

Transient Stability Enhancement of Grid-forming Inverter-based Resources by Optimizing Angle of Saturated Current

Ali Arjomandi-Nezhad, *Member, IEEE*, and Bikash C. Pal, *Fellow, IEEE*

Abstract—The current saturation challenges the transient stability of grid-forming (GFM) inverter-based resources (IBRs) during large disturbances by introducing the current-saturated stable equilibrium point (CS-SEP). Convergence into the post-fault CS-SEP is an undesired post-disturbance scenario. The angle of the saturated current significantly affects the post-disturbance trajectory. Moreover, the voltage immediately after the converter returns to the normal operation mode depends on this angle. If the difference between this voltage and the reference voltage is large, huge power oscillations occur superimposed on the second-order power swing. The voltage-error-induced power oscillation appears as a disturbance on the active power control loop and affects transient stability. In this paper, the angle of the saturated current is adjusted to minimize the voltage error immediately after the GFM IBR returns to the normal operation mode and prevent the convergence into CS-SEP. To do so, a closed-form expression for the angle of the saturated current at which the voltage transient is minimized is derived in the first stage. Then, an optimization is formulated to minimize the deviation of the angle of the saturated current from the angle calculated in the first stage while ensuring that CS-SEP convergence is avoided. This optimal control method, which enhances transient stability by adaptively tuning the angle of the saturated current, is validated through simulation.

Index Terms—Current saturation, fault recovery, grid-forming (GFM) converter, inverter-based resource (IBR), current-saturated stable equilibrium point (CS-SEP), transient stability.

NOMENCLATURE

ϵ Deviation of angle of current-saturated stable equilibrium point (CS-SEP) from $\mathcal{S}$. Throughout this paper, the term “angle of the saturated current” refers to the phase angle of the saturated current with respect to the local reference frame.

v Angle between terminal voltage and d -axis
 η_1 Deviation of angle of CS-SEP from $\mathcal{R}$ if $-45^\circ \leq \beta \leq 0^\circ$
 η_2 Deviation of angle of CS-SEP from $\mathcal{R}$ if $-90^\circ \leq \beta \leq -45^\circ$
 ρ_1 Margin for inclusion of angle of CS-SEP inside $\overline{\mathcal{S}}$
 ρ_2 Margin for inclusion of angle of CS-SEP inside $\mathcal{R}$
 ζ Small positive value
 β Angle of saturated current
 β^* Optimal angle of saturated current
 β_v Angle of saturated current for which voltage deviation from reference is minimized upon returning to normal operation mode
 $\beta_{\min}$ The minimum allowable angle of saturated current
 $\beta_{\max}$ The maximum allowable angle of saturated current
 δ Active power controller (APC) angle $\theta - \theta_g$
 δ_{af} APC angle right after fault clearing
 δ_r APC angle at which grid-forming (GFM) inverter-based resource (IBR) returns to normal operation mode
 δ_u The maximum angle of set $\mathcal{R}$
 θ Angle of local reference frame
 $\theta(t)$ Angle of local reference frame at time t
 θ_g Angle of common reference frame
 $\theta_g(t)$ Angle of common reference frame at time t
 δ_1^{UE} Angle of positive unstable equilibrium point
 δ_{cs}^{SE} Angle of CS-SEP
 δ_{sat} Threshold angle of entering to current-saturation operation mode
 δ_d^p The maximum angle for which $V_d^{sat} \leq V_d$ during current-saturation operation mode
 δ_q^p The minimum angle for which $0 \leq V_q^{sat}$ during current-saturation operation mode
 α Angle complementary to impedance angle ($\arctan \frac{R}{X}$)

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A. Arjomandi-Nezhad (corresponding author) and B. C. Pal are with the Department of Electrical and Electronics Engineering at Imperial College London, London SW7 2AZ, United Kingdom (e-mail: ali.arjomandi.nezhad@gmail.com; b.pal@imperial.ac.uk).

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ϕ	Total Impedance angle from point of measurement (POM) ($\arctan \frac{X}{R}$)	ΔP	Deviation of $\tilde{P}$ from P^{unsat}
ω	Per unit frequency of APC	P^{sat}	Active power output in current-saturation operation mode
ω_n	Nominal frequency	R	Total resistance from POM
ω_0	Reference per unit frequency	R_g	Thevenin grid resistance
$\omega_{\max}$	The maximum APC frequency	R_{tr}	Transformer resistance
$\Delta\omega$	Per unit frequency of APC deviation from its reference value	$\mathcal{R}$	Set of returning angles
$\Delta\omega_{\max}$	The maximum per unit frequency of APC deviation from its reference value	$\mathcal{R}(\beta)$	Set of returning angles for angle of saturated current of β
a_1	Binary variable that is zero if $-45^\circ \leq \beta \leq 0^\circ$	S_b	Nominal apparent power
a_2	Binary variable that is zero if $-90^\circ \leq \beta \leq -45^\circ$	$\mathcal{S}$	Set of entering angles
a_3	Binary variable that is zero if $\delta_u \leq \delta_{sat}$	$\overline{\mathcal{S}}$	Complement of set $\mathcal{S}$
a_4	Binary variable that is zero if $\delta_{sat} \leq \delta_u$	s	Laplace transform variable
C	Capacitance of LC filter	t	Time from arbitrary reference
D_p	Active power droop coefficient	u_d	Output of proportional-integral (PI) controller of d -axis voltage controller
f_n	Nominal frequency	u_q	Output of PI controller of q -axis voltage controller
H	Virtual inertia	$u_{\max}$	The maximum output of PI controller of voltage controller
I_d	Grid-side current along d -axis of local reference frame	V	Terminal voltage of GFM IBR
I_q	Grid-side current along q -axis of local reference frame	V_b	Nominal AC output voltage of inverter
I_{sd}	Inverter-side current along d -axis of local reference frame	V_{DC}	DC input voltage of inverter
I_{sq}	Inverter-side current along q -axis of local reference frame	V_d	Terminal voltage along d -axis of local reference frame
I_{sd}^{ref}	Reference inverter-side current along d -axis of local reference frame	V_d^{ref}	Reference terminal voltage along d -axis of local reference frame
I_{sq}^{ref}	Reference inverter-side current along q -axis of local reference frame	V_d^{sat}	Terminal voltage along d -axis of local reference frame in current-saturation operation mode
$\overline{I_{sd}^{ref}}$	Saturated reference inverter-side current along d -axis of local reference frame	$V_{g_abc}(t)$	Grid voltage for phases a, b, and c at time t
$\overline{I_{sq}^{ref}}$	Saturated reference inverter-side current along q -axis of local reference frame	V_q	Terminal voltage along q -axis of local reference frame
$I_s^{\max}$	The maximum inverter current output	V_q^{ref}	Reference terminal voltage along q -axis of local reference frame
K	Large parameter penalizing deviations of angle of CS-SEP from $\mathcal{R}-\mathcal{S}$	V_q^{sat}	Terminal voltage along q -axis of local reference frame in current-saturation operation mode
L_f	Inductance of LC filter	ΔV_d	Voltage error along d -axis
M_1	Large parameter used in optimization modelling	ΔV_q	Voltage error along q -axis
M_2	Large parameter used in optimization modelling	ΔV_d^0	Initial voltage error along d -axis upon returning to normal operation mode
n	Number of parallel inverters	ΔV_q^0	Initial voltage error along q -axis upon returning to normal operation mode
P	Active power output	V_g	Thevenin grid voltage
P_0	Active power output reference	X_{tr}	Transformer reactance
P^{unsat}	Active power output during normal operation mode in absence of voltage error	X	Total reactance from POM
$\tilde{P}$	Active power output during normal operation mode in presence of voltage error	X_g	Thevenin grid reactance
		y	Shunt impedance of LC filter
		Z	Total impedance from POM
		Z_g	Thevenin grid impedance

I. INTRODUCTION

RENEWABLE energy resources are increasingly being installed in power grids in response to environmental concerns. These resources are mainly interfaced with the grid through inverters, termed inverter-based resources (IBRs) [1]. The replacement of synchronous generators, which are responsible for most grid services, with IBRs challenges the safe and stable operation of power systems [2]. As a response, research revising the control structure of some IBRs was proposed to compensate for the retirement of synchronous generators. These IBRs, which act as voltage sources and provide the grid with several services, e.g., virtual inertia, voltage control, and black-start capability, are called grid-forming (GFM) converters [3]–[7]. It is defined as an IBR whose control architecture is structured to maintain a constant (or nearly constant) internal voltage phasor in sub-transient to transient time frames [8]. It demonstrates an improved dynamic behavior compared to traditional IBRs, namely grid-following (GFL) IBRs, particularly under weak grid conditions [9].

GFM IBR utilization is subjected to security and stability requirements such as transient stability, which is the ability to retain synchronism with the grid upon facing a severe disturbance [10]. This type of stability is associated with that of the angle and frequency of the local reference frame, which is generated by the active power controller (APC) [11]. Numerous works in literature have considered enhancing the transient stability of the grid-forming converters. Reference [12] proposed to adaptively update the damping coefficient and virtual inertia parameters for this purpose. Research in [13] introduced a transient damping term to the APC to increase the transient stability margin. This transient damping term was optimized in [14]. The control signals of APC were saturated in [11] to enhance the transient stability. Reference [15] proposed a new type of APC for which the sign of the voltage error is reversed once the APC angle passes the stability border so that the APC angle turns back to the domain of attraction.

None of [11]–[15] has considered the effect of current limitations of GFM IBRs. GFM IBRs have a limited overcurrent capability, which is easily exceeded when the GFM IBR faces a severe disturbance, e.g., a short-circuit fault or a phase jump [16]. Therefore, a current limitation mechanism should be implemented within the control system of GFM IBRs to prevent the overcurrent [17]. However, the current limitation may adversely affect the transient stability [18], low voltage ride-through [19], phase jump ride-through [20], and voltage stability [21], etc. Thus, it is imperative to study the effect of current limitation mechanisms, and propose effective mitigation for undesired consequences.

There are two main categories of current limitation methods: ① virtual impedance (VI)-based methods, and ② current reference saturation (CRS)-based methods. In the former category of methods, the voltage reference is reduced to limit the output current [22]. Although VI-based methods are intended to maintain the voltage-source behaviour, they may fail to limit the current of GFM IBR stringently at the very beginning due to the limited bandwidth of the voltage control loop [23]. In the CRS-based methods, the current refer-

ence generated by the voltage controller is directly saturated to the maximum allowable value [22].

There are different mechanisms of the current reference saturation. The most famous types of current reference saturation methods are circular limiter, d -axis priority current reference saturation, q -axis priority current reference saturation, and constant angle current reference saturation (CACRS). In the circular limiter, the magnitude of the current reference is limited to the maximum allowable value while its angle follows the same value as the unsaturated reference current [24]. In the d -axis priority current saturation, the saturated current along the d -axis follows the d -axis component of the unsaturated current while the remaining capacity is dedicated to the q -direction [25]. This is the other way around for the q -axis priority current reference saturation [26]. The angle of the saturated reference from the local reference frame is constant in CACRS [27], [28].

While the magnitude of the saturated current for the CACRS cannot be increased, there is the opportunity to modify the angle of the magnitude-saturated current to achieve an enhanced disturbance ride-through. The predominant effect of this angle on the transient stability of GFM IBRs is outlined in [10]. This paper considers CACRS as the implemented current reference saturation method.

The active power output of the GFM IBR plays a prominent role in the dynamics of the APC because it is an input signal of the APC. This power, in turn, is a function of the angle of the saturated current. Therefore, the value for the angle of the saturated current has a significant role in shaping the transient stability behaviour of GFM IBRs. Reference [29] proposed a Lyapunov-based method for selecting a value of the angle of the magnitude-saturated current for which the GFM IBR converges to a stable equilibrium point (SEP) during a severe voltage drop, e.g., a three-phase fault.

Reference [27] pointed out that the operation of a GFM IBR in the current-saturation operation mode poses a new challenge to the transient stability of GFM IBRs, which is the introduction of a stable equilibrium point in the post-fault current-saturation operation mode to the set of equilibrium points. This angle is called the current-saturated stable equilibrium point (CS-SEP) throughout this paper. When a GFM IBR converges to the CS-SEP, it undesirably fails to return to the normal operation mode as a voltage source. Reference [27] proposed to tune the angle of the saturated current so that the angle of CS-SEP is out of the range of angles for which the GFM IBR is in the current-saturation operation mode. This range of angle is named the set of entering angles (denoted by $\mathcal{S}$) in this paper. It was demonstrated in [28] that there are circumstances in which the GFM IBR converges to the CS-SEP even though the angle of CS-SEP is out of $\mathcal{S}$. Reference [28] outlined that the GFM IBR does not necessarily return to the normal operation mode if the APC angle is out of $\mathcal{S}$, and additionally, a set of returning angles (denoted by $\mathcal{R}$) was identified, in which the GFM IBR returns to the normal operation mode. The exclusion of CS-SEP from $\mathcal{S}$ is not a sufficient condition for avoiding convergence to CS-SEP because there might be cases that the GFM IBR does not enter $\mathcal{R}$ while it is converging to a CS-SEP located in $\overline{\mathcal{R} \cup \mathcal{S}}$ [28]. Reference [28] suggested

that the sufficient condition for avoiding the convergence to the CS-SEP is that the angle of CS-SEP is located inside $\mathcal{R}-\mathcal{S}$. Nevertheless, [28] did not propose a methodology for tuning the angle of the saturated current for this purpose.

The convergence to the CS-SEP can be avoided by properly regulating the angle of the magnitude-saturated current (denoted as β). The other concern addressed in this paper, particularly, is minimizing the active power oscillations induced by the transient response of voltage controller while avoiding the convergence to the CS-SEP. During the operation in the current-saturation operation mode, the voltage controller is bypassed. This controller is re-activated when the GFM IBR returns to the normal operation mode. The error of the voltage from its set-point upon returning to the normal operation mode is reflected as an extra undesired power oscillation superimposed on the power swing induced by the APC. Oscillations might lead to the tripping of IBRs [30]. Moreover, these power oscillations, in turn, propagate into the grid as a disturbance to the swing-based dynamics of APC. This specific type of disturbance, which is modeled in detail in this paper, does not exist in synchronous generator-based power systems. This disturbance is, indeed, the effect of the internal voltage controller of the GFM IBR on transient stability.

Tuning β for minimizing the magnitude of the voltage-error-induced power oscillations and avoiding convergence to CS-SEP is the main aim of this paper. To do so, at first, the voltage-error-induced power oscillation, which is a consequence of voltage transients, is modeled. After that, an analytical formula for β for which the voltage transient is minimized is derived. Then, an optimization whose objective function is a summation of two parts is formulated to determine the optimal value of β , which are ① minimizing the angular deviation of the saturated current β from this angle, and ② minimizing the angular deviation of the CS-SEP from $\mathcal{R}-\mathcal{S}$. And this optimization tunes β for the sake of a desired post-fault transient behavior. The optimization is performed adaptively after a change in the operational condition of the GFM IBR, e.g., a change in loading. And this optimization is performed before a fault occurs. It should be noted that the proposed method is distinct from the corrective control methods, which are performed during the immediate post-fault period. The proposed pre-event tuning strategy can be coupled with corrective post-event methods, e.g., the method proposed in [31] to enhance transient stability margins. To summarize, the main contributions of the paper are as follows.

- 1) The voltage-error-induced power oscillation, which acts as a disturbance on APC loop dynamics, is modeled.
- 2) A closed-form expression for the angle of the saturated current at which this disturbance is minimized is presented.
- 3) An optimization is proposed to tune the angle of the saturated current of the GFM IBR with two objectives: ① avoiding convergence to the CS-SEP, and ② minimizing the voltage-error-induced power oscillations.

The remainder of this paper is organized as follows. Section II presents a brief review of the structure of the GFM IBR. Section III reviews the model of the GFM IBR in the current-saturation operation mode and its transient stability.

Section IV models the effect of voltage transient state on the output power of the GFM IBR. Then, an analytical formulation for the angle of saturated current guaranteeing a smooth transition from the current-saturation operation mode to the normal operation mode is presented in Section V. Section VI formulates the proposed optimization. This is followed by verifying the method by case studies in Section VII. Finally, the conclusions are drawn in Section VIII.

II. BRIEF REVIEW OF STRUCTURE FOR GFM IBR

A schematic of the structure of a virtual synchronous generator (VSG) GFM IBR is shown in Fig. 1 [11], [32]-[35]. The GFM IBR is connected to a grid with Thevenin impedance of $R_g + jX_g$ through a transformer with the impedance of $R_{tr} + jX_{tr}$ and an LC filter with the inductance of L_f and capacitance of C . The equivalent impedance of the grid and transformer from the terminal of the GFM IBR is $(R_g + jX_g) + (R_{tr} + jX_{tr}) = R + jX = Z \angle \phi$. In Fig. 1, PWM and PI stand for pulse width modulation and proportional-integral, respectively.

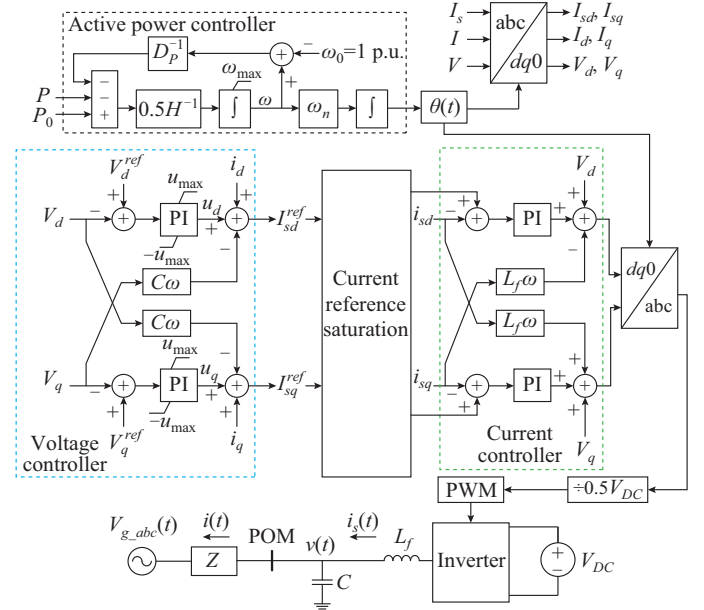


Fig. 1. Structure of studied GFM IBR.

The angle of the local reference frame (dq -frame), shown as $\theta(t)$ in Fig. 1, is determined by APC. This angle is used for transforming voltages and currents from the original abc domain to the dq domain. The difference between this angle and the angle of the Thevenin voltage of the grid (global reference frame) is defined as the APC angle ($\delta = \theta(t) - \theta_g(t)$). This angle is the key to the research on transient stability.

The value of the voltage reference along d -axis, V_d^{ref} , is usually determined by the reactive power controller [36]. In this paper, it is assumed that it is a constant value. The value of the voltage reference along q -axis, V_q^{ref} , is set to be zero. These references are given to the voltage controller, which generates the current reference to track the voltage reference [32]. If the magnitude of the generated current reference is less than the maximum allowable current I_s^{max} , it is

given to the current controller. Otherwise, the saturated reference is given to the current controller [27]. The current controller, in turn, generates the reference PWM signal to track the current reference [32].

III. GFM IBR IN CURRENT-SATURATION OPERATION MODE

This section reviews the conditions for transiting between the normal operation mode and the current-saturation operation mode. In addition, it provides an overview of the operation of the GFM IBR in the current-saturation operation mode. Furthermore, it reviews the large-signal stability model of GFM IBRs. Contents of this section are extracted from [28] unless another reference is explicitly referenced.

A. Transition to Current-saturation Operation Mode

During the steady-state normal operation mode, the output current of the GFM IBR, which is $(\dot{V} - \dot{V}_g)/Z \angle \phi$, is less than $I_s^{\max}$. However, if a disturbance causes a voltage sag in V_g or a large angle difference between $\dot{V}$ and $\dot{V}_g$, the GFM IBR enters the current-saturation operation mode. It is proven in [33] and [37] that if the APC angle is in the set of entering angles $\mathcal{S} = [-180^\circ, -\delta_{sat}] \cup [\delta_{sat}, 180^\circ]$, the GFM IBR enters the current-saturation operation mode. δ_{sat} depends on the grid voltage, the Thevenin impedance of grid, and the voltage reference of GFM IBR.

In the current-saturation operation mode, the saturated current reference is $(\overline{I}_{sd}^{ref}, \overline{I}_{sq}^{ref}) = (I_s^{\max} \cos \beta, I_s^{\max} \sin \beta)$. Since the voltage controller in the current-saturation operation mode no longer gives the current reference to the current controller, the voltage does not follow its reference, which is on the d -axis with the magnitude of V_d^{ref} . The terminal voltages in the current-saturation operation mode are expressed as:

$$V_d^{sat} = V_g \cos \delta + Z I_s^{\max} \sin(\alpha - \beta) \quad (1)$$

$$V_q^{sat} = -V_g \sin \delta + Z I_s^{\max} \cos(\alpha - \beta) \quad (2)$$

It is also proven and simulated that the exclusion from $\mathcal{S}$ is not the sufficient condition for returning to the normal operation mode. The voltage controller generates a reference with the magnitude less than $I_s^{\max}$ once the APC angle enters the set of returning angles $\mathcal{R}$, which is defined as:

$$\mathcal{R} = \begin{cases} [-\delta_d^p, \delta_d^p] & \beta \in [-45^\circ, 0^\circ] \\ [\delta_q^p, 180^\circ - \delta_q^p] & \beta \in [-90^\circ, -45^\circ] \end{cases} \quad (3)$$

δ_d^p and δ_q^p are defined as:

$$\delta_d^p = \arccos\left(\frac{V_d^{ref} - Z I_s^{\max} \sin(\alpha - \beta)}{V_g}\right) \quad (4)$$

$$\delta_q^p = \arcsin\left(\frac{Z I_s^{\max} \cos(\alpha - \beta)}{V_g}\right) \quad (5)$$

The details of the interpretation behind this expression are discussed in [28].

It is evident that unlike $\mathcal{S}$, which is independent of β , $\mathcal{R}$ is a function of β . Thereafter, it is denoted as $\mathcal{R}(\beta)$.

Depending on whether the APC angle is inside or outside $\mathcal{R}(\beta)$ and $\mathcal{S}$, the GFM IBR operates in the normal operation

mode or the current-saturation operation mode. This dependency is listed as:

- 1) If $\delta \in \mathcal{S} - \mathcal{R}(\beta)$, the GFM IBR operates in the current-saturation operation mode.
- 2) If $\delta \in \mathcal{R}(\beta) - \mathcal{S}$, it operates in the normal operation mode.
- 3) If $\delta \in \mathcal{S} \cap \mathcal{R}(\beta)$, it oscillates between the current-saturation and the normal operation modes. Mode-oscillations are significantly reduced using forced saturation introduced in [31].
- 4) If $\delta \notin \mathcal{S} \cup \mathcal{R}(\beta)$, the GFM IBR continues operating in the current mode. Therefore, if the APC angle is in this set, information about its previous operation mode is required to determine its behavior.

B. Transient Stability of GFM IBRs

A GFM IBR synchronizes itself to the main grid through APC. APC angle and frequency follow the second-order swing equation [38] if the GFM IBR is designed as a VSG, expressed as:

$$P_0 - P = 2H \frac{d\omega}{dt} + \frac{1}{D_p} (\omega - \omega_0) \quad (6)$$

$$\frac{d\delta}{dt} = \omega_n (\omega - \omega_0) \quad (7)$$

P is a function of δ , and depending on whether the GFM IBR is in the normal operation mode or the current-saturation operation mode, it might follow the normal or the saturated curves shown in Fig. 2. Intersections of these curves and P_0 form the set of equilibrium points, which are listed as follows.

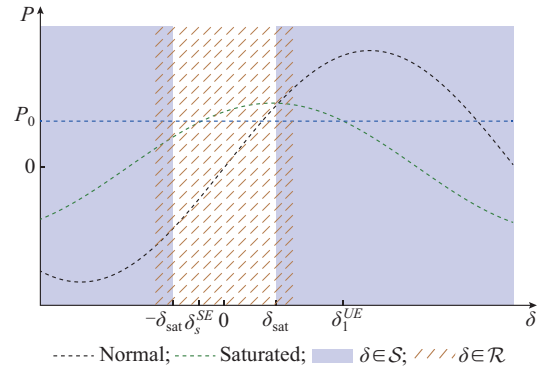


Fig. 2. Power-angle curves of GFM IBR in normal and current-saturation operation modes.

1) SEP: this angle is the post-fault stable equilibrium point in normal operation mode. The convergence to this point is desired.

2) Unstable equilibrium 1: this angle is the maximum post-fault APC angle at which the GFM IBR retains its stability. If the GFM IBR reaches this point with a positive $\Delta\omega$, the GFM IBR becomes unstable. It is an intersection of P_0 and the power-angle curve in the current-saturation operation mode when the curve is descending.

3) Unstable equilibrium 2: this angle is the minimum post-disturbance APC angle at which the GFM IBR retains its stability. If the GFM IBR reaches this point with a negative

$\Delta\omega$, the GFM IBR becomes unstable. It is also an intersection of P_0 and the power-angle curve in the current-saturation operation mode when the curve is descending.

4) CS-SEP: this point is the intersection of P_0 and the power-angle curve in the current-saturation operation mode when the curve is ascending. Although convergence to this point is considered stable theoretically, it is not desired as the GFM IBR locks into the current-saturation operation mode. This angle is calculated as:

$$\delta_{cs}^{SE} = -\beta - \arccos\left(\frac{P_0 - R(I_s^{\max})^2}{V_g I_s^{\max}}\right) \quad (8)$$

The sufficient condition for avoiding convergence to the CS-SEP is the inclusion of the angle of CS-SEP in the set of returning angles and its exclusion from the set of entering angles. In this situation, the GFM IBR cannot stay in the current-saturation operation mode when the APC angle is δ_{cs}^{SE} . In other words, if $\delta_{cs}^{SE} \in \mathcal{R}(\beta) - \mathcal{S}$, the GFM IBR never converges to the CS-SEP. Finding β for which the mentioned sufficient condition is met is a complicated task. Set $\mathcal{R}(\beta)$ depends on the equivalent impedance in addition to β . δ_{cs}^{SE} is a function of P_0 in addition to β . Therefore, different operating points and grid conditions cause variation in the set of β for which the condition is satisfied. Figures 3 and 4 present a graphical demonstration of the sets of β for which the condition is met (green) and not met (blue) for different values of equivalent impedance and power reference set-points. Therefore, an adaptive β optimization is needed to fulfil this condition. This optimization is modelled in Section VI. Another objective of the optimization in Section VI is to minimize the voltage-error-induced power oscillation, which is modelled in the following section.

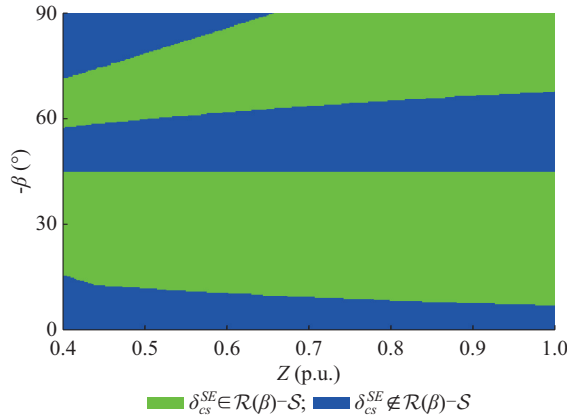


Fig. 3. Regions of saturated-current angle β that satisfy (green) or do not satisfy (blue) the condition $\delta_{cs}^{SE} \in \mathcal{R}(\beta) - \mathcal{S}$ for different values of equivalent impedance Z .

IV. EFFECT OF VOLTAGE TRANSIENT ON OUTPUT POWER OF GFM IBR

In this section, the error in the active power output caused by the voltage error from the reference voltage is modelled. In steady-state normal operation mode, the voltage error is zero, and the terminal voltage follows the voltage reference $(V_d^{ref}, 0)$.

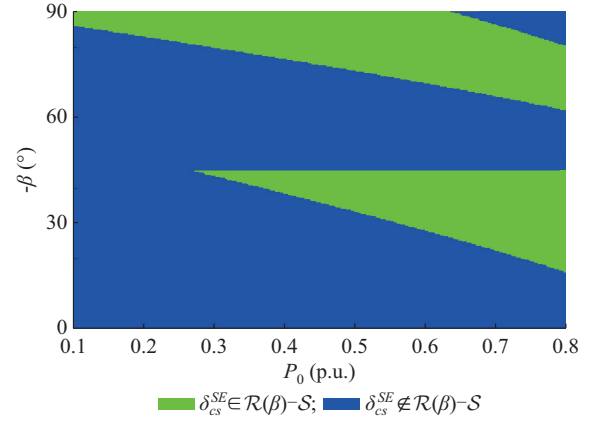


Fig. 4. Regions of saturated-current angle β that satisfy (green) or do not satisfy (blue) condition $\delta_{cs}^{SE} \in \mathcal{R}(\beta) - \mathcal{S}$ for different values of the active power reference P_0 .

In this situation, the terminal voltage is along the d -axis of the local reference frame. Thus, the angle between the terminal voltage of the GFM IBR and the Thevenin voltage of the grid is the APC angle δ . Therefore, the active power output is given by:

$$P_{unsat} = \frac{(V_d^{ref})^2}{Z} \sin \alpha + \frac{V_g V_d^{ref}}{Z} \sin(\delta - \alpha) \quad (9)$$

The value of α is small for inductive grids.

During the voltage transient, the terminal voltage is not exactly $(V_d^{ref}, 0)$ as demonstrated in Fig. 5.

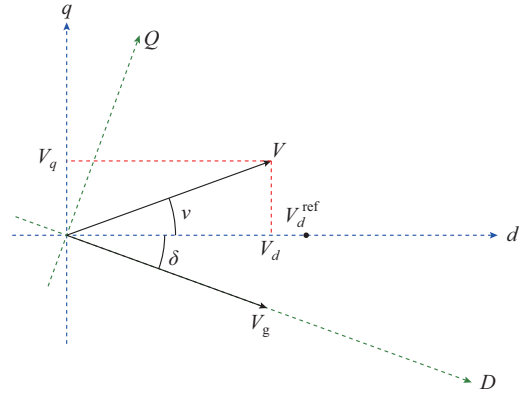


Fig. 5. Terminal voltage of GFM IBR and Thevenin voltage of grid in normal operation mode considering voltage control loop error.

Hence, the angle between the terminal voltage of GFM IBR and the Thevenin voltage of grid is $v + \delta$. v equals $\arctan(V_q/V_d)$. In this situation, the active power output is given by:

$$\tilde{P} = \frac{V^2}{Z} \sin \alpha + \frac{V_g V}{Z} \sin(\delta + v - \alpha) \quad (10)$$

By expanding the sinusoidal part, (10) is equivalent to:

$$\tilde{P} = \frac{V_d^2 + V_q^2}{Z} \sin \alpha + \frac{V_g V_d}{Z} \sin(\delta - \alpha) + \frac{V_g V_q}{Z} \cos(\delta - \alpha) \quad (11)$$

The constant terms $\frac{V_d^2 + V_q^2}{Z} \sin \alpha$ and $\frac{(V_d^{ref})^2}{Z} \sin \alpha$ are ap-

proximately equal for inductive grids. Hence, the error of the active power output induced by the voltage controller error is calculated as:

$$\Delta P = \tilde{P} - P^{unsat} = \frac{V_g \Delta V_d}{Z} \sin(\delta - \alpha) + \frac{V_g \Delta V_q}{Z} \cos(\delta - \alpha) \quad (12)$$

where $\Delta V_d = V_d^{ref} - V_d$ and $\Delta V_q = 0 - V_q$. This equation states that the power error is proportional to the voltage error along d - and q -axes. The transients in voltage errors along d - and q -axes upon returning to the normal operation mode are reflected as the power oscillations superimposed on the power swing caused by APC.

These oscillations can be modelled as a disturbance on the APC loop, causing unpredicted transient stability behaviour, as shown in Fig. 6.

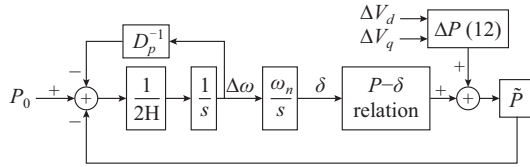


Fig. 6. Equivalent block diagram of APC loop.

The frequency and the damping ratio of the voltage-error-induced power oscillations depend on the poles of the voltage control loop. These poles can be placed by proper tuning of the parameters for voltage controller [39]. On the other hand, the magnitude of oscillations depends on the initial voltage error upon returning to the normal operation mode. The initial voltage is the voltage during the current-saturation operation mode at the exact moment of returning to the normal operation mode, which depends on the angle of saturated current β . In order to minimize the magnitude of undesired power oscillations, this paper proposes to minimize the voltage error upon returning to the normal operation mode. The angle of the saturated current β for which this error is the minimum is calculated in the following section.

V. VOLTAGE TRANSIENT AFTER TRANSITING TO NORMAL OPERATION MODE

The voltage controller is deactivated when the GFM IBR is in the current-saturation operation mode. Once it returns to the normal operation mode, the voltage controller is re-activated to adjust the frequency to $(V_d^{ref}, 0)$. It follows a transient with the initial value of the error voltage at the moment of re-activation. The shape of this transient depends on the closed-loop block diagram of the voltage control loop shown in Fig. 7 [32], [33].

It is inferred from this figure that the voltage transient follows a second-order response. The values of eigenvalues of the voltage control loop are a function of the coefficients for PI controller and the capacitance of filter. The magnitude of the voltage oscillations is proportional to the initial voltage error. The initial voltage errors are given by:

$$\Delta V_d = V_d^{ref} - V_g \cos \delta_r - Z I_s^{\max} \sin(\alpha - \beta) \quad (13)$$

$$\Delta V_q = V_g \sin \delta_r - Z I_s^{\max} \cos(\alpha - \beta) \quad (14)$$

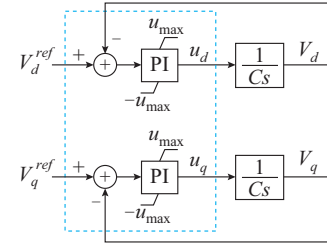


Fig. 7. Equivalent block diagram of voltage control loop assuming a time constant of current control loop is neglectable.

where δ_r is calculated as the minimum value between δ_{sat} and δ_u .

The second-order norm of the initial voltage error $(\Delta V_d, \Delta V_q)$ is at its minimum for the angle of the saturated current $\beta = \beta_v$, such that:

$$\tan(\alpha - \beta_v) = \frac{1 - \cos \delta_r}{\sin \delta_r} \quad (15)$$

Since δ_r is a function of the total grid impedance (Thevenin impedance of grid plus transformer impedance), β_v is also a function of the total grid impedance. With the change of the total impedance, β for which the voltage error is the minimum β_v also changes. To co-optimize the voltage error minimization while avoiding convergence to CS-SEP, β should be chosen in a way that the angle of CS-SEP is included in $\mathcal{R}(\beta) - \mathcal{S}$ and brings close to β_v . It is shown in (8) that the angle of the CS-SEP is a function of the active power reference. Therefore, an adaptive optimization is needed while ① the total grid impedance variations change β_v and ② the active power reference variations change the angle of CS-SEP. This multi-objective adaptive optimization is presented in the following section.

VI. PROPOSED OPTIMIZATION

This section presents the proposed optimization for avoiding convergence to the CS-SEP and a smooth transition to the post-disturbance normal operation mode. The output of the proposed optimization is the optimal angle of the saturated current β . To realize the first objective, the deviation of the CS-SEP from $\mathcal{R}(\beta) - \mathcal{S} = \mathcal{R}(\beta) \cap \bar{\mathcal{S}}$ is minimized. For the second objective, the deviation of β from β_v is minimized. Thus, the objective function is formulated as:

$$\min \left[K(\epsilon + \eta_1 + \eta_2) + (\beta - \beta_v)^2 \right] \quad (16)$$

The deviations η_1 and η_2 are penalized by multiplied by the big parameter K . The modelling constraints, which model the relation between η_1 , η_2 , and ϵ with β , are detailed in the following paragraphs.

The inclusion of the angle of the CS-SEP into $\mathcal{R}(\beta) \cap \bar{\mathcal{S}}$ is broken into two components: ① inclusion of this angle into $\bar{\mathcal{S}}$ and ② inclusion of this angle into $\mathcal{R}(\beta)$. This paragraph models the former, while the latter will be formalized in the few next paragraphs. The angle of the CS-SEP is included within $\bar{\mathcal{S}} = [-\delta_{sat}, \delta_{sat}]$ with the deviation of ϵ , which is minimized in the objective function. Since the resistance is neglectable, this inclusion is formulated as:

$$-(\epsilon + \delta_{sat} - \rho_1) \leq -\beta - \arccos\left(\frac{P_0}{V_g I_s^{\max}}\right) \leq \epsilon + \delta_{sat} - \rho_1 \quad (17)$$

To model the inclusion of the CS-SEP inside $\mathcal{R}(\beta)$, the boundaries of $\mathcal{R}(\beta)$ should be computed. It is discussed in Section III that this boundary is expressed with different expression for $\beta \in [-90^\circ, -45^\circ]$ and $\beta \in [-45^\circ, 0^\circ]$. Two auxiliary binary variables a_1 and a_2 are introduced to the set of the modelling decision variables to reflect the inclusion of β in either of these two intervals, which are expressed as:

$$a_1 + a_2 \leq 1 \quad a_1, a_2 \in \{0, 1\} \quad (18)$$

$$-M_1 a_2 \leq -\beta - 45^\circ \quad (19)$$

$$-\beta - 45^\circ \leq M_1 a_1 \quad (20)$$

The angle of CS-SEP is included in $\mathcal{R}(\beta)$ boundaries with the deviations of η_1 and η_2 if $\beta \in [-45^\circ, 0^\circ]$ and $\beta \in [-90^\circ, -45^\circ]$. These constraints are expressed as:

$$-(\eta_1 + \delta_d^p + M_2 a_1 - \rho_2) \leq -\beta - \arccos\left(\frac{P_0}{V_g I_s^{\max}}\right) \leq \eta_1 + \delta_d^p + M_2 a_1 - \rho_2 \quad (21)$$

$$-(\eta_2 + \delta_q^p + M_2 a_2 - \rho_2) \leq -\beta - \arccos\left(\frac{P_0}{V_g I_s^{\max}}\right) \leq \eta_2 + 180^\circ - \delta_q^p + M_2 a_2 - \rho_2 \quad (22)$$

M_2 is a big parameter for releasing inequalities if the binary variables are zero. The positive parameter ρ_2 is the conservativeness margin. According to (4) and (5), the variables δ_d^p and δ_q^p are formulated as:

$$\delta_d^p = \arccos\left(\frac{V_d^{\text{ref}} - Z I_s^{\max} \sin(\alpha - \beta)}{V_g}\right) \quad (23)$$

$$\delta_q^p = \arcsin\left(\frac{Z I_s^{\max} \cos(\alpha - \beta)}{V_g}\right) \quad (24)$$

The second component of (16) minimizes the deviation of β from β_v . β_v is modelled in Section V as:

$$\tan(\alpha - \beta_v) = \frac{1 - \cos \delta_r}{\sin \delta_r} \quad (25)$$

The angle δ_r is the lowest value among δ_{sat} and δ_u . To compare these two angles, two auxiliary binary variables a_3 and a_4 are introduced to the set of modelling decision variables. The following inequalities are added to the set of constraints.

$$a_3 + a_4 \leq 1 \quad a_3, a_4 \in \{0, 1\} \quad (26)$$

$$-M_2 a_4 \leq \delta_u - \delta_{sat} \leq M_2 a_3 \quad (27)$$

a_3 is zero if δ_u is lower than δ_{sat} . Otherwise, $a_4 = 0$. Followed by modelling a_3 and a_4 , δ_r is modeled as:

$$-M_2 a_3 \leq \delta_r - \delta_u \leq M_2 a_3 \quad (28)$$

$$-M_2 a_4 \leq \delta_r - \delta_{sat} \leq M_2 a_4 \quad (29)$$

The modelling expression for δ_u depends on whether β is more than -45° or less than -45° . Based on (3), δ_u is formulated as:

$$-M_2 a_1 \leq \delta_u - \delta_d^p \leq M_2 a_1 \quad (30)$$

$$-M_2 a_2 \leq \delta_u - (180^\circ - \delta_q^p) \leq M_2 a_2 \quad (31)$$

Equation (25) has a periodic solution for β_v because tangent is a trigonometric function. Only the solution in (32) is acceptable.

$$-90^\circ \leq \beta_v \leq 0^\circ \quad (32)$$

β is limited within upper and lower limits to avoid under-voltage and over-voltage during the post-fault current-saturation operation mode. Hence we can obtain:

$$\beta_{\min} \leq \beta \leq \beta_{\max} \quad (33)$$

After running the optimization code, we observed that the solver struggles to find the solution unless an additional constraint is added to bound the lower value of δ_r to a small positive value:

$$\zeta \leq \delta_r \quad (34)$$

ζ is a small positive value. Since the final value of δ_r is not around zero, inequality (34) does not affect the final solution. It only helps the solver avoid division by zero in constraint (25), which has $\sin \delta_r$ in its denominator.

To summarize this section, the proposed multi-objective optimization is formulated as minimizing the objective function of (16) which is subjected to (17)-(34), with the continuous decision variables β , β_v , ϵ , η_1 , η_2 , δ_r , δ_u , δ_d^p , δ_q^p , and the binary decision variables a_1 , a_2 , a_3 , a_4 .

VII. CASE STUDIES

This section examines the capability of the proposed optimization to tune the angle of the saturated current to prevent convergence to CS-SEP and to smooth the transition from the current-saturation operation mode to the normal operation mode. The system in Fig. 1 with parameters in Table I, adopted from [28], is simulated in MATLAB/Simulink [40] throughout this section, and the studied GFM farm consists of parallel identical GFM IBRs with the same share of loadings, modelled as a single equivalent GFM IBR according to [35]. The proposed optimization is solved using the Artelys Knitro solver [41], [42].

TABLE I
PARAMETERS OF SIMULATED GFM FARM

Parameter	Description	Value
S_b	Nominal apparent power	310 MVA
P_0	Active power reference	270 MW
V_b	Nominal voltage	400 V
V_{DC}	DC link voltage	1200 V
n	Number of parallel GFM IBRs	816
f_n	Nominal frequency	60 Hz
D_p	Active droop coefficient	0.03 p.u.
H	Virtual inertia	2 p.u.
$\Delta\omega_{\max}$	The maximum frequency deviation	0.0066 p.u.
V_d^{ref}	Voltage reference magnitude	1 p.u.
$I_s^{\max}$	The maximum allowed current	1.2 p.u.
X_{lr}	Total reactance of transformer windings	0.16 p.u.

Seven cases in two scenarios are simulated to capture the post-fault behaviour of the GFM IBR with different angles of the saturated current under different grid strengths. These two scenarios are represented as follows.

1) Scenario 1: the GFM IBR is connected to a grid with the Thevenin impedance of 0.3 p.u. and X/R ratio of 20. In this situation, $\beta^* = \beta_v = -13.66^\circ$.

2) Scenario 2: the GFM IBR is connected to a grid with the Thevenin impedance of 0.6 p.u. and X/R ratio of 20. In this scenario, $\beta^* = \beta_v = -24.57^\circ$.

A. Scenario 1: Connection to Strong Grid

Three cases A, B, and C, whose angles of the saturated currents are $\beta_A = \beta^* = -13.66^\circ$, $\beta_B = -30^\circ$, and $\beta_C = -90^\circ$ are simulated under the condition of scenario 1. For all of these three cases, a short-circuit fault with the duration of 0.1 s causes the APC angle to increase to the post-fault angle $\delta_{af} = 34.96^\circ$. The fault is simulated between $t = 0.1$ s and $t = 0.2$ s. Figure 8 shows the APC angles of GFM IBR before, during, and after the three-phase short-circuit fault for these three cases. The post-fault angle-frequency trajectories are shown in Fig. 9. These two figures depict that the GFM IBR settles in the SEP in cases A and B. In contrast, it converges to the CS-SEP in case C. In this case, the angle of CS-SEP $\delta_{cs}^{SE} = 44.52^\circ$ is inside $\mathcal{S} = [-180^\circ, -32.05^\circ] \cup [32.05^\circ, 180^\circ]$. Therefore, the sufficient condition for avoiding convergence to CS-SEP is not satisfied, and indeed, the convergence to CS-SEP happens for case C with $\delta_{af} = 34.96^\circ$.

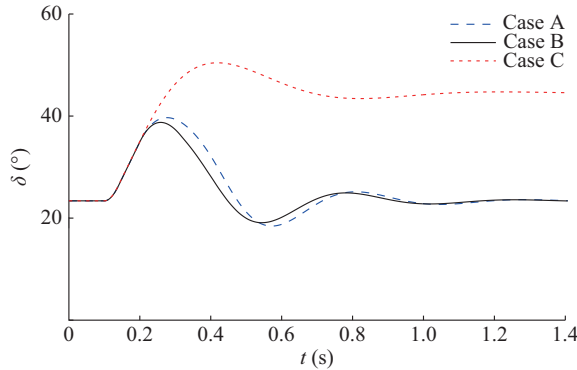


Fig. 8. APC angles of GFM IBR before, during, and after three-phase short-circuit fault in cases A, B and C.

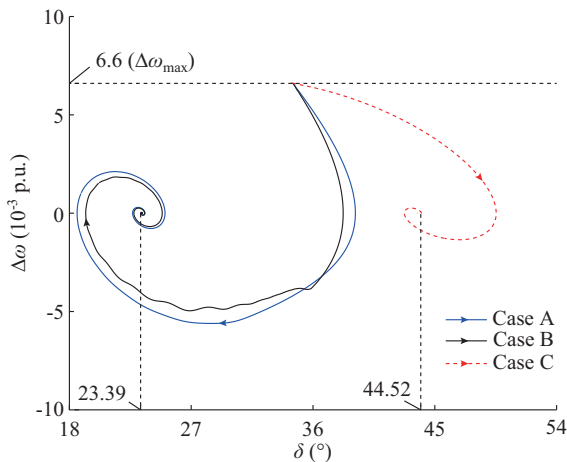


Fig. 9. Post-fault angle-frequency trajectories in cases A, B, and C.

To further investigate the effect of β on the post-fault trajectory in scenario 1, the post-fault trajectories for different β and post-fault APC angles δ_{af} are calculated. Figure 10 demonstrates whether the GFM IBR converges to the SEP, converges to the CS-SEP, or becomes unstable. This figure shows that if β is selected as -90° (case C), the GFM IBR converges to CS-SEP for a big range of post-fault APC angles. In contrast, the GFM IBR does not converge to CS-SEP if the angle of the saturated current is -13.66° or -30° , i.e. cases A and B. The angle of the CS-SEP δ_{cs}^{SE} in the optimal case (case A) is -29.80° , which is inside $\mathcal{R}(\beta^*) - \mathcal{S} = [-32.05^\circ, 32.05^\circ]$. Therefore, the sufficient condition for avoiding convergence into the CS-SEP is satisfied.

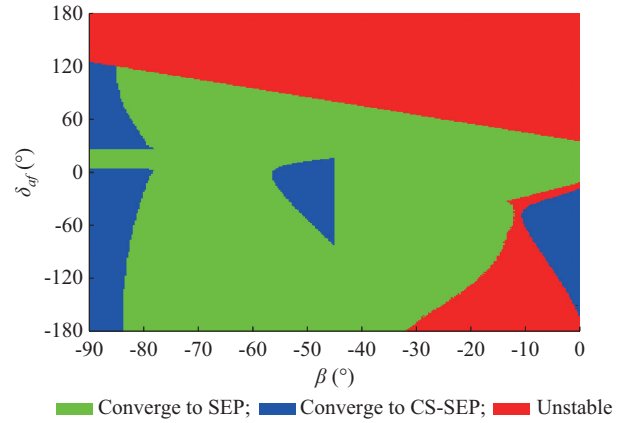


Fig. 10. APC angle for which GFM IBR converges to SEP, converges to CS-SEP, or becomes unstable for different β in scenario 1.

Previous paragraph confirms that the aim of avoidance to converge to the CS-SEP is satisfied for the optimal β . In this paragraph, it is investigated whether the voltage-error-induced power oscillations after returning to the normal operation mode are minimized for the optimal β . Figure 11 depicts that the GFM IBR returns to the normal operation mode at about $t = 0.4$ s (about 0.2 s after clearing the fault) in cases A and B. The post-fault voltage transients of GFM IBR after returning to the normal operation mode for these two cases are shown in Fig. 12. This figure depicts that the voltage transient for case A is neglectable because $\beta_A = \beta_v$. On the other hand, there is a considerable voltage transient in case B. This voltage transient is reflected as an extra oscillation of the active power output superimposed on the power swing, as shown in Fig. 13.

B. Scenario 2: Connection to Weak Grid

To examine the proposed optimization under the condition of connection to the weak grid, i.e., $Z_g = 0.6$ p.u., three cases of D, E, and F are simulated. For these three cases, the post-fault APC angle is 52.07° , following a three-phase fault occurs between $t = 0.1$ s and $t = 0.2$ s. The angles of the saturated current for these three cases are different, i.e., $\beta_D = \beta^* = -24.57^\circ$, $\beta_E = 0^\circ$, and $\beta_F = -30^\circ$, respectively. In the following paragraphs, these two hypotheses are verified under the mentioned conditions:

1) The GFM IBR does not converge to the post-fault CS-SEP for the optimal β .

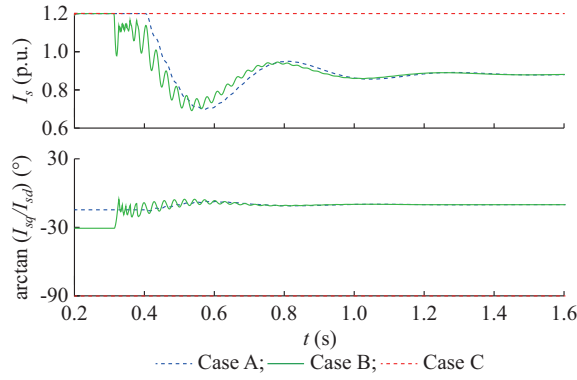


Fig. 11. Post-fault currents in cases A, B, and C.

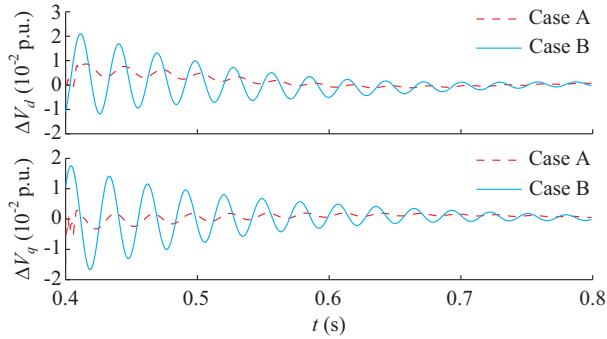


Fig. 12. Post-fault voltage transients of GFM IBR after returning to normal operation mode in cases A and B.

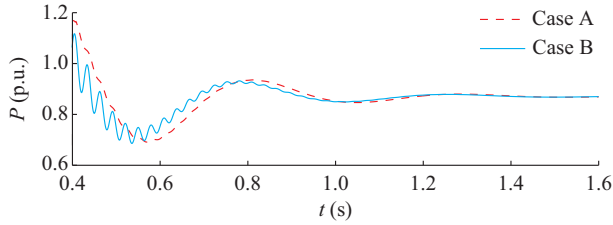


Fig. 13. Active power output of GFM IBR after returning to normal operation mode in cases A and B.

2) The voltage-error-induced power oscillation after returning to the normal operation mode is minimized for the optimal β .

Figure 14 shows the APC angles of GFM IBR before, during, and after the three-phase short-circuit fault for these three cases, and the post-fault angle-frequency trajectories are shown in Fig. 15. These figures show that case E is unstable due to the lack of sufficient post-fault deceleration when the GFM IBR is in the post-fault current-saturation operation mode with $\beta_E = 0^\circ$. Cases D and F are stable; and the GFM IBR converges to SEP in these two simulated cases.

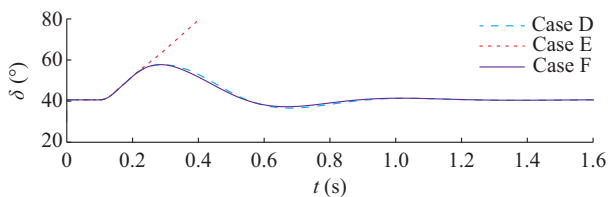


Fig. 14. Short-circuit APC angles of GFM IBR before, during, and after three-phase fault in cases D, E, and F.

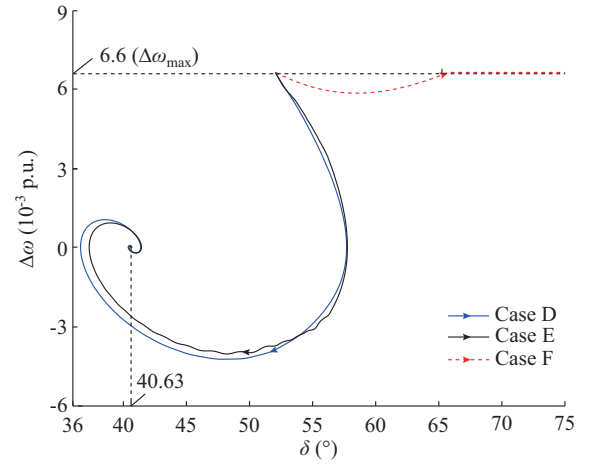
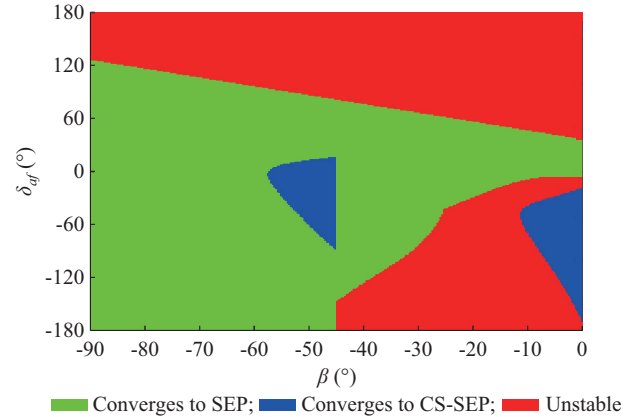


Fig. 15. Post-fault angle-frequency trajectories in cases D, E, and F.

To observe the post-fault behaviour of the GFM IBR for different β and δ_{ap} , post-fault trajectories for all possible combinations of $\beta \in [-90^\circ, 0^\circ]$ and $\delta_{ap} \in [-180^\circ, 180^\circ]$ are calculated. Figure 16 demonstrates the final outcome of each combination in scenario 2 with color coding. Green, blue, and red colors represent convergence to SEP, convergence to CS-SEP, and instability, respectively. The range of post-fault APC angles for which the GFM IBR converges to SEP is narrow for $\beta = 0^\circ$ (case E). If $\beta = \beta^* = -24.57^\circ$ or $\beta = -30^\circ$, which represent cases D and F, respectively, the GFM IBR does not converge to the CS-SEP for any post-fault APC angles. For the optimal case (case D), the angle of the CS-SEP (-18.90°) is inside the $\mathcal{R}(\beta^*) - \mathcal{S} = [-54.26^\circ, 54.26^\circ]$. Therefore, convergence to CS-SEP is impossible if $\beta = \beta^*$.

Fig. 16. APC angle for which the GFM IBR converges to SEP, converges to CS-SEP, or becomes unstable for different values of β in scenario 2.

The post-fault currents in cases D, E, and F are shown in Fig. 17. According to this figure, the GFM IBR returns to the normal operation mode at about $t = 0.375$ s and $t = 0.3$ s in cases D and F, respectively. Figure 18, which visualizes the post-fault voltages in d and q directions after returning the normal operation mode, confirms that the voltage error in case D for which $\beta = \beta^* = \beta_v$ is smaller than that in case F. This voltage error is reflected as extra power oscillations demonstrated in Fig. 19.

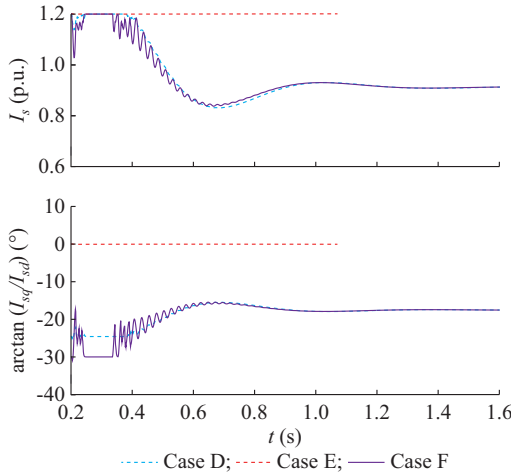


Fig. 17. Post-fault currents in cases D, E, and F.

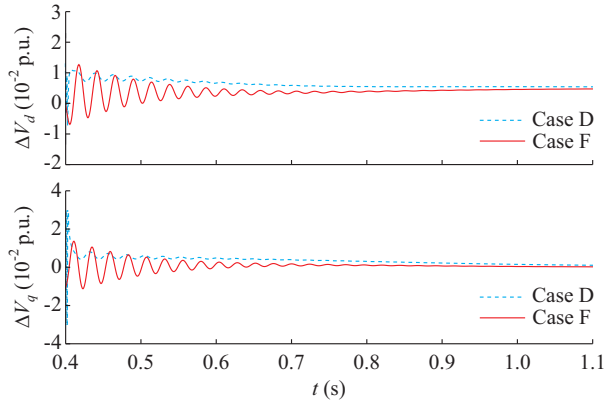


Fig. 18. Post-fault voltage transients of GFM IBR after returning to normal operation mode in cases D and F.

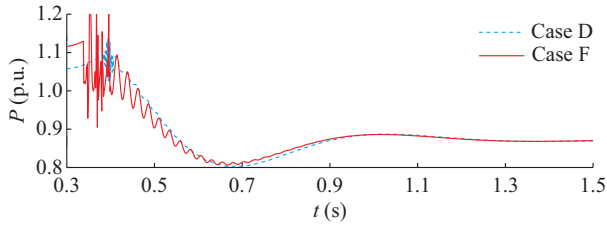


Fig. 19. Active power output of GFM IBR after returning to normal operation mode in cases D and F.

VIII. CONCLUSION

This paper aims to find the optimal angle of the saturated current. The objectives are ① theoretically ensuring avoidance of convergence to the CS-SEP, and ② minimizing the voltage-error-induced power oscillations upon returning to the normal operation mode. The first objective is formulated as ensuring the minimum deviation of the angle of CS-SEP from the set of angles in which the GFM IBR returns to and stays in the normal operation mode. Thereby, the sufficient condition for avoiding locking into the CS-SEP is satisfied. It has been observed that this condition depends on the grid condition and the active power reference. The second objective is to keep the angle of the saturated current close to the one that minimizes the initial voltage error. This angle is al-

so a function of the grid Thevenin impedance. This calls for re-running the optimization as the grid condition or operating point changes. Simulation results confirm that the GFM IBR does not converge to the CS-SEP and exhibits the least voltage transient until converging to the voltage reference. On the other hand, if the angle of the saturated current is selected to one value other than the optimal value, the GFM IBR either converges to CS-SEP or exhibits a high value of voltage oscillations. In case of convergence to the CS-SEP, the GFM IBR is not capable of acting as a voltage source as it is expected. In the presence of severe voltage oscillations, the corresponding power output oscillations are injected into the grid.

In this paper, only three-phase balanced faults, which are extreme events, are simulated. For future research, it is suggested to study and extend the scope of the proposed method to post-unbalanced-fault events.

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Ali Arjomandi Nezhad received the B.Sc. degree in electrical engineering from the Amirkabir University of Technology, Tehran, Iran, in 2016, the M. Sc. degree in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 2018, and the Ph.D. degree in electrical engineering from Imperial College London, London, UK, in 2025. He is currently a Power Systems Engineer at Wartsila Energy Storage UK Ltd. His research interests include dynamics and stability analysis of IBR plants.

Bikash Pal is a Professor of Power Systems at Imperial College London, London, UK. He is research-active in power system stability, control, and estimation. He won the 2025 IEEE PES Prabha Kundur Award for his contribution to robust control and estimation of power systems. His research interests include power system stability, control and protection in renewable dominated operation.