Research on topology and control strategy of distribution network flexible interconnected device based on single-phase control unit and contact switch in series

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There is an urgent need for flexible interconnection in the distribution network. However, due to the complex topology, control strategy and development cost of the existing flexible interconnected device (FID), the existing FID is difficult to be popularized and applied in the above scenarios. In view of the above problems, this paper constructs the FID topology based on the series connection of single-phase control unit and contact switch, and constructs the equivalent circuit of the interconnection line between FID and contact switch in series. The working principle of FID flexible closing loop and power flow control is studied from the dimension of FID output voltage and equivalent impedance. The FID flexible closing loop energy extraction strategy is proposed, and the FID system-level and device-level control strategies with flexible closing loop and power flow control functions are proposed. The simulation results show that the flexible interconnection device based on the proposed topology and control strategy can effectively compensate the pressure difference of the connecting points in the distribution network, regulate the power flow of the active distribution network, and realize the interconnection and mutual assistance of the distribution network.

KEYWORDS

single-phase control unit, interconnection switch, flexible interconnected device, flexible closing loop, power flow control

1 Introduction

With the access of a large number of new energy sources such as wind, solar and energy storage to the distribution network (Gui et al., 2024; Kabirifar et al., 2021), the access of wind and solar resources and the demand for load power in different stations of the distribution network show different characteristics. There are a large number of regional large-scale mutual energy in the interval (Kumar, 2024; Kumar et al., 2023a; Kumar et al., 2020; Satapathy and Kumar, 2020). Through feeder automation technology and distribution network reconfiguration technology, the distribution network can realize the interconnected operation of the station area,

and then effectively use the mutual energy of the station area to improve the operation efficiency of the distribution network. The interconnection of the distribution network needs to be closed and unclosed through the sectional switch and the contact switch on the line. However, the conventional closing loop method is limited by machinery, and the response speed is slow and the closed loop impulse current is generated, which not only endangers the safe and stable operation of the distribution network system, but also may cause the protection action to lead to the failure of the closed loop (Liang et al., 2022; Cai et al., 2022; Kumar et al., 2023b).

In order to maximize the absorptive capacity of the distribution network to new energy sources such as wind power and photovoltaic power and the power supply capacity of new flexible loads such as electric vehicle charging piles, researchers have proposed the concept of flexible interconnected device (FID) (Fuad et al., 2020; Deakin et al., 2022). Based on power electronics technology, FID provides flexible power control and flexible interconnection capabilities for distribution networks through flexible and adjustable voltage source converters. Through flexible interconnection technology, non-impact closed loop can be realized, the power flow between phases can be balanced, the constraints of network reconfiguration can be reduced, the operation state of distribution network can be optimized, and the level of wind and solar consumption can be improved (Xu et al., 2022; Alwash et al., 2023; Zolfaghari et al., 2022).

In order to meet the characteristics of different application scenarios of power systems and the requirements of flexible interconnection function modes, scholars at home and abroad have proposed different FID topologies and corresponding control strategies. In Reference Wu et al. (2019), FID based on back-to-back converter is used as the topology of the interconnection device. A multi-mode operation method of power conversion under normal operation and power recovery under single-side fault is proposed, and a smooth switching strategy based on multiple control modes is proposed. In reference Li et al. (2022), a flexible interconnection scheme of distribution network based on the parallel connection of back-to-back converter FID and tie switch is proposed, and a smooth switching control strategy of transfer power supply is proposed. Reference Ouyang et al. (2020) proposed a three-terminal FID topology and a new DC voltage control strategy to improve the flexibility and robustness of DC voltage control. However, the above flexible interconnection scheme using back-to-back FID requires more full-rated power three-phase voltage source converters, resulting in high equipment cost and large device volume, and it is difficult to achieve economic operation in low-voltage distribution network interconnection scenarios. Reference Qi et al. (2023) proposed that FID based on single-phase full-bridge converter can be flexibly interconnected by means of series connection to the system. In the case of islanding, the proposed series SOP can automatically suppress the short-circuit current and restore the power supply voltage. Reference Zhang et al. (2023) proposed a series split multi-port FID and series split arrangement based on cascaded H-bridge structure. The proposed topology can easily expand its ports by increasing the number of sub-modules with small rated power, thereby reducing device cost and volume. However, the energy extraction method of the existing series FID is the traditional DC voltage control, and the energy extraction problem before the closing of the interconnection device is not considered. Based on the above analysis, although FID can meet the demand of power flow distribution of modern distribution network rapid adjustment and optimization system, the complex topology, control strategy and high development cost of back-to-back FID hinder its popularization and application in distribution network, especially in low-voltage distribution network, while the series FID fails to effectively solve the problem of energy extraction before closing the loop. Therefore, it is of great significance to study FID, which is more simple in topology and control strategy, cheaper in device cost and suitable for low voltage AC station area of distribution network.

In order to solve the high cost and energy acquisition problems of the existing FID, this paper proposes the FID based on single-phase regulation unit as a flexible interconnection scheme, constructs the equivalent circuit of the interconnection line with the series FID and the contact switch, researches the working principle of the station differential pressure compensation and power flow control with the direct closed-loop and FID flexible closed-loop, investigates the energy acquisition strategy of the FID flexible closed-loop and researches the FID control strategy with the functions of the flexible closed-loop and power flow control. The energy acquisition strategy of FID flexible closed-loop is studied, and the FID control strategy with flexible closed-loop and power flow control is investigated. The proposed FID based on single-phase control unit has the following technical advantages:

(a) In terms of topology, the FID proposed in this paper selects a group of small-capacity single-phase voltage-source converters as power electronic power units, and adopts the idea of integrating the design of traditional mechanical contact switches and power electronic power units in series, so as to make the topology of the FID simple, have a low development cost, reduce the cost of transformation of the distribution network, and have a simple control strategy.

(b) In terms of the energy extraction method, the FID proposed in this paper uses the DC voltage source on the DC side to provide energy support for the distribution network before the flexible closing of the loop, for example, it can be used as an energy extraction module by using the distribution network intelligent terminal equipment to design the information acquisition module FTU, UPS, or super capacitors and other energy storage devices. And then replace the existing multi-winding transformer and shunt valve based on the energy extraction method, reducing the cost and volume of the device.

2 Topology of flexible interconnection device with single-phase control unit and contact switch in series

The single-phase topology of FID main circuit is shown in Figure 1. This topology consists of three parts: switching module, converter module and energy supply module. In this paper, the flexible interconnection scheme of FID and contact switch S_c in series is adopted. Through the coordination of FID and contact switch, the flexible loop closing and capacity mutual aid of low voltage station area of distribution network are realized.

For the existing back-to-back or multi-terminal FID flexible interconnection scheme requires more full-rated power three-phase

FIGURE 1
FID main circuit single-phase topology.
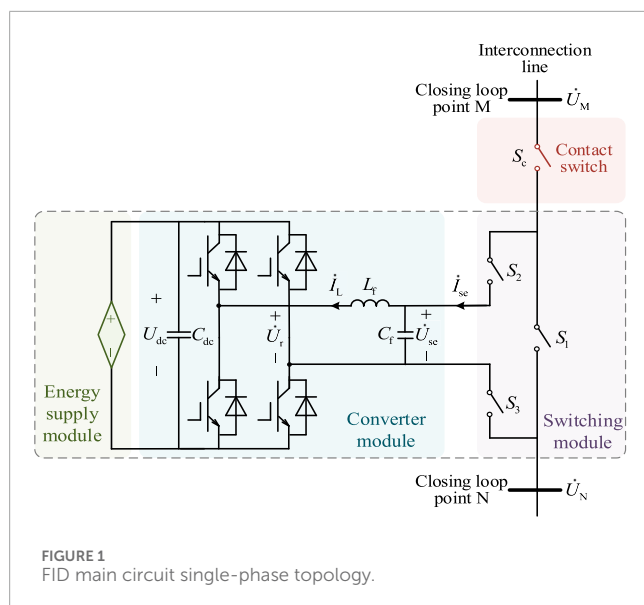
voltage source converter shortcomings, this paper proposes the FID to make full use of the existing distribution network loop device, the small-capacity single-phase regulator unit and the traditional mechanical contact switch for the integration of the design, the device cost is low; for the existing unified current controller type FID flexible interconnection scheme with the shunt side of the converter for the device to take energy, resulting in high cost of the device to take energy. In view of the shortcomings of the existing unified current controller type FID flexible interconnection scheme, which uses the shunt side converter to fetch energy for the device, resulting in the high cost of fetching energy for the device, the FID proposed in this paper is connected in parallel on the DC side with DC voltage sources such as inexpensive and many times charging and discharging energy storage batteries, supercapacitors, etc., to reduce the cost of the device, and at the same time, it can also provide the active power support for the FID before the FID flexible loop closing.

In Figure 1, $\dot{U}_M$ and $\dot{U}_N$ are the closing point voltage of the station area M and the station area N, respectively. The switch module, converter module and energy supply module in FID are introduced below.

The switch module consists of a bypass switch S_1 and two closed-loop switches S_2 and S_3. By closing the closed-loop switches S_2 and S_3, the FID can be connected in series to compensate the closed-loop pressure difference between the station area M and the station area N, thereby reducing the voltage at both ends of the contact switch S_c to achieve flexible closed-loop.After the completion of the loop closing, if there is no other control demand for the interconnected line, the FID bypass is withdrawn from operation by using the bypass switch S_1, which reduces the line loss of the distribution network and prolongs the service life of the FID.

The converter module is composed of three single-phase full-bridge voltage source converters and filter circuits. Its main function is to output an output voltage $\dot{U}_{se}$ with flexible adjustable amplitude and phase angle according to the control command, so as to realize the non-impact closing loop between the stations and the power flow control, harmonic control, three-phase imbalance and other control functions of the interconnected lines (Tang et al., 2022a,

2022b; Tang et al., 2024; Tang et al., 2023). In the topology, C_f is an AC filter capacitor, L_f is an AC filter inductor, $\dot{U}_r$ is the modulation voltage of the FID converter inverter, $\dot{I}_{se}$ is the current flowing into the FID, and $\dot{I}_L$ is the current flowing through the FID filter inductor, C_{dc} is DC capacitor and U_{dc} is DC capacitor voltage. The energy supply module is connected to the DC side of the converter module through the DC capacitor C_{dc}, and its main function is to provide active power support for the device before the FID is closed. Therefore, energy supply devices such as supercapacitors, uninterruptible power supplies, and optical storage systems can be used as energy sources for FID. Since the focus of this paper is on the AC characteristics of the interaction between FID and the station, the energy supply module is equivalent to the DC voltage source in the later analysis.

3 The working principle of flexible interconnection device regulation

3.1 The working principle of flexible closing loop of flexible interconnection device

In this paper, the scheme of FID and contact switch in series based on single-phase control unit is used to flexibly interconnect the low-voltage station area of distribution network. The schematic diagram of FID flexible interconnection of low-voltage AC bus in the station area is shown in Figure 2.

In Figure 2, FID is installed in the interconnection line between the closing point M and the closing point N in the station area. The three single-phase control units of FID can output voltage $\dot{U}_{se}$ with flexible amplitude and phase angle. When it is necessary to close the low-voltage AC bus of the station area M and the station area N, FID is connected in series to the system and controls the output voltage $\dot{U}_{se}$ to track the differential pressure $\Delta\dot{U}$ between the two stations under the active support of the energy supply module, so that the voltage at both ends of the contact switch is reduced, and then the contact switch is closed to realize the flexible closing loop, thereby reducing the impact of the impulse current generated by the closing loop.After the closed loop is completed between the FID access stations, if there is no control demand, the bypass switch can be closed to withdraw the FID from operation and reduce the operating loss of the FID. If there is a demand for power flow control, FID can continue to operate in the system to improve the power flow distribution between stations, or to mitigate the impact of power flow reversal caused by DG.

The equivalent circuit diagram of the traditional mechanical contact switch is shown in Figure 3. Among them, $\dot{U}_c$ is the voltage at both ends of the contact switch, and Z_L is the equivalent impedance of the interconnected line. $\dot{U}_M$ and $\dot{U}_N$ are the closing point voltage of the station area M and the station area N, respectively.

It can be seen from Figure 3 that when the traditional mechanical contact switch is closed, the relationship between the voltage $\dot{U}_c$ at both ends of the switch and the pressure difference $\Delta\dot{U}$ between the two areas is

$$\dot{U}_c = \dot{U}_M - \dot{U}_N = \Delta\dot{U} \tag{1}$$

It can be seen from Equation 1 that there is a voltage difference between the two connecting points. If the loop is closed by directly
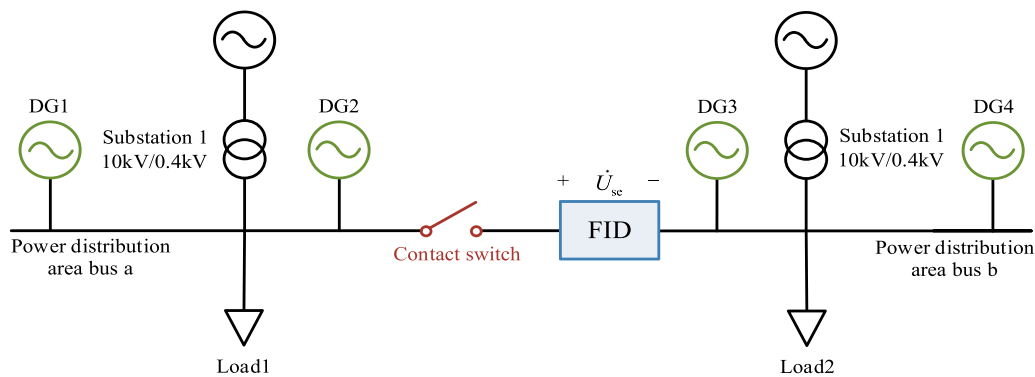
FIGURE 2
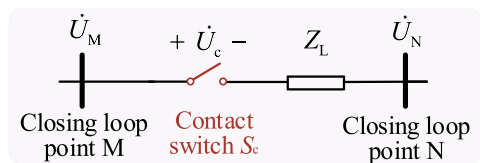FID schematic diagram of flexible interconnection of low voltage AC bus in station area.

FIGURE 3
Traditional mechanical contact switch closing loop equivalent circuit diagram.

FIGURE 4
FID equivalent circuit diagram before and after the flexible loop closing of the station area.

closing the contact switch, the loop closing impulse current will be generated. Excessive loop closing impulse current may lead to line protection action, which seriously affects the success rate of loop closing and the safe and stable operation of the distribution network system. If it is necessary to improve the success rate of loop closing and suppress the inrush current in the process of loop closing, the loop closing operation specification of the phase angle difference between the two sides of the loop closing point is within 20° and the voltage difference is within 20% should be met. The key is how to control the voltage $\dot{U}_c$ at both ends of the contact switch to reach the loop closing standard.

By controlling the output voltage $\dot{U}_{se}$ of the single-phase control unit, FID can flexibly compensate the amplitude and phase angle of the pressure difference between the two zones that need to be closed, and reduce the voltage at both ends of the contact switch. Therefore, FID can be equivalent to an ideal controlled voltage source under the condition of ignoring the loss of power electronic switch. According to Figure 2, the equivalent circuit of FID before and after closing the loop in the station area is shown in Figure 4.

From Figure 4, it can be seen that before the contact switch is closed, the line between the closing point M and the closing point N is not connected, and no current flows in the interconnecting line MN, so the line impedance voltage drop is 0. The FID control output voltage compensates for the difference in voltage at the closing point, and the voltage across the contact switch is thus obtained as

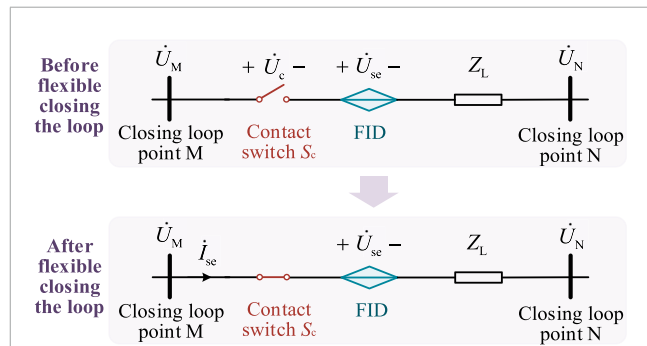$$\dot{U}_c = \Delta\dot{U} - \dot{U}_{se} = \dot{U}_M - \dot{U}_N - \dot{U}_{se} \tag{2}$$

After the contact switch S_c is closed, if the loss of the contact switch S_c is ignored, the relationship between the voltage and current of the interconnected line is expressed as

$$\Delta\dot{U} = \dot{U}_M - \dot{U}_N = \dot{U}_{se} + \dot{I}_{se}Z_L \tag{3}$$

In order to facilitate the analysis of the relationship between the electrical quantities in FID, the phasor $\dot{U}_b$ is used as the reference phasor, and $\dot{U}_N = U_N\angle0°$, $\dot{U}_M = \dot{U}_M\angle\delta_M$, $\dot{U}_{se} = U_{se}\angle\delta_{se}$, $\dot{I}_{se} = I_{se}\angle\delta_i$ are set, so the flexible loop phasor relationship diagram of each electrical quantity in FID is shown in Figure 5.

From Equations 1–3 and Figure 5, it can be seen that under the condition of ignoring the switching loss, by controlling the output voltage $\dot{U}_{se}$ of the FID single-phase control unit to compensate the differential pressure at the closing point of the station area, the voltage at both ends of the contact switch in series with FID is reduced to 0, thus satisfying the closing condition, realizing the flexible closing of the low-voltage AC line of the distribution network while controlling the instantaneous current at the closing point.

Due to the use of single-phase full-bridge voltage source converter, FID based on single-phase control unit needs to sacrifice a control degree of freedom to maintain the active power balance of the device. In order to realize the full-angle control of the voltage difference amplitude and phase angle of the FID connection
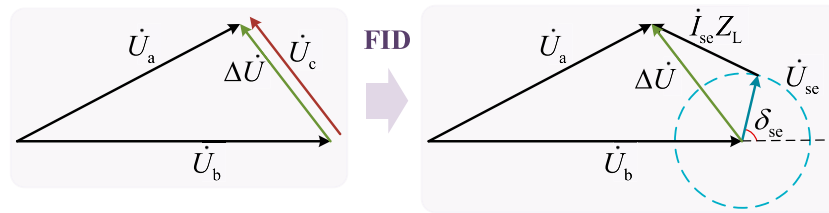
FIGURE 5
FID phase relationship diagram.

point, additional power supply modules need to be connected in parallel on the DC side to provide active power support.Therefore, FID needs to balance the active power transmission between the single-phase control unit and the energy supply module. From Figure 5 and Equation 4, it can be obtained that the active power required by FID for flexible loop closing is

$$P_{se} = U_{se} I_{se} \cos(\delta_{se} - \delta_i) \tag{4}$$

When FID compensates the pressure difference for flexible closing, if the operating loss is ignored, the active power P_{ens} provided by the energy supply module to FID should be equal to the active power P_{se} issued by FID to the system. Therefore, FID needs to meet the following power balance relationship (Equation 5).

$$P_{ens} + P_{se} = 0 \tag{5}$$

When the FID completes the flexible closing loop to reach the steady-state operation state, the FID exits the power supply module and controls the stable DC capacitor voltage by self-powering.If there are control requirements in the station area, FID can further complete power flow control, three-phase imbalance control, harmonic suppression and other control functions according to the control instructions. If there is no need for subsequent regulation in the station area, the FID bypass will be withdrawn from operation while maintaining the interconnection of the station area, so as to reduce the line loss of the distribution network and prolong the service life of the FID.

3.2 Working principle of power flow control of flexible interconnection device

When FID is running in the steady state of the interconnected line, the equivalent impedance of the line can be changed by controlling the output voltage $\dot{U}_{se}$ of the single-phase control unit, thus changing the power flow distribution on the line.The steady-state operation equivalent circuit of the interconnection line of the direct closed loop and the FID flexible closed loop is shown in Figure 6. $\dot{I}_{L0}$ is the current of the interconnection line after the direct closed loop, $P_{L0} + jQ_{L0}$ is the power transmitted by the interconnection line after the direct closed loop, and $P_L + jQ_L$ is the power transmitted by the interconnection line after the FID flexible closed loop.

Define Z_{se} as the equivalent impedance of FID output, let R_{se} be the equivalent resistance of FID output, X_{se} be

the equivalent reactance of FID output, R_L be the equivalent resistance of interconnection line, X_L be the equivalent reactance of interconnection line, then Equation 6.

$$\begin{cases} Z_{se} = R_{se} + jX_{se} \\ Z_L = R_L + jX_L \end{cases} \tag{6}$$

The output voltage $\dot{U}_{se}$ of FID single-phase control unit can be expressed as Equation 7.

$$\dot{U}_{se} = Z_{se} \dot{I}_{se} \tag{7}$$

If it is stipulated that the junction points M and N of the station area are the head and end of the interconnected line respectively, the current $\dot{I}_{L0}$ flowing through the interconnected line after the direct loop closure can be obtained from Figure 6 as Equation 8:

$$\dot{I}_{L0} = \frac{\dot{U}_M - \dot{U}_N}{Z_L} = \frac{U_M \cos \delta_M - U_N + jU_M \sin \delta_M}{R_L + jX_L} \tag{8}$$

The active power flow P_{L0} and reactive power flow Q_{L0} at the end of the interconnected line after direct loop closure are respectively (Equation 9).

$$\begin{cases} P_{L0} = \dfrac{U_M U_N (R_L \cos \delta_M + X_L \sin \delta_M) - U_N^2 R_L}{R_L^2 + X_L^2} \\ Q_{L0} = \dfrac{U_M U_N (X_L \cos \delta_M - R_L \sin \delta_M) - U_N^2 X_L}{R_L^2 + X_L^2} \end{cases} \tag{9}$$

When the FID and the series connection switch cooperate to complete the flexible closing loop, the current $P_{L0} + jQ_{L0}$ of the interconnected line is

$$\dot{I}_{se} = \frac{\dot{U}_M - \dot{U}_N}{Z_L + Z_{se}} = \frac{U_M \cos \delta_M - U_N + jU_M \sin \delta_M}{R_L + R_{se} + j(X_L + X_{se})} \tag{10}$$

After the flexible loop closing, the active power flow P_L and reactive power flow Q_L at the end of the interconnected line are respectively

$$\begin{cases} P_L = \dfrac{U_M U_N [(R_L + R_{se}) \cos \delta_M + (X_L + X_{se}) \sin \delta_M] - U_N^2 (R_L + R_{se})}{(R_L + R_{se})^2 + (X_L + X_{se})^2} \\ Q_L = \dfrac{U_M U_N [(X_L + X_{se}) \cos \delta_M - (R_L + R_{se}) \sin \delta_M] - U_N^2 (X_L + X_{se})}{(R_L + R_{se})^2 + (X_L + X_{se})^2} \end{cases} \tag{11}$$

It can be seen from Equation 10 that when FID controls the power flow of the interconnected line, the equivalent impedance of
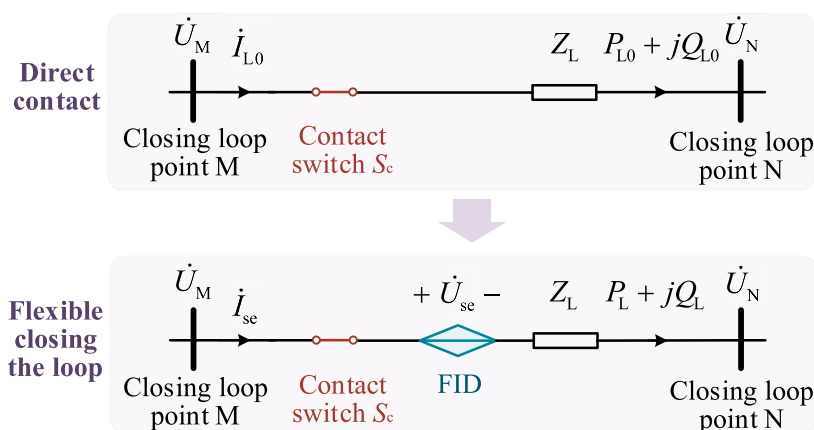
FIGURE 6
The steady-state operation equivalent circuit diagram of the interconnected line of direct closed loop and FID flexible closed loop is shown.

the interconnection device under the target value of the power flow can be calculated according to the FID output voltage and the line current, that is, by changing the amplitude and phase angle of the overall external equivalent impedance $Z_L + Z_{se}$ of the interconnected line, the power distribution on the line can be changed, and the power flow regulation function between the stations can be realized.

4 Control strategy of flexible interconnection device

When FID performs flexible loop closing and power flow control in the station area, its compensation station interval differential pressure and power flow control functions are realized by controlling the output voltage $\dot{U}_{se}$ of the single-phase control unit. The differential pressure compensation equation is shown in Equation 3 when the low-voltage bus in the station area is flexibly closed, and the power equation is shown in Equation 11 when the power flow control in the station area is realized. This section studies the FID system-level and device-level control strategies based on the working principle of FID for flexible loop closing and power flow control in the station area.

4.1 System level control strategy

In order to realize the above control functions, the interconnection operation of FID in series with the contact switch is divided into the following four stages: (1) device start-up stage; (2) Flexible closing loop stage; (3) power flow regulation stage; (4) The device out of operation stage. The following will be combined with the FID interconnection operation process and device action state diagram shown in Figure 7 to analyze these four operation stages.

Stage I: Device start-up. FID carries out real-time monitoring of the data such as the voltage of the junction point and the line current in the station area. When receiving the loop closing instruction of the station area, FID starts the power supply module to charge the DC side capacitor, and controls the converter to output the compensation voltage of the station area according to type (3).

Stage II: Flexible closing loop. The closed loop switches S_2 and S_3 in the FID switch module are closed, and the FID is connected in series to the interconnection line to reduce the voltage at both ends of the contact switch to 0, and then the contact switch S_c is closed to complete the flexible loop closing of the station area. After FID starts the self-powered control, the energy supply module withdraws from operation, so that the DC capacitor voltage can withstand the impact of the energy supply module cut-out, and always maintain the stability of the DC voltage.

Phase III: Power flow regulation. After the flexible loop is closed, if the power flow control instruction is received, the FID control converter adjusts the output voltage $\dot{U}_{se}$ according to Equation 11, and then completes the control of the active power flow of the line.

Stage IV: Device out of operation. After the flexible closing stage is completed, if there is no subsequent regulation demand, the bypass switch S_1 is closed, and the FID bypass is withdrawn from operation.

Based on the above analysis, according to the FID power balance characteristics and control function requirements, the system-level control strategy is divided into energy control strategy, flexible closed loop control strategy and power flow control strategy. The following will study the above three control strategies respectively.

4.1.1 Energy extraction control strategy

The actual value of the DC voltage output by the power supply module is $U_{dc_{ens}}$. Before the FID starts the self-powered control, the DC side capacitor voltage is the voltage $U_{dc_{ens}}$ provided by the power supply module. After the FID starts the self-powered control, the energy supply module is cut out from the FID, which prolongs the
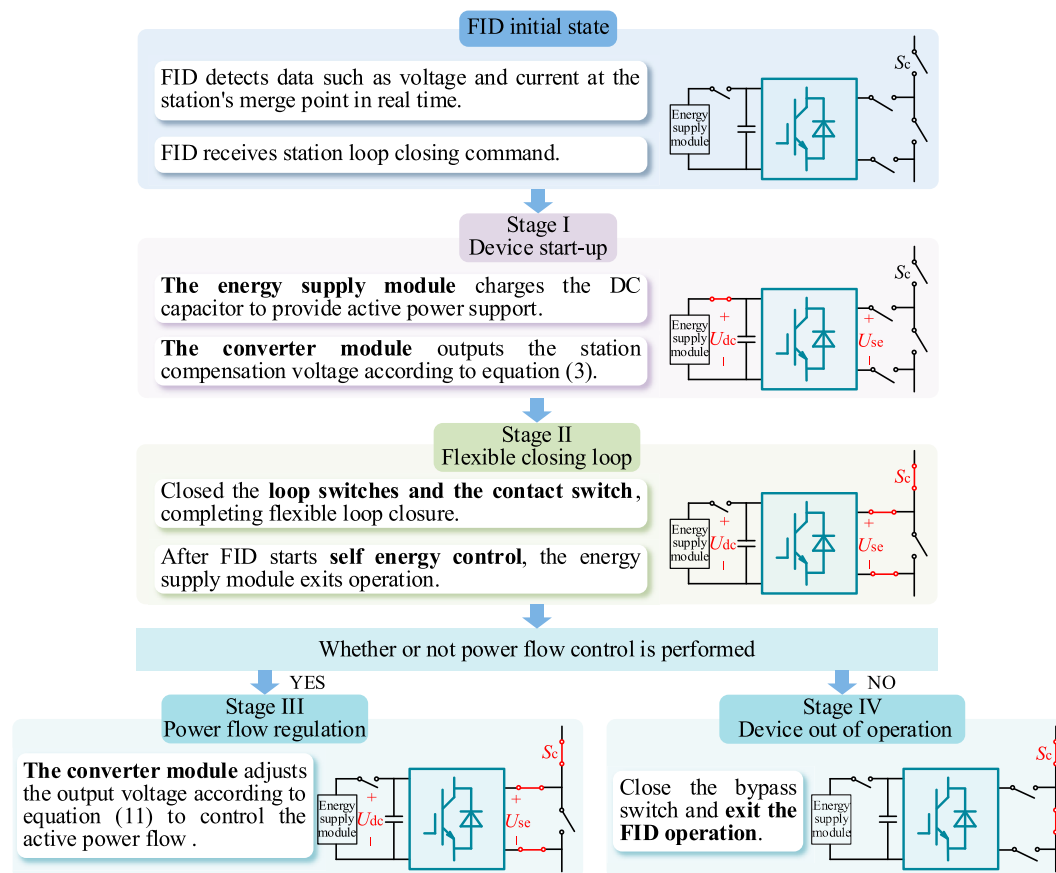
FIGURE 7
FID interconnection operation process and device action state diagram.

service life of the energy supply module and saves its operating cost. Thus, the expression of DC capacitor voltage (Equation 12) is

$$U_{dc} = \begin{cases} U_{dc\_ens} & ,Sigudc = 0 \\ U_{dc}^* & ,Sigudc = 1 \end{cases} \quad (12)$$

where U_{dc}^* is the instruction value of FID DC-side capacitor voltage in the power flow regulation stage; $Sigudc$ denotes the enabling signal of the energy extraction control strategy, $Sigudc = 0$ denotes that the FID DC-side capacitor voltage is provided by the energy supply module, and $Sigudc = 1$ denotes that the FID completes self-energy extraction according to the DC voltage command value.

The instruction values of the d-axis component U_{sed} and the q-axis component U_{seq} obtained by the single-phase Park transformation of the FID output voltage $\dot{U}_{se}$ are U_{sed}^* and U_{seq}^*, respectively. During the start-up stage and the flexible closing process of the device, the energy supply module provides active power support for the FID, so the U_{sed}^* can be set to 0. After the energy supply module is out of operation, in order to maintain the stability of the DC capacitor voltage, FID starts the self-energy control, and the output of the DC capacitor voltage outer loop control strategy is used as the instruction value U_{sed}^* of the FID output voltage d-axis component U_{sed}. Therefore,

the FID system-level energy acquisition control strategy can be obtained as Equation 13:

$$U_{sed}^* = \begin{cases} 0 & ,Sigudc = 0 \\ \left(K_{P1} + \dfrac{K_{I1}}{s}\right)\left(U_{dc}^* - U_{dc}\right) & ,Sigudc = 1 \end{cases} \quad (13)$$

where K_{P1} and K_{I1} are the proportional coefficient and integral coefficient of the PI controller, respectively.

4.1.2 Flexible closing loop control strategy

According to the Equation 3, the pressure difference $\Delta\dot{U}$ of the joint point of the station area is obtained. After the single-phase Park transformation, the obtained d-axis component ΔU_d and q-axis component ΔU_q are used as the modulation voltage of the SPWM, so that the output voltage $\dot{U}_{se}$ required by the FID output is compensated for the pressure difference of the joint point. From this, the FID system-level flexible closing loop control strategy can be obtained as Equation 14:

$$U_{sed}^* = \begin{cases} \Delta U_d & ,Siguse = 0 \\ U_{rd} & ,Siguse = 1 \end{cases}$$

$$U_{seq}^* = \begin{cases} \Delta U_q & ,Siguse = 0 \\ U_{rq} & ,Siguse = 1 \end{cases} \quad (14)$$

where U_{rd} and U_{rq} represent the d-axis component and q-axis component of $\dot{U}_r$ in the dq0 coordinate system, respectively. *Siguse* represents the enabling signal of FID flexible closing loop control strategy, where *Siguse* = 0 represents that FID is in the start-up stage or flexible closing loop stage, and *Siguse* = 1 represents that FID is in the power flow control stage.

4.1.3 Power flow control strategy

In addition to the flexible loop closing function, FID can also carry out line power flow regulation to alleviate the problem of power flow reversal in distribution network caused by the large generation of distributed power sources such as wind power and photovoltaic, or realize the secondary distribution of power between adjacent stations through cross-station mutual assistance, so as to improve the utilization rate of system reserve capacity.Since FID needs to achieve DC voltage stability by self-energy in the power flow control stage, there is only one control degree of freedom for regulating the line power flow. Therefore, the active power P_L of the line can be controlled by adjusting the equivalent reactance X_{se} output by FID. Thus, the FID system-level power flow control strategy is obtained as Equation 15:

$$U_{seq}^* = \begin{cases} 0 & , Sigp = 0 \\ \left(K_{P2} + \dfrac{K_{I2}}{s}\right)(P_L^* - P_L) & , Sigp = 1 \end{cases} \tag{15}$$

where K_{P2} is the proportional coefficient of PI controller; K_{I2} is the integral coefficient of PI controller; P_L^* is the active power command value of the line; *Sigp* represents the enabling signal of the FID power flow control strategy, where *Sigp* = 0 indicates that the FID is not in the power flow control stage, and *Sigp* = 1 indicates that the FID is in the power flow control stage.

4.2 Device level control strategy

By controlling the output voltage, FID can perform flexible loop closing or power flow regulation, so its compensation for the differential pressure difference of the station area and the regulation of the line power flow can be transformed into the control of the d-axis component U_{sed} and q-axis component U_{seq} of the FID output voltage. In order to realize the error-free tracking of the FID output voltage to the d-axis component instruction value U_{sed}^* and the q-axis component instruction value U_{seq}^*, this section studies the FID device-level control strategy.

Taking the current $\dot{I}_{se}$ flowing into the single-phase control unit as the reference phasor, the loop equation (Equations 16, 17) of the FID single-phase control unit in the dq0 synchronous rotating coordinate system can be obtained according to Figure 1.

$$\begin{cases} U_{rd} = U_{sed} - L_f \dfrac{dI_{Ld}}{dt} + \omega L_f I_{Lq} \\ U_{rq} = U_{seq} - L_f \dfrac{dI_{Lq}}{dt} - \omega L_f I_{Ld} \end{cases} \tag{16}$$

$$\begin{cases} I_{Ld} = I_{sed} - C_f \dfrac{dU_{sed}}{dt} + \omega C_f U_{seq} \\ I_{Lq} = I_{seq} - C_f \dfrac{dU_{seq}}{dt} - \omega C_f U_{sed} \end{cases} \tag{17}$$

where U_{sed} and U_{seq} represent the $\dot{U}_{se}$ d axis component and the q axis component in the dq0 coordinate system, respectively. I_{Ld} and I_{Lq} denote the d-axis and q-axis components of $\dot{I}_L$ in the dq0 coordinate system, respectively. I_{sed} and I_{sed} represent the d-axis component and q-axis component of $\dot{I}_{se}$ in dq0 coordinate system, respectively.

The instruction value of the output voltage $\dot{U}_{se}$ of the single-phase control unit is set to $\dot{U}_{se}^*$. Considering the closed-loop control method with feedforward term, the FID device-level control strategy using PI controller is obtained as follows:

$$\begin{cases} U_{rd} = \left(K_{P3} + \dfrac{K_{I3}}{s}\right) \cdot \left(U_{sed}^* - U_{sed}\right) + \omega L_f I_{seq} \\ U_{rq} = \left(K_{P4} + \dfrac{K_{I4}}{s}\right) \cdot \left(U_{seq}^* - U_{seq}\right) - \omega L_f I_{sed} \end{cases} \tag{18}$$

where K_{P3} and K_{P4} are the proportional coefficients of the PI controller; K_{I3} and K_{I4} are the integral coefficients of the PI controller.

Based on the above analysis, it can be seen that the output of the system-level control is used as the command values U_{sed}^* and U_{seq}^* of the device-level control input. The quantities U_{rd} and U_{rq} in the dq0 coordinate system of the modulation voltage of the single-phase control unit are calculated by Equation 18. The modulation voltage $\dot{U}_r$ in the abc three-phase stationary coordinate system is obtained after the single-phase Park transformation. After SPWM modulation, the obtained trigger pulse is sent to the power electronic switch in the single-phase control unit to invert the required output voltage $\dot{U}_{se}$.

Based on the above analysis, the FID system-level and device-level control strategy block diagram is shown in Figure 8.

5 Simulation verification

In order to verify the effectiveness of the proposed flexible loop closing and power flow control strategy of the FID series contact switch in the low-voltage area of the distribution network, the simulation model shown in Figure 2 is constructed in PSCAD/EMTDC software.The main parameters of the simulation model are set as shown in Table 1.

The effectiveness of the proposed control strategy is analyzed by the simulation of the flexible closing loop control strategy of the FID series contact switch and the simulation of the power flow control strategy.

5.1 Simulation analysis of flexible closing loop control strategy of FID series contact switch

In order to verify the effectiveness of the flexible closing loop control strategy and the energy extraction control strategy of the FID series liaison switch, the following simulation settings are carried out: the total simulation time is 2s, the system is initialized before 0.2s, the FID device is started during 0.2–0.4s, the energy supply module charges the DC side capacitor, and the FID controls the converter to output the station area compensation voltage. At 0.4 s, the closed loop switch and the contact switch are closed, so that the
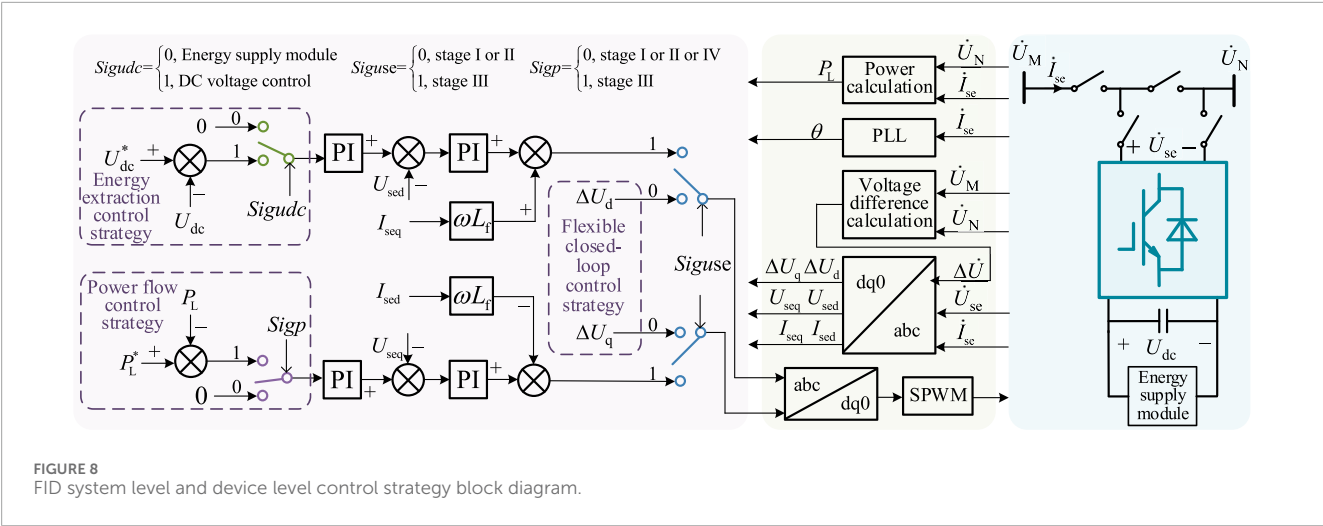
FIGURE 8
FID system level and device level control strategy block diagram.

TABLE 1 Main parameter settings of simulation model.

Parameter	Numerical value
The M bus voltage of the station area	0.4∠0° kV
The N bus voltage of the station area	0.38∠3° kV
The M comprehensive load of the station area	0.10 MW
The N comprehensive load of the station area	0.12 MW
FID rated capacity	0.1 kVA
FID filter capacitance	577.55 μF
FID filter inductance	0.078 mH
FID DC capacitance	20000 μF
FID DC capacitor rated voltage	0.10 kV
DC voltage of energy supply module	0.10 kV

FID is connected in series between the station area M and the station area N to complete the flexible loop closing. At 0.4 s, the FID starts the self-energy control. At 0.6 s, the energy supply module exits, and the FID begins to run on its own.

The FID output voltage and the pressure difference waveform of the closing point are shown in Figure 9. FID does not start before 0.2 s, and its output voltage is 0. The pressure difference amplitude of the two closing points before 0.4 s is about 0.078 kV. During 0.2–0.4 s, FID tracks the pressure difference of the station area to output the corresponding compensation voltage. It can be seen from Figure 9 that the FID output voltage tracks the pressure difference of the station area well. After 0.4 s, FID is connected to the station area through a closed loop switch to complete the flexible loop.

The voltage waveforms at both ends of the contact switch under the flexible closing loop and the direct closing loop are shown in Figure 10. During 0.2–0.4 s, FID is not connected in

series to the closing point of the station area, but the compensation voltage is output under the active support of the energy supply module. Under the action of FID compensation voltage, the voltage amplitude at both ends of the contact switch is reduced to 0.002 kV. The 0.4 s access switch is closed, and the interconnected line only needs to withstand a voltage shock with an amplitude of about 0.002 kV after compensating the differential pressure of the closing link point by FID.For the direct interconnection of the two areas, the closed-loop switch needs to bear a voltage shock with an amplitude of 0.078 kV.

The DC-side capacitor voltage of the FID is shown in Figure 11. The energy supply module provides a stable DC voltage for the FID during the 0–0.6 s period. The FID starts the self-powered control strategy at 0.4 s. After 0.6 s, the energy supply module exits, and the FID stabilizes the DC voltage at the command value of 0.10 kV by self-powered. When the exit of the energy supply module is delayed by the FID strategy, the DC capacitor voltage can withstand the impact of the switching between the energy supply module and the self-starting control, and always maintain the voltage stability. The output voltage can also be effectively controlled according to the command value.When the delay strategy is not adopted, that is, FID starts self-powering and the energy supply module withdraws from operation, the DC voltage oscillates at this time. If there is a subsequent demand for power flow regulation, the problem of DC voltage instability may occur.

Based on the above analysis, FID can effectively track the pressure difference of the closing point in the station area and complete the voltage compensation. Compared with direct interconnection, FID can compensate about 97.44% of the pressure difference of the closing point. The delayed exit of the energy supply module can successfully maintain the stability of the DC capacitor voltage and ensure the stable operation of the FID.

5.2 FID power flow control strategy simulation analysis

In order to verify the effectiveness of the FID power flow control strategy, the following simulation settings are carried out: the total
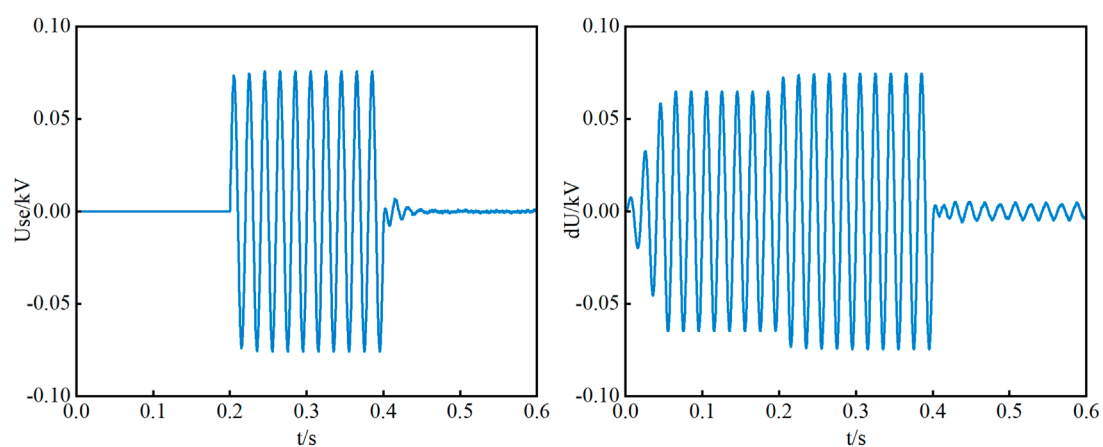
FIGURE 9
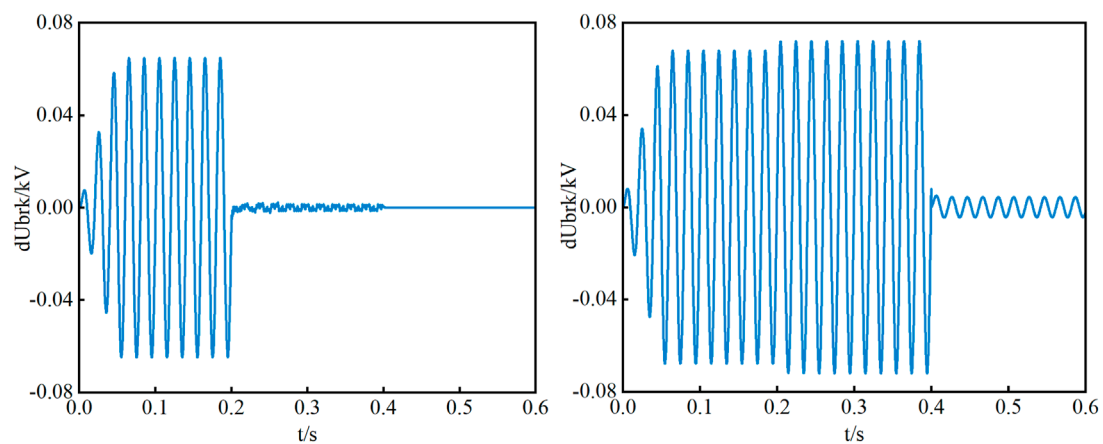FID output voltage and pressure difference waveform of closing point.

FIGURE 10
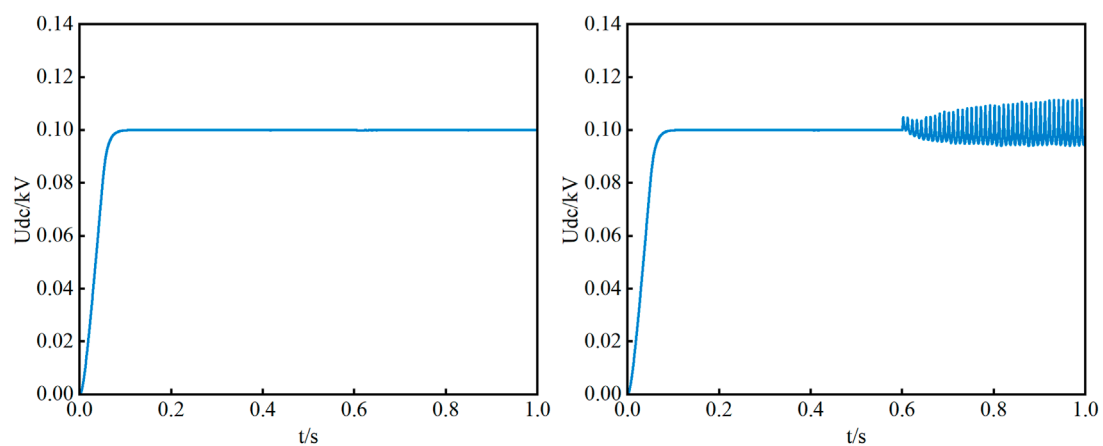Voltage waveforms at both ends of the contact switch under flexible closing loop and direct closing loop.

FIGURE 11
The FID DC side capacitor voltage waveform under the energy extraction strategy and the non-energy extraction strategy.
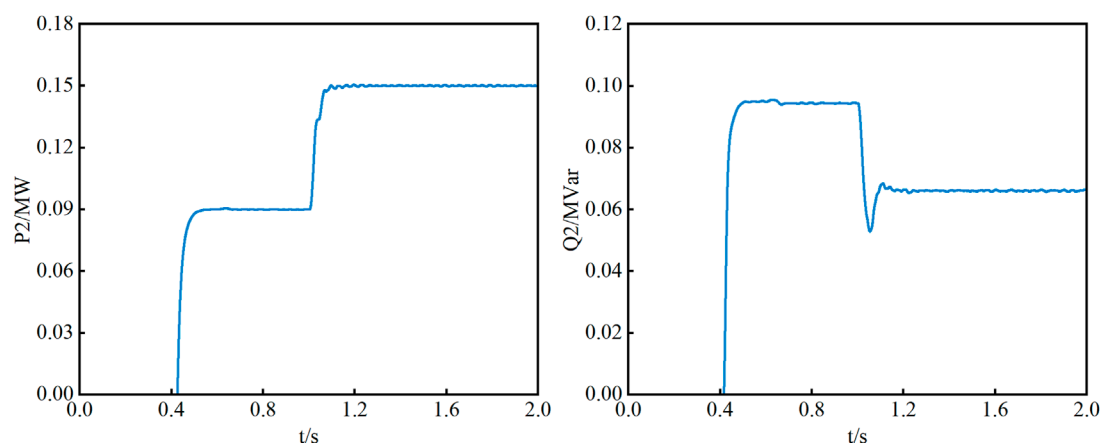
FIGURE 12
The waveform of N active power flow and reactive power flow in the station area.

simulation time is 2 s, the system is initialized before 0.2 s, the FID device is started during 0.2–0.4 s, the FID is connected in series with the station area M and the station area N to complete the flexible closing loop at 0.4 s, the FID is self-powered after 0.6 s, and the active power flow of the FID control station area N rises to the command value of 0.15 MW at 1.0 s.

The active power flow and reactive power flow waveforms of the station area N are shown in Figure 12. During 0.4–1.0 s, FID is connected in series between the station area M and the station area N to complete the flexible closing loop, and the active power of the station area N is 0.05 MW.After 1.0 s, FID began to control the power flow, and the N active power flow in the station area increased from 0.09 MW to 0.15 MW.At 1.5 s, due to the disturbance of the load in the station area N, the active power of the station area N fluctuates by 0.03 s and quickly restores the 0.09 MW command value operation. The N reactive power in the station area decreases from 0.095 MVar to 0.072 MVar after 1.0 s.

The FID output voltage and output current waveforms are shown in Figure 13. During 0.2–0.4 s, the FID device starts the output compensation voltage, and after 0.4 s, the series connection is connected to the flexible loop between the station areas, and the output voltage is consistent with Figure 8. During 0.4–1.0 s, FID only controls the DC voltage, and its output voltage is close to 0.After 1.0 s, the FID output voltage increases to regulate the N active power flow in the station area.

The capacitor voltage waveform of FID DC side is shown in Figure 14. During 0–0.6 s, the energy supply module provides a stable DC voltage for FID. After 0.6 s, FID stabilizes the DC voltage at the command value of 0.10 kV by self-energy.At 1.0 s, FID controls the active power of the station area N by controlling the output voltage, and the FID DC voltage fluctuates but stabilizes near the command value of 0.10 kV.

Based on the above analysis, FID can adjust the active power of the line in the station area by adjusting the output voltage of the converter, and can effectively maintain the active power of the line running at the command value, which shows the effectiveness of the FID power flow control strategy proposed in this paper.
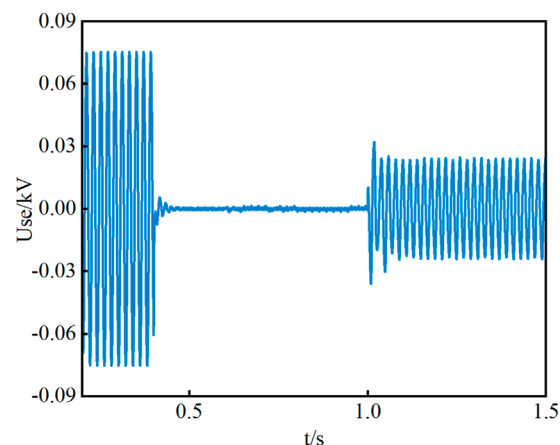

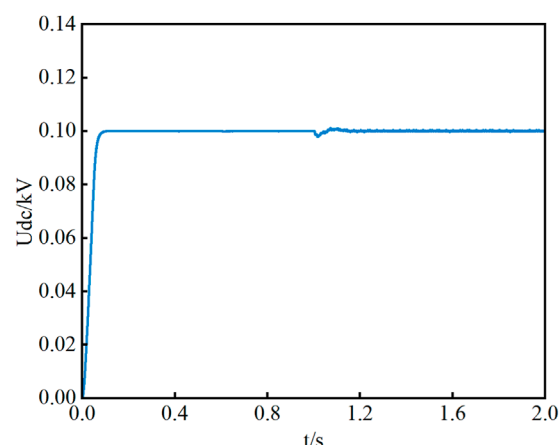**FIGURE 13**
FID output voltage waveform.

FIGURE 14
FID DC side capacitor voltage waveform.

6 Conclusion

In this paper, FID based on single-phase control unit and contact switch in series is proposed as the AC flexible interconnection scheme of low-voltage distribution network. The interconnection equivalent circuit of FID and contact switch in series is constructed. The working principle of FID flexible closing loop and power flow control is studied from the dimension of FID output voltage and equivalent impedance. The control strategies of FID energy extraction, flexible closing loop and power flow control are proposed. Finally, the proposed control strategy is simulated and verified in PSCAD/EMTDC. The following conclusions are obtained:

(1) The FID energy extraction control strategy proposed in this paper, after the successful closing of the FID, in order to prolong the service life of the energy supply module, by controlling the delayed exit of the energy supply module, the FID is switched from the energy supply module to the self-energy extraction control. The process successfully maintains the stability of the DC capacitor voltage and ensures the stable operation of the FID. Compared with the direct switching method, the extracted energy control strategy can reach the DC voltage command value within 0.01 s.

(2) The FID system-level and device-level control strategies with flexible loop closing and power flow control functions proposed in this paper can effectively track the pressure difference of the closing point and complete the voltage compensation. Compared with the direct interconnection, FID can compensate about 97.44% of the pressure difference of the closing point.In the process of power flow control, FID can adjust the output voltage of the converter to realize the effective regulation of the active power of the line in the station area, so that the active power of the controlled line can be maintained at the command value.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

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YL: Conceptualization, Writing–original draft, Writing–review and editing. CD: Investigation, Writing–original draft, Writing–review and editing. XN: Methodology, Writing–original draft, Writing–review and editing. PQ: Data curation, Writing–original draft, Writing–review and editing. YS: Methodology, Writing–original draft, Writing–review and editing. ZW: Methodology, Writing–original draft, Writing–review and editing.

Author contributions

Conflict of interest

The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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