

Effect of IBR Negative-Sequence Control on Phase-to-Phase Fault Direction Determination

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Abstract—Protective relays implement algorithms to determine the direction to the fault. Phase-to-phase fault detection, can rely on negative sequence components. If the negative sequence currents provided by an inverter-based resource (IBR) are not reliable, the directional determination of the fault is not consistent. In this paper, we compare two types of IBRs: grid-following (GFL) and grid-forming (GFM), for their dynamic performance when subject to phase-to-phase faults on the high side of the step-up transformer. The GFL-IBR behaves as a positive-sequence current source, while the GFM-IBR behaves as a voltage source behind an inductive impedance in the positive-sequence circuit, and as an inductive impedance in the negative-sequence circuit. It is found that the GFM-IBR ensures proper fault ride-through, while the GFL-IBR cannot ride through such a fault. Additionally, the GFM-IBR ensures correct fault detection via negative-sequence directionality check, while this check fails for the GFL-IBR case. Therefore, the GFM design presented in this paper appears to have two advantages compared to the legacy GFL design: better capability of fault ride-through and assurance of correct fault direction determination.

Index Terms—Inverter-based resources, grid-following, grid-forming, fault direction detection, negative-sequence control design

I. INTRODUCTION

PROTECTIVE relays, in power systems, detect power system faults. Several algorithms are utilized, and an important one for line protection is the directional element, which determines the direction to the fault [1]. The unbalance due to the fault generates negative- and zero-sequence components in voltages and currents. They are used by protective relays to determine the direction of the fault. Near an IBR, zero-sequence quantities are provided by the step-up transformer (or a ground source, like a zig-zag transformer) and ground fault directional determination is reliable when using zero-sequence quantities. On the other hand, there is no zero-sequence currents generated for phase-to-phase faults. Therefore, negative-sequence components are used to determine the direction to phase-to-phase faults [1]. If the negative sequence quantities provided by the IBR are not reliable, the directional determination to the fault will not be reliable.

Prior research conducted by Electric Power Research Institute (EPRI) [2] finds that compared to a synchronous generator, an IBR provides much smaller negative-sequence current and leads to a very different angular relationship of

the negative-sequence current and voltage. These two elements may result in the misoperation of a relay. Prior to IEEE 2800, the VDE German grid code has required IBRs to provide desired negative-sequence currents, and this requirement has been addressed by research on designing grid-following (GFL)-IBRs, e.g., [3]–[6]. On the other hand, the US grid industry has reported that few legacy IBRs provide negative-sequence currents [7], [8]. Experiments conducted in 2020 measuring the dq admittance for a 2.3-MVA inverter [9] also show that the inverter control reduces the negative-sequence current component when subject to voltage unbalance.

This paper aims to compare various IBR control designs and evaluate their impact on phase-to-phase fault ride-through and fault direction determination using negative-sequence components. In particular, a GFL type with negative-sequence current suppression control and a GFM type are compared for their dynamic performance when subject to phase-to-phase faults.

The GFL-IBR's control design is based on the well-known phase-locked loop (PLL)-based current vector control [10], [11], supplemented by a negative-sequence current controller that drives the negative-sequence current to zero. Thus, this GFL-IBR behaves as a positive-sequence current source.

The GFM-IBR control design is based on the recent GFM design for a high-voltage STATCOM [12]. This design incorporates both positive-sequence and negative-sequence control. The resulting GFM-IBR behaves as a voltage source behind an inductive impedance in the positive-sequence circuit, and as an inductive impedance in the negative-sequence circuit.

It is found that the particular GFM-IBR ensures proper fault ride-through, and correct fault detection via negative-sequence directionality check, while the GFL-IBR cannot ride through a double-phase fault close-by, and the negative-sequence directionality check fails to pick up the fault. Therefore, the GFM design presented in this paper appears to have two advantages compared to the legacy GFL design: better capability of fault ride-through, and ensuring correct relay operation.

Our *contribution* is three-fold. *First*, we have successfully demonstrated that the negative-sequence directional element is capable of determining fault directions, as long as the IBR control design is proper.

Second, we have successfully designed and tested an IBR control scheme that complies with IEEE Standard 2800-2022 [13], which requires an IBR to supply negative-sequence current leading the negative-sequence voltage by 90° during forward unbalanced faults.

Third, the virtual admittance-based GFM-IBR is found to be robust for operation in a hybrid power plant along with legacy

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lead to small fault current magnitude, which may prevent a directional relay to detect the negative-sequence current. Alternative directional determination mechanism may be used for small negative-sequence current scenarios, e.g., line current differential (negative-sequence current-based) [1].

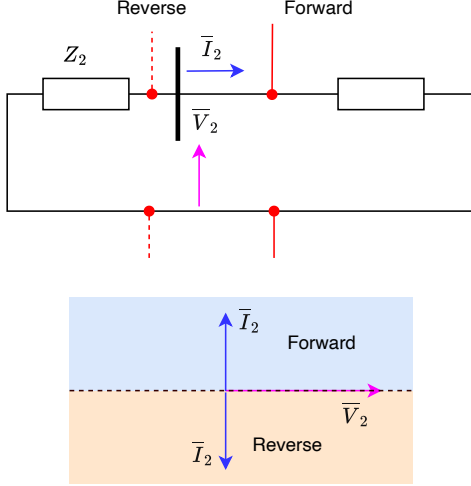


Fig. 2: Negative sequence network and directional determination.

When an IBR behaves as an inductive impedance in the negative-sequence network, the relays near the IBR should be able to correctly detect a forward fault or a reverse fault.

When the IBR behaves as a positive-sequence current source, $\bar{I}_2$ becomes very small in the forward fault case. Additionally, the relationship between the negative-sequence current and voltage is dependent on the implemented current controller. Therefore, it is difficult to ensure that $\bar{I}_2$ leads $\bar{V}_2$. On the other hand, when the fault is in the reverse direction, the current and voltage seen by the relay reflect the inductive impedance of the grid. Therefore $\bar{I}_2$ will lag $\bar{V}_2$ in the reverse fault cases.

Legacy IBRs often adopt PLL-based grid-following control. The IBRs behave as a positive-sequence current source. Therefore, it is expected that GLF-IBRs may have issues to detect forward faults.

III. TWO TYPES OF IBR CONTROL SCHEMES

Fig. 3 shows an illustration of an IBR grid integration system. The parameters of the circuit are listed in Table I. The IBR's inverter control uses its three-phase current measurements and the voltage measurement at the PCC bus as the two inputs, while outputs modulation signals to the power electronic converter's pulse width modulation (PWM). Based on the PCC voltage measurement, a synchronization angle for the positive-sequence is generated by a PLL. And the control in the positive sequence is implemented in the PLL frame.

A. Grid-following control

Grid-following control with zero negative-sequence current enforcement is shown in Fig. 4. The control structure incorporates both positive-sequence and negative-sequence control.

TABLE I: Main parameters of the circuit

Description	Item	
Rated Power	S_{base}	100 MW
Delta side rated voltage	V_p	400 V
Y side rated voltage	V_s	13.2 kV
Nominal frequency	ω_0	377 rad/s
Filter (RL)	Z_{RL}	$0.001 + j0.108$ pu
Filter (C)	B_C	0.0803 pu
Transformer impedance	Z_{xfm}	$0.02 + j0.0702$
Grid impedance	Z_g	$0.03 + j0.3$ p.u.

Outputs from the two parts are aggregated into the reference voltage signal $v_{t,abc}$. Detailed parameters of each unit and control bandwidth are listed in Table II.

TABLE II: Main parameters of the GFL control.

Description	Item	Values	Bandwidth
Current control	PI	$0.3 + 5/s$ p.u.	150 Hz
Choke filter	L_f	$0.108/\omega_0$	
Real power control	PI	$0.25 + 25/s$ p.u.	3.3 Hz
Reactive power control	PI	$0.25 + 25/s$ p.u.	3.3 Hz
PLL	PI	$60 + 1400/s$ p.u.	13 Hz

The positive-sequence control consists of three units: the voltage-based synchronization or the PLL, the inner current control, and the outer real and reactive power control unit. The inner current control is designed to be very fast with a bandwidth above 150 Hz. The outer control unit generates the current orders. Current limits can be easily imposed on those orders. The measurements in the positive-sequence control are the positive-sequence components in the dq frame setup by the PLL (this frame has a displacement angle of θ against the static frame, where θ is the PLL's output angle). In the subcycle time scale, the IBR can be viewed as a current source. The detailed design principles and parameter setting procedure can be found in [11].

The negative-sequence control has the current control only, with a control objective to enforce the negative-sequence current components to 0. This control objective is adopted based on real-world observations of legacy IBR power plants that majority of them do not provide negative-sequence current in the US power grid [7], [8], [17].

The measurements are the negative sequence components (notated by subscript 2) viewed in the dq^- frame (which is a frame with a displacement angle of $-\theta$ against the static frame. This frame rotates in the opposite direction of the dq frame). The negative-sequence current control forces the negative-sequence currents to 0. This characteristic reflects many legacy IBRs' feature of providing negligible negative-sequence currents during unbalanced faults.

A brief explanation on the measurement is provided here. A set of negative-sequence signals is described as follows:

$$\begin{aligned}
 v_a &= \text{Real}\{\bar{V}_2 e^{j\omega_0 t}\}, \\
 v_b &= \text{Real}\{\bar{V}_2 e^{j(\omega_0 t + \frac{2\pi}{3})}\}, \\
 v_c &= \text{Real}\{\bar{V}_2 e^{j(\omega_0 t - \frac{2\pi}{3})}\}.
 \end{aligned} \tag{1}$$

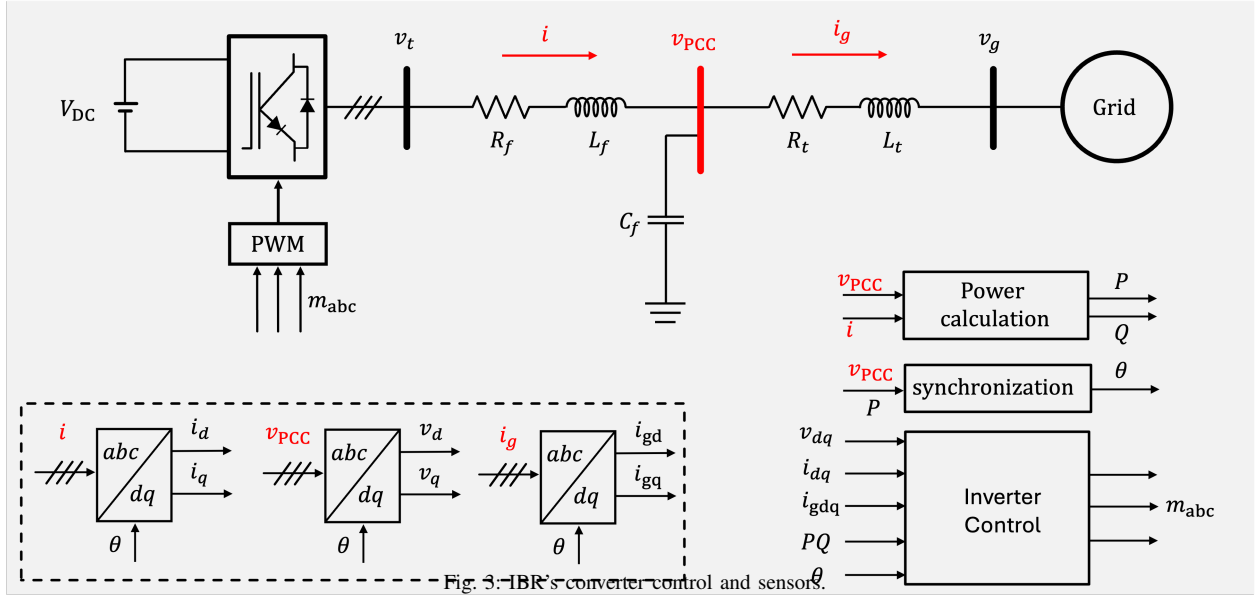


Fig. 3: IBR's converter control and sensors.

They form a space vector rotating at the negative direction at the nominal speed.

$$\begin{aligned}\vec{v}_2 &= \frac{2}{3}(v_a + e^{j\frac{2\pi}{3}}v_b + e^{-j\frac{2\pi}{3}}v_c), \\ &= (\bar{V}_2 e^{j\omega_0 t})^* = \bar{V}_2^* e^{-j\omega_0 t}\end{aligned}\quad (2)$$

Viewed in the dq^- frame that is rotating with a speed of $-\omega_0$, this space vector becomes

$$\bar{V}_2^* = v_{d2}^- + jv_{q2}^-, \quad (3)$$

where the dq components are dc variables and they form the negative-sequence phasor.

Therefore, this GFL control ensures that the IBR acts as a positive-sequence current source during normal and unbalanced operating conditions.

Enabling negative-sequence control requires extracting the negative-sequence components and using them as measurements. Additionally, it is desirable to have those components as dc variables at steady state, so that they can be regulated using proportional integral (PI) controllers. In this context, a dq frame rotating in the negative direction at a speed of ω_0 at steady state is necessary. The negative-sequence components, viewed in this frame notated as dq^- , become dc variables. This frame can be set up by using the negative of the angle set up by the PLL. In the PLL, a low-pass filter (LPF) is usually applied, so that the negative-sequence components are filtered out. Therefore, the angle generated by the PLL aligns with the angle of the positive-sequence component of the voltage.

In the static frame, the converter current $\vec{i}$, the converter terminal voltage $\vec{v}_t$, and the PCC bus voltage $\vec{v}$, have the following relationship.

$$\vec{v}_t - \vec{v} = (R_f + L_f s)\vec{i}, \quad (4)$$

where R_f and L_f are the choke filter's resistance and inductance. In the dq^- frame, their relationship becomes:

$$\bar{V}_t - \bar{V} = (R_f + L_f(s - j\omega))\bar{I}, \quad (5)$$

$$\Rightarrow (R_f + L_f s)\bar{I} = \underbrace{\bar{V}_t - \bar{V}}_{\bar{u}} + j\omega L_f \bar{I}. \quad (6)$$

To ensure that the dq^- components of the current track the orders, PI controllers may be deployed to have the error signals as input while outputs u_d and u_q in the dq^- frame. The negative-sequence current control unit is shown in Fig. 4 (also in Fig. 5) as the essential block to realize negative-sequence current control.

Proportional integral (PI) controllers are designed based on the plant model of $\frac{1}{R_f + L_f s}$, with the dq components of $\bar{u}$ as inputs and the dq components of the current as outputs. Furthermore, the PI controllers enforce the dq components of the current tracking their orders. Therefore, the converter's terminal voltage can be generated by combining the PI controllers' output, the PCC bus voltage feedforward, and the cross-coupling terms:

$$\begin{aligned}\bar{V}_t &= \bar{u} + \bar{V} - j\omega L_f \bar{I} \\ &= G_{PI}(\bar{I}^* - \bar{I}) + \bar{V} - j\omega L_f \bar{I} \\ \Rightarrow v_{td} &= v_d + \omega L_f i_q + G_{PI}(i_d^* - i_d),\end{aligned}\quad (7)$$

$$v_{tq} = v_q - \omega L_f i_d + G_{PI}(i_q^* - i_q). \quad (8)$$

In Fig. 4, this negative-sequence current control is implemented, with the measurements as the negative-sequence components viewed in the dq^- frame. Therefore, the subscript 2 is used to notate the negative-sequence components, while the superscript $-$ is used to notate the dq^- frame. Similarly, the measurements in the positive-sequence control are the positive-sequence components viewed in the dq frame. Therefore, the subscript 1 is used to notate the positive-sequence components.

The positive-sequence control generates the positive-sequence components of the converter voltage viewed in the dq frame, while the negative-sequence control generates the negative-sequence components of the converter voltage viewed in the dq^- frame. These two components are summed after they are converted to the same static abc frame. Eventually,

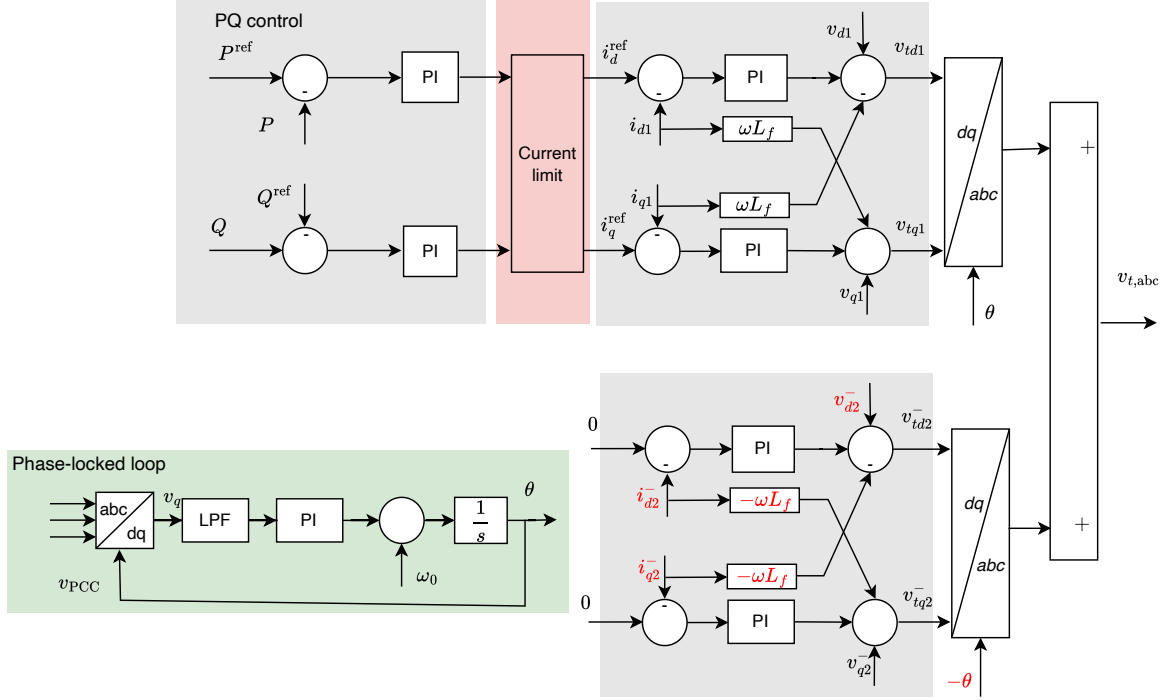


Fig. 4: Grid-following control scheme, supplemented by a negative-sequence current controller.

the overall converter voltage reference $v_{t,abc}$ is generated.

B. Grid-forming virtual admittance control

The grid-forming control adopts the virtual admittance design philosophy presented in [12]. The control structure incorporates inner current control in both positive- and negative-sequence, as shown in Fig. 5. The parameters of the GFM control are shown in Table III.

TABLE III: Main parameters of the GFM control.

Description	Item	Values	Bandwidth
Nominal frequency	ω_0	$2\pi 60$ rad/s	150 Hz
Current control	PI	$0.3 + 5/s$ p.u.	
Current control	L_f	$0.108/\omega_0$	
Virtual admittance	R_v	0.03 pu	
Virtual admittance	X_v	0.2 pu	
Virtual admittance	L_v	$X_v/(2\pi\omega_0)$	
P-f droop control	R	0.05 pu/pu	

If there exists only current control, the IBR can again be viewed as a current source in the subcycle time scale. To make the IBR as a voltage source behind an impedance in the positive- and negative- sequence circuits, the outer control units may be added to emulate such a circuit characteristic.

In the static frame, the relationship between the PCC bus voltage $\vec{v}$, the fictitious internal voltage source $\vec{v}_s$, and the converter current $\vec{i}$ is as follows.

$$\vec{v}_s - \vec{v} = (R_v + L_v s)\vec{i}, \quad (9)$$

where R_v and L_v are the virtual impedance parameters. In the dq frame set up by the PLL, the relationship becomes:

$$\begin{aligned} \bar{V}_s - \bar{V} &= (R_v + L_v(s + j\omega))\bar{I}. \\ \Rightarrow v_{sd} - v_d + \omega L_v i_q &= (R_v + L_v s)i_d \\ v_{sq} - v_q - \omega L_v i_d &= (R_v + L_v s)i_q \end{aligned} \quad (10)$$

The internal voltage source's dq components may be set accordingly with v_{sd} reflecting the voltage reference V^{ref} while v_{sq} at 0. The desired circuit relationship can be implemented using the virtual admittance control unit shown in Fig. 5. The outer voltage control leads to the current orders:

$$\begin{aligned} i_{d1}^{\text{ref}} &= \frac{1}{R_v + L_v s} (v_{sd} - v_{d1} + \omega L_v i_{q1}^{\text{ref}}) \\ i_{q1}^{\text{ref}} &= \frac{1}{R_v + L_v s} (v_{sq} - v_{q1} - \omega L_v i_{d1}^{\text{ref}}) \end{aligned} \quad (11)$$

In the dq^- frame, the relationship becomes:

$$\begin{aligned} \bar{V}_s - \bar{V} &= (R_v + L_v(s - j\omega))\bar{I}. \\ \Rightarrow 0 - v_d - \omega L_v i_q &= (R_v + L_v s)i_d \\ 0 - v_q + \omega L_v i_d &= (R_v + L_v s)i_q \end{aligned} \quad (12)$$

Note that the voltage source in the negative-sequence circuit is set as 0. This also reflected in the virtual admittance control shown in Fig. 5. The outer voltage control leads to the current orders:

$$\begin{aligned} i_{d2}^{\text{ref}} &= \frac{1}{R_v + L_v s} (-v_{d2}^- - \omega L_v i_{q2}^{\text{ref}}) \\ i_{q2}^{\text{ref}} &= \frac{1}{R_v + L_v s} (-v_{q2}^- + \omega L_v i_{d2}^{\text{ref}}) \end{aligned} \quad (13)$$

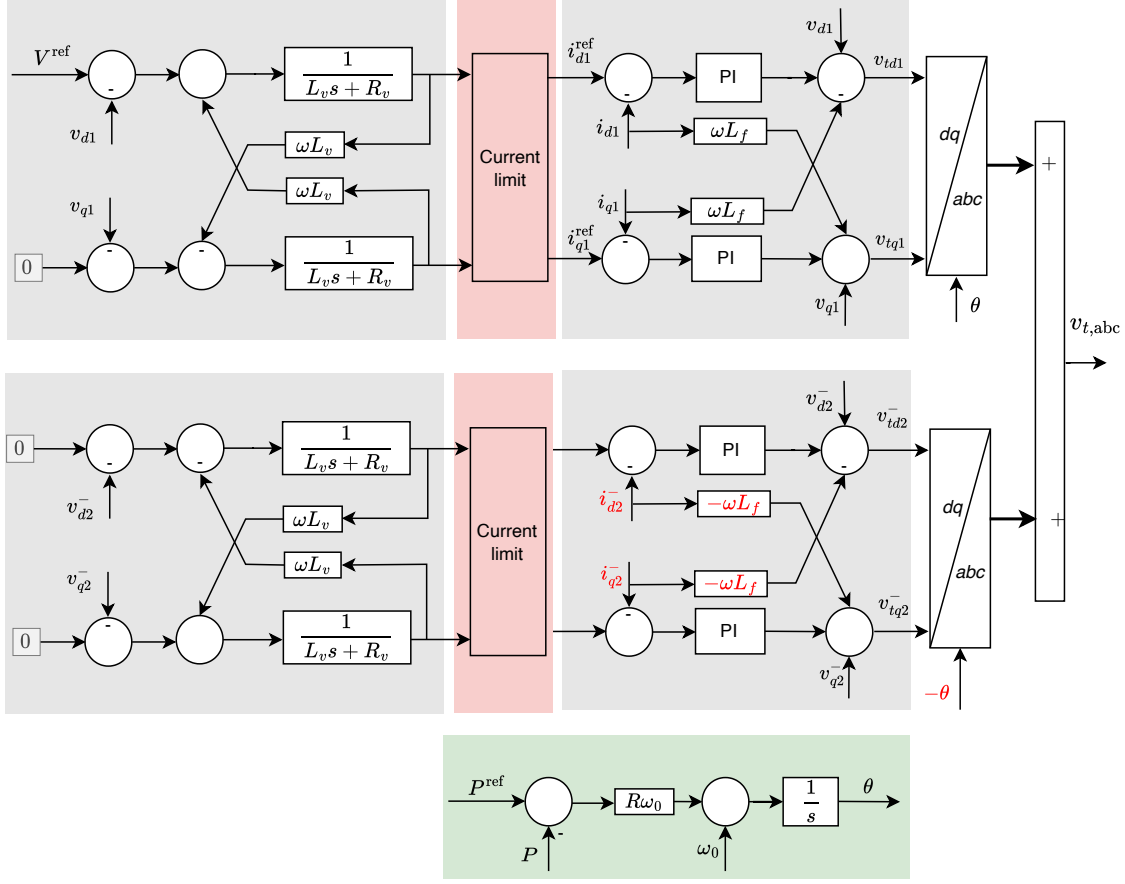


Fig. 5: Grid forming control with virtual admittance design. This GFM acts as a voltage source behind a virtual impedance.

C. Sequence component extraction

In both the GFL and GFM control systems, positive- and negative-sequence components of the voltage and current are required in the control units. These sequence components can be extracted by transforming the three-phase signals to a rotating frame and then passing the signals to a low-pass filter. If the rotating frame has a speed of ω , the extracted signals are the positive-sequence signals viewed in the dq frame. If the rotating direction is the opposite and the rotating speed is $-\omega$, the extracted signals are the negative-sequence signals viewed in the dq^- frame.

Suppose that a set of three-phase signals have both positive- and negative-sequence components:

$$\vec{v} = \vec{v}_1 + \vec{v}_2 = \bar{V}_1 e^{j\omega t} + (\bar{V}_2 e^{j\omega t})^*.$$

When they are transformed into the dq frame or the dq^- frame, the output signals consist of both DC signals and the second harmonic signals:

$$dq : e^{-j\omega t} \vec{v} = \bar{V}_1 + (\bar{V}_2 e^{j2\omega t})^*, \quad (14)$$

$$dq^- : e^{j\omega t} \vec{v} = \bar{V}_1 e^{j2\omega t} + (\bar{V}_2)^*. \quad (15)$$

The DC signals or the sequence component's phasors are desired. They can be extracted by a LPF, as shown in Fig. 6(a). However, this implementation struggles to extract DC signals

with minimal harmonics quickly enough. The LPF cannot completely filter out the double-nominal frequency harmonics. If the LPF has a low bandwidth, the second harmonics can be reduced. However, the response of DC signal tracking becomes slow. This can make the controllers not work well. If the LPF has a high bandwidth, the response of DC signal tracking becomes fast. However, the second harmonic components become significant. This again influences the performance of control units.

To ensure fast DC signal extraction and negligible second harmonic components in the extracted signal, we adopt both dq and dq^- frames for signal extracting. The idea is to subtract the second harmonics from the signal converted in a frame. The second harmonics are generated by the filtered DC signal in one dq frame converted to another dq frame with opposite rotating direction. For example, the following implementation is to extract $\bar{V}_1$.

$$\begin{aligned} & e^{-j\omega t} \vec{v} - G_{\text{LPF}}(s) \cdot e^{j\omega t} \vec{v} \cdot e^{-j2\omega t} \\ &= \bar{V}_1 + (\bar{V}_2 e^{j2\omega t})^* \\ & \quad - (G_{\text{LPF}}(j2\omega) \bar{V}_1 e^{j2\omega t} + G_{\text{LPF}}(j0) (\bar{V}_2)^*) \cdot e^{-j2\omega t} \\ &= (1 - G_{\text{LPF}}(j2\omega)) \bar{V}_1 \approx \bar{V}_1 \end{aligned} \quad (16)$$

This implementation is shown in Fig. 6(b). The static signals are passed through both dq frames. To extract the positive-sequence component, the signals in the dq^- frame are first

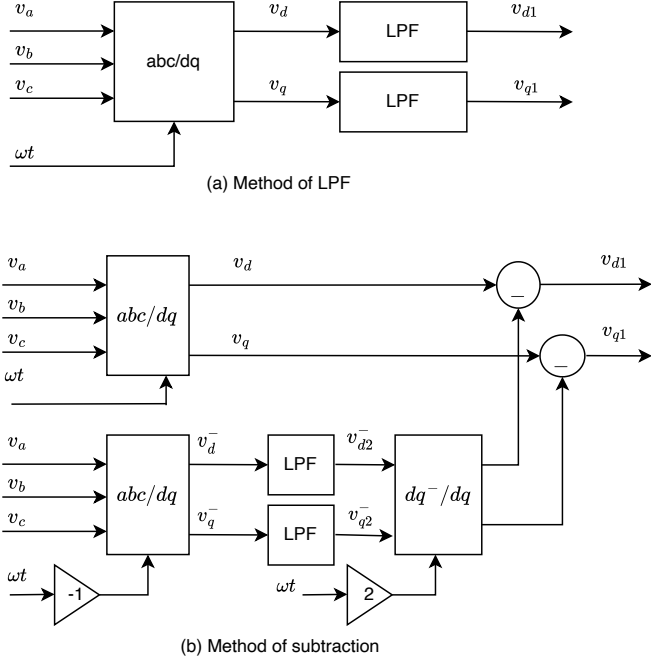


Fig. 6: Sequence components extraction using two methods: the block diagrams.

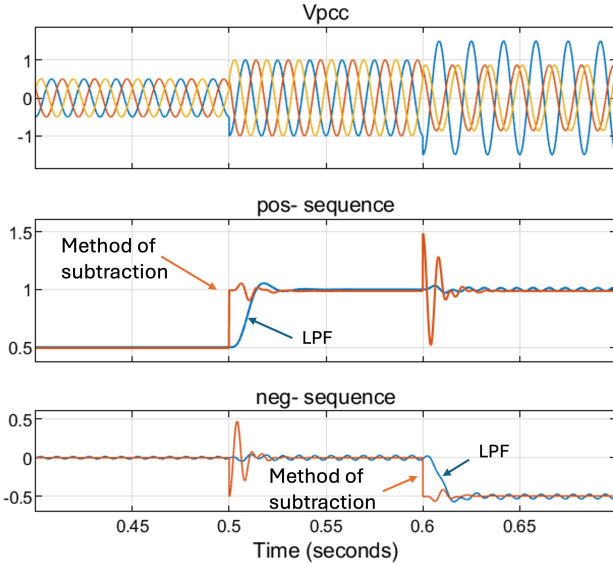


Fig. 7: Sequence components extraction using two methods: the simulation results. A 4th-order Butterworth low-pass filter with a cutoff frequency at 50 Hz is used. The method of subtraction leads to faster responses and negligible harmonics compared to the method of LPF.

passed through a LPF to filter out their DC components. These DC components correspond to the negative-sequence components. Next, the DC signals are converted from the dq^- frame to the 2nd harmonics in the dq frame. These harmonics are then subtracted from the signals in the dq frame. The outputs are DC signals representing the positive-sequence components.

Fig. 7 shows the simulation results comparing the two signal extraction methods. The initial magnitude of the positive-

sequence three-phase signals is 0.5. At 0.5 seconds, the magnitude increases to 1. At 0.6 seconds, a negative-sequence set with a magnitude of 0.5 is added to the input signals. The two methods are implemented to extract the positive- and negative-sequence components. It can be seen that the method of subtraction leads to much faster extraction. This method has been deployed in the converter control.

IV. COMPARISON OF DOUBLE-LINE FAULT BEHAVIOR

A. Fault Direction Detection

Comparison is conducted using electromagnetic transient (EMT) simulation in MATLAB Simscape Specialized Power Systems environment. A testbed shown in Fig. 1 with an IBR is constructed. A phase-to-phase fault is applied at $F1$ (very close to Bus S, in the forward direction) or $F2$ (very close to Bus S, reverse direction).

The parameters of the control and the circuit are shown in Tables I, II and III. The three-phase voltage and current measurements at the relay as well as at the inverter's delta side are taken. Additionally, the real and reactive power from the inverter are also plotted. For the voltage and currents seen by the relay, their sequence components are extracted. And the angles between the voltage and current phasors in positive and negative sequences are plotted.

Fig. 8 shows the performance of a GFL-IBR for the forward phase-to-phase fault (B-C) and the reverse fault (also B-C phase-to-phase fault). Fig. 8(a) and (b) show the time-domain simulation results for two faults. It can be seen that in both faults cases, the IBR's output currents (the 4th subplots of Fig. 8(a) and (b), I - Delta) look symmetrical, implicating very small negative- and zero-sequence components. On the other hand, the wye side of the currents measured by the relay (the second subplots of Fig. 8(a) and (b), I-Yside) appear quite different for the forward and reverse faults. For the forward fault, the wye side currents appear symmetric, while for the reverse fault, phase B and phase C currents are out of phase, which implies the existence of a significant negative-sequence component.

The positive-, negative-, and zero-sequence (PNZ) components of the current seen by the relay are presented in Fig. 8(c)(d). It can be seen that the positive- and negative-sequence voltage components during the phase-to-phase fault have the same magnitudes. This agrees with the knowledge on such faults: the positive-sequence network and the negative-sequence network are connected in parallel at the fault location. Hence, the positive- and negative-sequence components of the voltage seen by the relay have the same magnitudes and angles.

In the forward fault case, the negative-sequence current seen by the relay is the same as that exported from the IBR. Since the inverter's control enforces the negative-sequence current component to 0, I_2 is quite small. Additionally, $\bar{V}_2$ leads $\bar{I}_2$. This makes the relay unable to distinct this fault as a forward fault.

In the reverse fault case, I_2 is pretty large and the voltage leads the current by approximately 90° . In this case, the relay will make correct determination of this fault as a reverse fault.

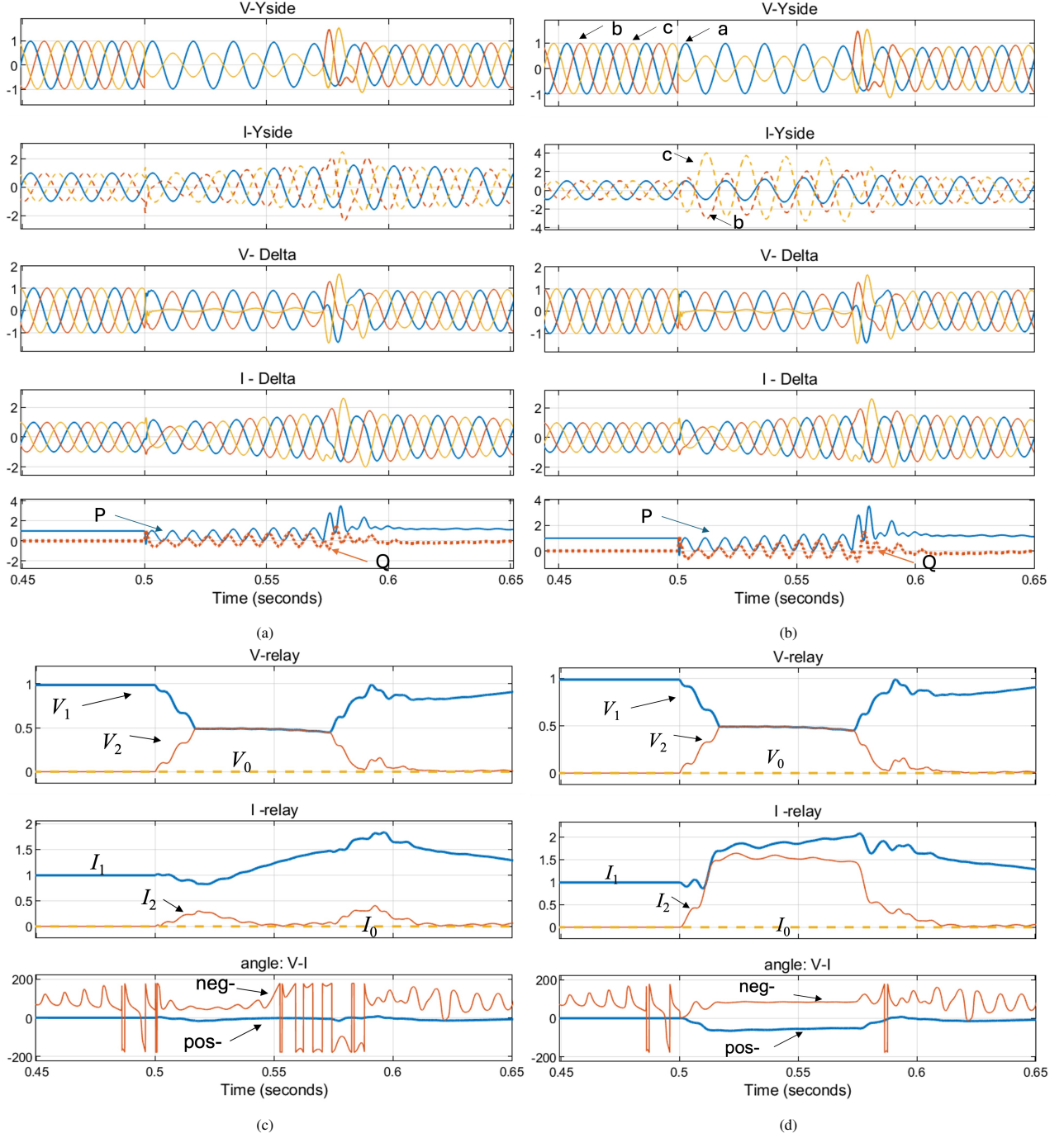


Fig. 8: Performance of the GFL on phase-to-phase fault behavior. Left column (a)(c): Forward fault. (a) Simulation results. (c) PNZ components. Right column (b)(d): Reverse fault. (b) Simulation results. (d) PNZ components. In both fault cases, $\bar{V}_2$ leads $\bar{I}_2$.

Additionally, with V_2 has a value of 0.5 pu and I_2 has a value of 1.5 pu, it can be found that the negative-sequence impedance seen by the relay is 0.3 pu. This corroborates the fact that the line impedance is indeed 0.3 pu.

Fig. 9 shows the performance of a GFM-IBR for the forward fault and the reverse fault. It can be seen that in both faults cases, the IBR's output currents are unsymmetrical, implying significant negative-sequence components.

The positive-, negative-, and zero-sequence components seen by the relay are presented in Fig. 9(c)(d). It can be seen

that the positive- and negative-sequence voltage components during the phase-to-phase fault have the same magnitudes. In the forward fault case, $\bar{V}_2$ lags $\bar{I}_2$. In the reverse fault case, $\bar{V}_2$ leads $\bar{I}_2$. Therefore, the relay can distinct the forward and reverse faults when the IBR has virtual admittance control implemented.

B. Fault Ride-Through Comparison

In the second test, the phase-to-phase fault is applied at Bus T very close to the grid. From Bus S to the grid, the

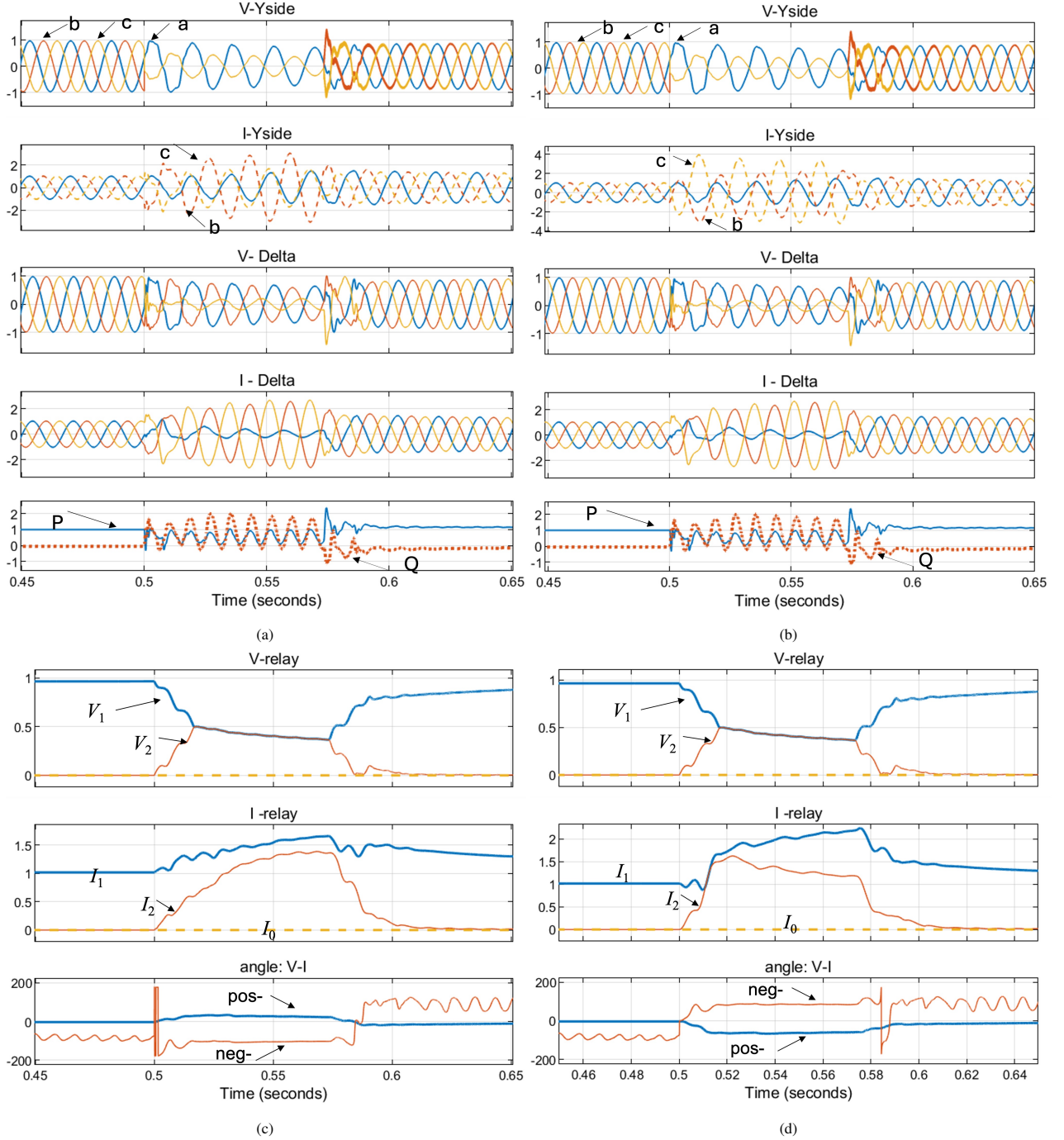


Fig. 9: Performance of the GFM on phase-to-phase fault behavior. Left column: Forward fault. (a) Simulation results. (c) PNZ components. Right column: reverse fault. (b) Simulation results. (d) PNZ components. In the forward fault case, $\bar{V}_2$ lags $\bar{I}_2$; in the reverse fault case, $\bar{V}_2$ leads $\bar{I}_2$.

line reactance is 0.3 pu. This is a weak grid. Fig. 10 shows the simulation results of the GFL case and the GFM case. At $t = 0.5$ s, the fault is applied and lasts for 4 cycles or 0.067 seconds.

It can be seen that the GFL is not able to ride through this fault. The angle of the PLL is shown to keep increasing even after the fault is cleared and eventually the GFL loses synchronism with the grid. On the other hand, in the GFM case, the synchronizing angle increases during the fault while returning back to the original operating point after the fault

clearance.

The different outcomes of fault ride-through are caused by GFL control and GFM control. It can be seen in Fig. 10(a) that during the phase-to-phase fault, the reactive power is kept at an average value of 0 due to the GFL-IBR's reactive power control requirement. Since there is a reduction in the positive-sequence voltage during the fault, the active power reduces as well. The GFL's real power control logic leads to an increase in the d -axis current or real current. Prior research [18] has found that the real current injection is proportional to the PCC bus

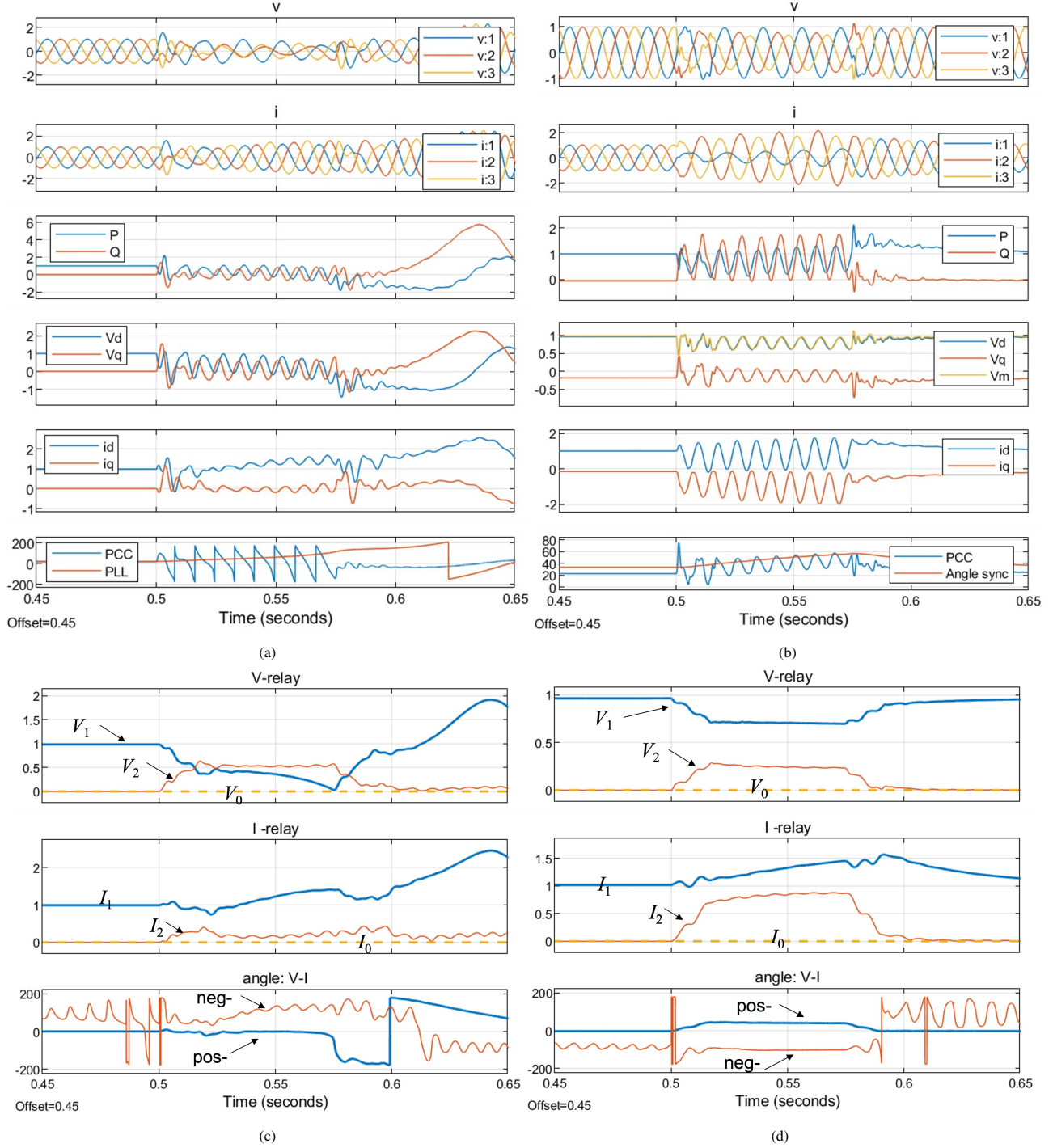


Fig. 10: Fault ride-through comparison. (a)(c) GFL. (b)(d) GFM.

voltage phase angle. Later, [19] has used a phasor diagram to show that increasing real current injection leads to an increase in the PCC voltage phase angle (positive-sequence) as well as the PLL angle. Additionally, [19] also shows that reducing the q -axis current or increasing the reactive current or power helps reduce the two angles.

The control scheme adopted by GFL leads to an increase in its real current injection, while intact in its reactive current injection. On the other hand, the GFM control leads to an increase in the reactive current and a decrease in the real

current. Therefore, the GFL makes the synchronizing angle increase more during the fault, while the GFM helps mitigate the synchronizing angle from increasing too much.

Hence, it can be seen that the GFM helps fault ride-through compared to the GFL.

The PNZ sequence components are shown in Fig. 10(c)(d). It can be seen that for a remote fault, the GFL-IBR provides insignificant negative-sequence current. Its behavior is consistent for an unbalance fault close to the IBR point of interconnection (POI). The GFM-IBR provides significant

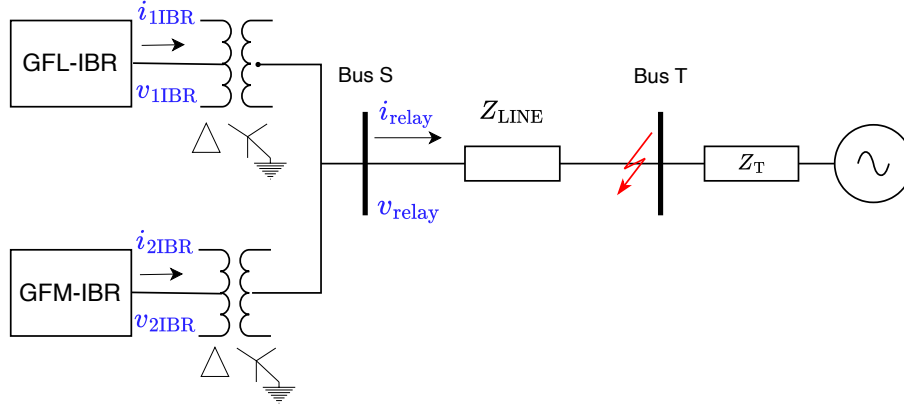


Fig. 11: A hybrid power plant with 50% GFL-IBR and 50% GFM-IBR.

negative-sequence current for a remote unbalanced fault. This behavior is consistent regardless the fault location.

C. Hybrid Power Plant Fault Ride-Through

In the last case study, we show that the virtual admittance control GFM-IBR can work with GFL-IBR without interactions. This feature enables that such GFM-IBR can be used to replace part of the legacy GFL-IBR in an IBR power plant. The resulting hybrid power plant (HPP) can have enhanced fault ride-through capability as well as providing desired negative-sequence current for unbalanced faults.

In the testbed shown in Fig. 1, the IBR represents aggregated effect of IBR units of same characteristics. For a legacy IBR power plant, all IBR units are GFL-IBRs. We now assume that 50% of the IBR units are replaced by GFM-IBRs. The resulting HPP can be represented by a GFL-IBR in parallel with a GFM-IBR, as shown in Fig. 11.

The same remote phase-phase fault is applied. The resulting simulation results and the PNZ components are shown in Fig. 12. It can be seen that with 50% of IBRs as GFM-IBRs, the IBR power plant can now ride-through the remote fault. As a comparison, the all GFL-IBR power plant cannot ride through this fault due to lack of reactive power support and resulting PLL loss of synchronism, as shown in Fig. 10a. For the negative-sequence current provision, the relay's measurements show that for the all GFM-IBR power plant, I_2 can reach close to 1 pu, while for the HPP, I_2 is about 0.5 pu, provided by the GFM-IBR, as shown in Fig. 12b. In addition, $\bar{I}_2$ leads $\bar{V}_2$ by approximately 90° . Therefore, the directional element of the relay can clearly see that this is a forward fault.

V. CONCLUSION

In this paper, we have examined two types of IBR control schemes and their effect on phase-to-phase fault ride-through as well as fault direction determination. It is found that a proper IBR control design is the key to provide negative-sequence currents and comply with the IEEE Standard 2800-2022. Additionally, it is found that making an IBR behave as a voltage source helps fault ride-through by keeping the synchronizing angle small during faults.

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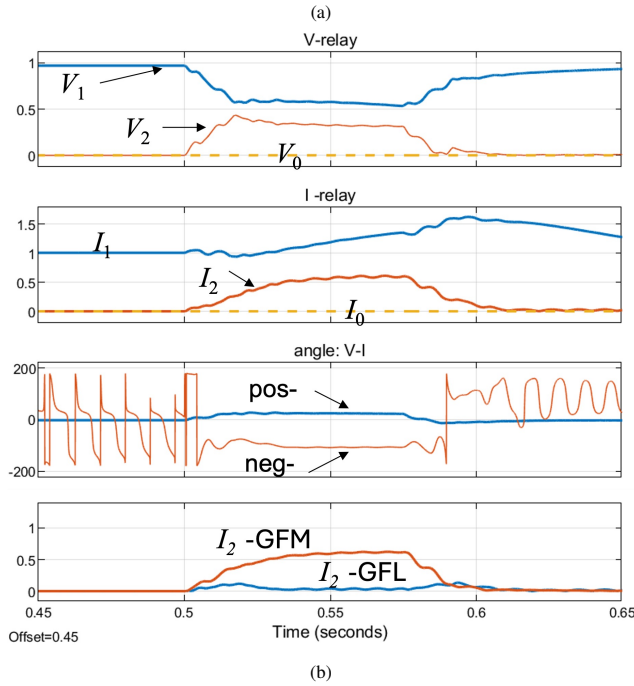
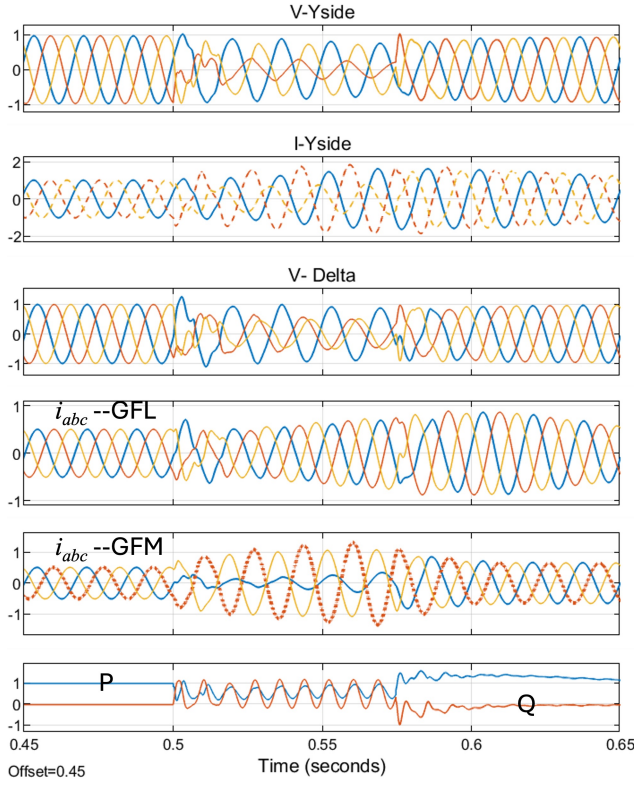


Fig. 12: Fault ride-through of an HPP power plant with 50% GFL-IBR and 50% GFM-IBR. (a) Phase voltage, phase currents, and total real and reactive power. (b) PNZ components.

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