/11.7 | 0.631/12.6 | 0.625/13.1 | 0.620/14.4 | |
| | 0.481/23.9 | 0.482/25.7 | 0.482/27.0 | 0.483/29.5 | |
| 35 | 0.612/11.7 | 0.605/12.6 | 0.600/13.1 | 0.595/14.4 | |
| | 0.452/23.9 | 0.452/25.7 | 0.453/27.0 | 0.454/29.5 | |
| 40 | 0.588/11.7 | 0.582/12.6 | 0.577/13.1 | 0.573/14.4 | |
| | 0.424/23.9 | 0.425/25.7 | 0.426/27.0 | 0.426/29.5 | |
TABLE 2  The practical lookup table for Example 2-ASD

| $\bar{U}_S = 0.65$ (p.u.) | $I_S/P_n = 28$ (A/kW) |
|--------------------------|---------------------|
| $U_100P_n/h_{max1}$ ($\mu$s) | $U_{50P_n}/h_{max2}$ ($\mu$s) | $C/P_n$ (μF/kW) |
| 140 | 150 | 160 | 170 | Sag type |
| 25 | 0.756/10.4 | 0.758/11.2 | 0.760/11.6 | 0.762/12.6 | Type III |
| 30 | 0.741/10.4 | 0.743/11.2 | 0.746/11.6 | 0.748/12.6 | |
| 35 | 0.727/10.4 | 0.730/11.2 | 0.733/11.6 | 0.735/12.6 | |
| 40 | 0.722/10.4 | 0.719/11.2 | 0.721/11.6 | 0.724/12.6 | |
| 0.693/22.1 | 0.691/23.8 | 0.694/24.2 | 0.698/26.7 |
| 25 | 0.700/10.4 | 0.693/11.2 | 0.686/11.6 | 0.680/12.6 | Type II |
| 30 | 0.673/10.4 | 0.667/11.2 | 0.661/11.6 | 0.655/12.6 | |
| 35 | 0.649/10.4 | 0.643/11.2 | 0.637/11.6 | 0.632/12.6 | |
| 40 | 0.641/10.4 | 0.623/11.2 | 0.616/11.6 | 0.611/12.6 | |
| 0.485/22.1 | 0.473/23.8 | 0.471/24.2 | 0.472/26.7 |

TABLE 3  Parameters of the simulation model

| Parameters of ASD |
|-------------------|
| RMS of rated input voltage $U_n$ (V) | 220 |
| Input voltage frequency (Hz) | 50 |
| DC-link inductor $L$ (μH) | 225 |
| DC-link capacitor $C$ (μF) | 1200 |
| DC-link resister $R_D$ (Ω) | 0.3 |

| Parameters of load motor |
|--------------------------|
| Rated power $P_n$ (kW) | 7.5 |
| Load rate (%) | 100/50 |

gives an application example, and it verifies the correctness of the assessment results of the practical lookup table through this example. In the case study, it is considered that the data obtained from the simulation test is real data.

(i) Calculation method for trip characteristics: The trip characteristics of the proposed method refer to two threshold voltages $U_{\text{V}1}$, $U_{\text{V}2}$ and one threshold duration $t_{\text{T}}$. First, $U_{\text{V}1}$, $U_{\text{V}2}$ and $t_{\text{T}}$ under different $U_S$ and $I_S/P_n$ are obtained according to the proposed calculation method. Then $U_{\text{V}1}^{\text{real}}$, $U_{\text{V}2}^{\text{real}}$ and $t_{\text{T}}^{\text{real}}$ are obtained through simulation test. The simulation test platform includes the programmable power supply, ASD module and load module. The programmable power supply has two parts: three phase voltage source module and the input signal module for control the three phase voltage source module. The voltage sags with different residual voltage and duration can be generated by the programmable power supply, which is controlled by the input signal module (the voltage, frequency and phase angle can be controlled by this module). $U_{\text{V}}^{\text{real}}$ and $U_{\text{V}}^{\text{real}}$ are tested by step-by-step method [9] with the step size of 0.01 p.u.. $t_{\text{T}}^{\text{real}}$ is tested by dichotomy method [24], and the accuracy is 0.01 ms. They are regarded the real values of the threshold voltages and threshold duration. Finally, the errors between $U_{\text{V}}^{\text{real}}$ and $U_{\text{V}}^{\text{real}}$, $t_{\text{T}}$ and $t_{\text{T}}^{\text{real}}$ are compared to illustrate the effectiveness of the calculation method.

(ii) The practical lookup table: Section 5.2 is to verify the correctness of the practical lookup table. In this case, the setting value $S$ is 0.6 p.u. and the setting value $I_{S}/P_n$ is 30 A/kW. The box-in method proposed in IEEE Std. 1668–2017 [8] is applied to get VTCs through the simulation test. In order to ensure accuracy, the time step size of the test is 1 ms, and the magnitude step size is 1%. VTCs obtained by simulation test are the real VTCs. The effectiveness of the look-up table is proved by comparing the VTC from the practical look-up table with the real VTC.

5.1 Verification of the calculation method for trip characteristic

5.1.1 The results of threshold voltages

Table 4 lists the $U_{\text{V}}^{\text{real}}$ and $U_{\text{V}}^{\text{real}}$ under different load rates and $U_S$. The range of $U_S$ is 0.55–0.75 p.u. Table 5 lists the $U_{\text{V}}$ and $U_{\text{V}}^{\text{real}}$ under different load rates and $I_{S}/P_n$. The range of $I_{S}/P_n$ is 20–40 A/kW. Subscript III in the table corresponds to Type III voltage sag and subscript II corresponds to Type II voltage sag.

It is obvious that $U_{\text{V}}$ increases with the increase of $U_S$, and $U_{\text{V}}$ decreases with the increase of $I_{S}/P_n$. There are the similar changing trends of the calculated characteristics and the
TABLE 4  The calculated threshold voltages and real values under Type III sag

| $U_S$ (p.u.) | 0.55  | 0.6  | 0.65 | 0.7  | 0.75 |
|--------------|-------|------|------|------|------|
| Load rate: 100% |       |      |      |      |      |
| $U_{T-III}$ (p.u.) | 0.627 | 0.671 | 0.716 | 0.762 | 0.808 |
| $U_{T-II}$ (p.u.) | 0.445 | 0.525 | 0.607 | 0.689 | 0.773 |
| $U_{real}^{T-III}$ (p.u.) | 0.61  | 0.66  | 0.71  | 0.76  | 0.81  |
| $U_{real}^{T-II}$ (p.u.) | 0.43  | 0.52  | 0.60  | 0.69  | 0.77  |
| $|\Delta U_{T-III}|$ (%) | 2.8  | 1.7  | 0.8  | 0.3  | 0.2  |
| $|\Delta U_{T-II}|$ (%) | 3.4  | 1.0  | 1.2  | 0.1  | 0.4  |
| Load rate: 50% |       |      |      |      |      |
| $U_{T-III}$ (V) | 0.596 | 0.642 | 0.689 | 0.736 | 0.784 |
| $U_{T-II}$ (V) | 0.269 | 0.366 | 0.461 | 0.555 | 0.649 |
| $U_{real}^{T-III}$ (V) | 0.59  | 0.64  | 0.69  | 0.74  | 0.79  |
| $U_{real}^{T-II}$ (V) | 0.27  | 0.37  | 0.47  | 0.56  | 0.66  |
| $|\Delta U_{T-III}|$ (%) | 1.0  | 0.3  | 0.1  | 0.5  | 0.8  |
| $|\Delta U_{T-II}|$ (%) | 0.4  | 1.0  | 1.9  | 0.9  | 1.7  |

TABLE 5  The calculated threshold voltages and real values under Type II sag

| $I_S/P_n$(A/kW) | 20  | 25  | 30  | 35  | 40  |
|-----------------|-----|-----|-----|-----|-----|
| Load rate: 100% |     |     |     |     |     |
| $U_{T-III}$ (p.u.) | 0.825 | 0.775 | 0.726 | 0.677 | 0.630 |
| $U_{T-II}$ (p.u.) | 0.804 | 0.714 | 0.625 | 0.537 | 0.450 |
| $U_{real}^{T-III}$ (p.u.) | 0.84  | 0.79  | 0.73  | 0.68  | 0.64  |
| $U_{real}^{T-II}$ (p.u.) | 0.81  | 0.72  | 0.63  | 0.54  | 0.44  |
| $|\Delta U_{T-III}|$ (%) | 1.8  | 1.9  | 0.5  | 0.4  | 1.5  |
| $|\Delta U_{T-II}|$ (%) | 0.7  | 0.8  | 0.8  | 0.6  | 2.3  |
| Load rate: 50% |     |     |     |     |     |
| $U_{T-III}$ (V) | 0.802 | 0.750 | 0.699 | 0.649 | 0.598 |
| $U_{T-II}$ (V) | 0.685 | 0.584 | 0.482 | 0.379 | 0.275 |
| $U_{real}^{T-III}$ (V) | 0.81  | 0.76  | 0.71  | 0.65  | 0.60  |
| $U_{real}^{T-II}$ (V) | 0.70  | 0.60  | 0.50  | 0.39  | 0.28  |
| $|\Delta U_{T-III}|$ (%) | 1.0  | 1.3  | 1.5  | 0.2  | 0.3  |
| $|\Delta U_{T-II}|$ (%) | 2.1  | 2.7  | 3.6  | 2.8  | 1.8  |

Table 6 lists the values of $t_T$ and $t_{real}$ under different load rates and $U_S$. The range of $U_S$ in the table is 0.6–0.75 p.u. Due to the uncertainty of POW, the duration of DC voltage dropping from the rated value to $U_S$ is different under the voltage sags with the same residual voltage. For each duration in the table, the minimum value and maximum value are given respectively, considering the effect by POW. As mentioned in Section 3.3.1, the difference between minimum and maximum duration is tiny, and the results in Table 6 verify it.

For example, the calculated minimum/maximum $t_T$ is 10.60/12.69 ms for ASD ($U_S$ is 0.65 p.u.) under voltage sags, the real value is 11.14/12.85 ms, the error of the duration is 0.54/0.16 ms. The absolute values of errors between $t_T$ and $t_{real}$ are less than 1 ms for all the cases in Table 6. It can be seen that the proposed method can accurately calculate the duration from the start of voltage sag to the shutdown of ASD.

5.2 Application and effectiveness verification of lookup table

It can be obtained that $I_n/P_n = 30 \mu F/kW$, $C/P_n = 160 \mu H/kW$, $U_S$ is 0.6 p.u. and $I_n/P_n = 30\ A/kW$, according to the parameters of the simulation model. Therefore, the “knee point” of the VTC of ASD can be lookup from Table 1. According to Table 1, the “knee point” coordinates under Type III sag are (13.5, 0.726) and (28.4, 0.699), and those under Type II sag are (13.5, 0.625) and (28.4, 0.482).

VTCs of ASD obtained by simulation and Table 1 are shown in Figures 11 and 12. The solid VTCs are real VTCs by the simulation test and the dashed VTCs are obtained by Table 1. Figure 11 shows the results under Type III sag. The differences are −0.9 ms and 0.04 p.u. for the duration and the magnitude between the real VTC and VTC obtained by Table 1 under Type III sag respectively, at the case of 100% load rate. The differences are −1 ms and 0.011 p.u. respectively, at the case of 50% load rate.

Figure 12 shows the results under Type II sag. The differences are −0.9 ms and 0.05 p.u. at the case of 100% load rate. And differences are only −1 ms and −0.08 p.u., at the case of 50% load rate.

It is obvious that VTCs obtained by the two methods are quite close in Figures 11 and 12. It proves that the “knee points” coordinates obtained from the lookup table can represent...
tolerance of ASD under voltage sag accurately. Therefore, the proposed practical lookup table is helpful for users to obtain VTC of ASD directly.

6 1 CONCLUSION

This paper proposes practical tables for tolerance assessment of ASD under voltage sag, including three trip characteristics calculation method and the VTC assessment model. With the easily accessible parameters from the manufacturer, the tolerance of ASD can be obtained by looking up the practical tables. The simulation tests prove the correctness of the proposed model and tables. The main conclusions of this paper are summarized as follows.

(i) The proposed trip characteristics calculation method is for analyzing whether ASD trips under Types III and Type II sags. It can calculate the two threshold voltages and threshold duration that ASD can tolerate. The correctness of the calculation method is verified by simulations tests.

(ii) The influence mechanism of various parameters on ASD under voltage sag has been fully investigated. Load size, DC-link capacitors, DC-link inductors, setting values of LVP and OCP are the key parameters affecting the tolerance of ASD to voltage sag. The tolerance of ASD under voltage sag can be calculated directly, based on the five key parameters.

(iii) This paper proposes practical lookup tables to help users obtain the tolerance of ASD conveniently. Based on the VTC assessment model, the coordinates of “knee points” can be calculated. The “knee points” under different typical parameters could form a practical table. The user gets the “knee points” of ASD by looking up the table, and VTCs of the ASD can be obtained by utilizing the “knee points”.

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