

Model-free predictive control of grid-tied inverter for reducing the current effect of common-mode voltage

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ABSTRACT

One of the solutions to reduce the magnitude of the leakage current in transformer-less photovoltaic systems is to minimize the common-mode voltage (CM voltage) fluctuations modulation-based modification. The modulation-based modification methods increase the grid current's steady-state total harmonic distortion (THD). Predictive control has been demonstrated to perform a viable approach for achieving more rapid and precise control. Finite set model predictive control can add extra terms for leakage current reduction. However, the system model's uncertainties and the grid voltage's unknown effects create some challenges in actual cases. In this context, a model-free methodology is proposed to estimate the grid current. Also, a new part is added to the observer to predict the leakage current. Subsequently, odd virtual vectors are integrated into the candidate vectors to mitigate CM voltage. Additionally, three optimal vectors are chosen to construct the reference voltage. The experimental results have validated the proposed method.

1. Introduction

Photovoltaic (PV) systems grid-tied transformerless have advantages such as cost-effectiveness, lower weight and size, easier expansion, and higher efficiency. The grid-tied inverter is the main part of these systems and its control technique plays an important role in its stable power delivery [1]. However, due to eliminating the galvanic isolation between the DC source and the grid, significant leakage current in such systems is an important challenge [2]. In a grid-tied transformerless system, inverter operation in high-frequency switching states creates a common-mode voltage (CM voltage) with high fluctuations. The cause of leakage current in such systems is also the CM voltage. The leakage current in a transformerless PV system flows toward the ground through stray capacitors between the PV array and the grounded PV frame [3]. The leakage current presents challenges such as electromagnetic interference, increased line current distortion in grid-tied systems, system losses, and safety hazards [4]. Hence, it is imperative to conduct additional research to develop solutions for minimizing leakage current and CM voltage fluctuations in grid-tied transformerless systems. Generally, two solutions have been proposed to reduce the intended challenges in the literature [5]: solutions based on modifying converters' structures (structure modification-based) and change in modulation (modulation-based modification). Structure modification-based so-

lutions require structural changes that increase implementation complexity, size, cost, and power loss [6,7]. The advancement of processing power and peripherals of digital signal processors (DSP) has led to the preference for using modulation-based modification solutions without increasing cost and complexity in implementation. For example, techniques such as active zero state pulse width modulation (PWM), remote state PWM (RSPWM), and near state PWM are classified within the category of modulation-based modification methods [8–11]. Using the RSPWM strategy in the controller of the voltage source inverter (VSI) creates limitations in the system. Still, it is the only method that can fully stabilize CM voltage. Some studies have also proposed the simultaneous use of modulation-based modification and structure modification-based methods in converters. In [12], using only odd voltage vectors (OPWM) and with a slight change in the structure of the grid-connected quasi-Z-source inverter, the CM voltage has been kept entirely constant, and the leakage current in the desired photovoltaic system has decreased significantly. In [13], a combination of modulation-based modification approaches and a change in the circuit structure of a conventional VSI are presented to reduce CM voltage fluctuations and double the DC link voltage. A modified three-phase impedance source inverter with a slight change in its control method is proposed in [14] to reduce the CM voltage fluctuations as well as the capability to enhance and improve the output voltage. Also, in [15], the CM voltage fluctuations in a four-leg

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inverter have been reduced, similar to the approach presented in [16]. It should be noted that the complexity of the hardware system has increased in all the above suggestions.

Implementing modulation-based modification methods requires current and voltage controllers to manage the switching in order to achieve the control goals. These controllers in transformerless inverters are usually based on traditional controllers such as proportional integral, proportional resonant, and proportional integrator derivative, all of which have inherently low dynamic responses [17,18]. In [19], an improved control method is applied by using the discrete model of the inverter. It optimizes the phase of the carrier signal based on the zero sequence current injection. In recent years, with the rapid development of DSP, novel control architectures featuring a swift dynamic response, multi-objective control capability, and simple implementation have become popular. Model predictive current control (MPCC) has been gradually developed in power electronics [20–22]. As is well-known, the MPCC method explicitly uses the system model to predict the future behavior of the control variable. In spite of the mentioned advantages, uncertainty and parameter mismatches are a challenge for the model predictive method. Unforeseen load changes, component aging, temperature variations, and grid voltage fluctuations are examples of uncertainties. This issue degrades the prediction and the whole control system [23]. Robust predictive control methods are one solution for this challenge [24,25]. In recent years, the model-free predictive current control (MF-PCC) approach has been proposed as a robust control method in facing the inherent uncertainties of the system model. Generally, approaches such as auto-regressive with exogenous variable (ARX) model, recursive least squares (RLS), ultra-local model, and learning-based are used to predict the future behavior of the control variable without using a physical model of the system [23,26–29]. The predictive controller's performance has improved by using the ARX approach as a disturbance estimator and combining it with the typical prediction model under uncertainty in the system model. However, we can see the dependence of this method on the detailed model of the desired system. Adaptation of model parameters by the RLS approach is done to estimate the future behavior of the control variable [28]. However, the versatility of the desired approach with the configuration of different systems is considered a limitation and is not straightforward. In [30], the output current of a VSI is controlled by the MFPC method, which is the RLS algorithm used to find the parameters of a generic ARX model. In [31], the model-free deadbeat predictive current control approach based on the proposed idea [32] is used to control a VSI with RL load [33–36] proposes predicting and estimating the system's future behavior using an ultra-local model structure based on the extended state observer (ESO), significantly reducing the controller's dependence on the system model parameters. In fact, the ESO configuration in the ultra-local model approach is such that it estimates the total disturbances and uncertainties as one of the system state variables [37–39]. Learning-based methods such as online learning predictive control, reinforcement learning, deep reinforcement learning, predictor neural networks, artificial intelligence, and artificial neural networks are less sensitive to uncertainties and the system's physical structure. Still, they have high execution and training times [40–44]. In [45], a combination of data-driven and generalized extended state observer is proposed to reduce the identification process.

This research addresses the challenge of CM voltage fluctuations and leakage current without increasing the grid current's THD. Also, the uncertainty of the parameters and the grid is addressed via the model-free predictive control. Almost all modulation-based modification techniques are such that without the simultaneous use of the structure modification-based approaches, they significantly increase the THD of the injected current into the grid. This challenge is due to reducing the number of switching voltage vectors. The approach of quasi-odd voltage vectors based on the model-free method has been used to increase the number of switching voltage vectors simultaneously, reducing CM voltage fluctuations, leakage current, and grid current THD. The pro-

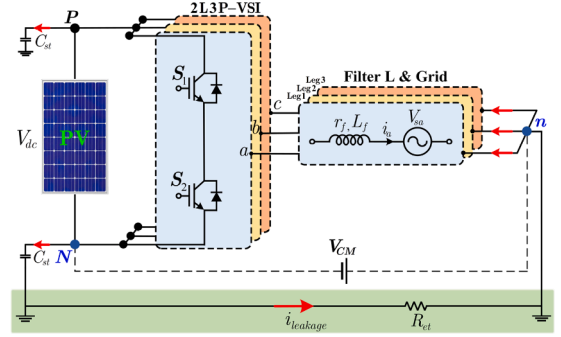


Fig. 1. Grid-tied transformerless PV system, the leakage current path, the stray capacitances.

Table 1
CM voltage in VSI.

Group	SwitchingStatus	Vector	V_{CM}/V_{dc}
1	000	$\vec{V}_0$	0
2	100,010,001	$\vec{V}_1, \vec{V}_3, \vec{V}_5$	1/3
3	110,011,101	$\vec{V}_2, \vec{V}_4, \vec{V}_6$	2/3
4	111	$\vec{V}_7$	1

posed method is independent from the grid voltage, resistance, and inductance. Therefore, a robust and efficient approach is achieved. The important contributions of this research are summarized below:

1. Including the leakage current predicted by the ultra-local model in the cost function
2. Adapting model-free predictive control in a grid-tied converter without the presence of grid voltage in the prediction model.
3. Using finite quasi-odd voltage vectors, set based on the MFPC, as a systematic and robust approach to achieving complete CM voltage stabilization and reducing leakage current without current THD increase.
4. Adjusting the model parameters according to the grid uncertainty using an analytical method.

2. Mathematical analysis and modeling

2.1. The CM voltage and leakage current in VSI

Fig. 1 shows the path of the leakage current through the solar panels' stray capacitors (C_{st}) and the ground resistance (R_{et}) in a grid-tied transformerless system. The C_{st} value varies in the $50 \leq C_{st} \leq 200$ nF/kW range. According to **Fig. 1**, the CM voltage in the desired transformerless system is defined as follows [4]:

$$V_{CM} = \frac{1}{3} \sum_{x=a,b,c} V_{xN} = \frac{1}{3} (V_{aN} + V_{bN} + V_{cN}) \quad (1)$$

$$= \frac{V_{dc}}{3} (S_1 + S_3 + S_5)$$

which $V_{aN} = S_1 V_{dc}$, $V_{bN} = S_3 V_{dc}$ and $V_{cN} = S_5 V_{dc}$ are the output voltages of each phase of the desired inverter. From (1), it can be concluded that different switching states directly influence the CM voltage fluctuations. **Table 1** shows the value of CM voltage for different switching states. The values of CM voltage for applying the vectors of each group indicate that its waveform fluctuates with different levels in a switching period. The equivalent circuit of the leakage current route of the discussed system is shown in **Fig. 2**. According to the equivalent circuit, the leakage current caused by the CM voltage and route impedance

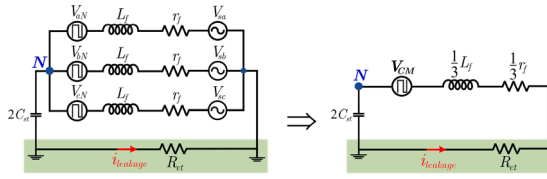


Fig. 2. The equivalent circuit of the leakage current route.

at a frequency of ω_k can be defined as follows:

$$Z_{leakage}(j\omega_k) = \frac{1}{3}(j\omega_k L_f + r_f) + \frac{1}{2j\omega_k C_{st}} + R_{et} \quad (2a)$$

$$i_{leakage} = \frac{V_{CM}}{Z_{leakage}(j\omega_k)} \quad (2b)$$

If ω_k 's harmonic is part of the CM voltage, then that harmonic will affect the leakage current due to the route impedance. The route's impedance at zero frequency is theoretically infinite, and it can be assumed to be an open circuit. Relation (2b) states that the amplitude of CM voltage also affects the leakage current. Therefore, a control approach that produces smaller CM voltage amplitude and fluctuations is preferred. According to (2b), a DC common-mode voltage will reduce the leakage current. Therefore, only odd vectors are viable candidates to maintain a constant CM voltage and minimize the leakage current, unlike the complete set of feasible vectors used in conventional methods.

2.2. Conventional and remote state MPCC

MPC depends on selecting the optimal voltage vector via a cost function. Thus, a predictive relationship for future control variable behavior is needed. The inverter's output current dynamics in continuous-time are described by this vector equation:

$$\frac{d}{dt}(i_{\alpha\beta}) = -\frac{r_f}{L_f}i_{\alpha\beta} + \frac{1}{L_f}(v_{\alpha\beta} - V_{s\alpha\beta}) \quad (3)$$

where $i_{\alpha\beta}$, $v_{\alpha\beta}$, and $V_{s\alpha\beta}$ are the injected current into the power grid, output voltage of the inverter, and grid voltage vectors in Fig. 1, respectively, in the $\alpha\beta$ frame. The predictive model for controlling the injected current into the grid at the sampling instant $(k+1)$ for all the values of the output voltage vectors of the inverter is defined as follows:

$$i_{\alpha\beta k+1}^p = \left(1 - t_s \frac{r_f}{L_f}\right)i_{\alpha\beta k} + \left(t_s \frac{1}{L_f}\right)(v_{\alpha\beta k} - V_{s\alpha\beta k}) \quad (4)$$

In (4), the predicted variables are marked with the superscript p , and t_s is the controller sampling time.

There is a discrete set of solutions for the inverter voltage ($\vec{v}_{\alpha\beta}$). A cost function selects the optimal voltage vector applied to the inverter based on the minimum predicted error.

$$g(s) = |i_{\alpha k}^* - i_{\alpha k+1}^p(s)| + |i_{\beta k}^* - i_{\beta k+1}^p(s)| \quad (5)$$

where s is the voltage vector candidate. In the remote state MPCC, the voltage candidates are limited to the fixed CM voltage switching states [10].

$$s \in \{V_1, V_3, V_5\} \quad (6)$$

While this method enables precise control, its dependence on physical model parameters and substantial current ripple are notable drawbacks.

3. Proposed model-free technique

3.1. Proposed leakage current reduction method

Though using the odd vectors should result in a zero leakage current because the CM voltage is constant, practical experiments show that uncertain values cause a tiny fluctuation in the leakage current. If the grid

voltage and the impedance of the leakage current path have uncertainties, as below

$$V_{sa} = \tilde{V}_{sa} + \Delta V_a \quad (7)$$

$$V_{sb} = \tilde{V}_{sb} + \Delta V_b \quad (8)$$

$$V_{sc} = \tilde{V}_{sc} + \Delta V_c \quad (9)$$

where ΔV is the grid voltage uncertainties, and $\tilde{V}_s$ is the certain part of the grid voltage. On the other hand, the leakage current can be written by the following equation based on the circuit in Fig. 2.

$$i_{leak} = \frac{V_t - V_{aN} - V_{sa}}{Z_f} + \frac{V_t - V_{bN} - V_{sb}}{Z_f} + \frac{V_t - V_{cN} - V_{sc}}{Z_f} \quad (10)$$

where $V_t = Z_{eq}i_{leak}$.

By defining $V_{CM} = \frac{V_{aN} + V_{bN} + V_{cN}}{3}$, and considering that $\tilde{V}_{sa} + \tilde{V}_{sb} + \tilde{V}_{sc} = 0$, the following equation can be obtained:

$$(Z_{eq} - \frac{Z_f}{3})i_{leak} = \frac{(\Delta V_a + \Delta V_b + \Delta V_c)}{3} + V_{CM} \quad (11)$$

If $Z_{eq} \gg \frac{Z_f}{3}$ is accepted, and the uncertainty ΔZ is added to Z_{eq} , the leakage current would become the following equation instead of (2b).

$$i_{leak} = \frac{(\Delta V_a + \Delta V_b + \Delta V_c)/3 + V_{CM}}{Z_{eq} + \Delta Z} \quad (12)$$

Note that if the method only applies the odd vectors, the CM voltage in (12) is constant and does not affect the leakage current because of the capacitive entity of the leakage path impedance. However, the fluctuation of the DC link voltage, and the dead-time effects are still inevitable. Thus, the leakage current can be written in the following form.

$$i_{leak} = \frac{(\Delta V_a + \Delta V_b + \Delta V_c)/3 + \Delta V_{INV}/3}{Z_{eq} + \Delta Z} \quad (13)$$

where ΔV_{INV} considers the the DC side voltage fluctuation, and the uncertainty caused by dead-time.

To reduce the leakage current as much as possible, the cost function of the proposed method is modified as below:

$$g(s) = |i_{\alpha k}^* - \hat{i}_{\alpha k+1}(s)| + |i_{\beta k}^* - \hat{i}_{\beta k+1}(s)| + |\hat{i}_{leak}(s)| \quad (14)$$

3.2. Proposed model-free current prediction

It can be seen from (4) and (12) that the prediction models consist of uncertain values for the grid impedance and the grid voltage value. The model-free technique lumps all uncertainties into a distortion value, $\hat{F}$. Then, a disturbance observer is needed to estimate the lumped disturbance. The disturbance observer has been widely applied to predict the current in drive application [34].

This research proposes a modified form of disturbance observer to simultaneously predict the grid current and leakage current. If all uncertainties of (13) are lumped as $\hat{F}_{leak}$ and a first order difference equation is considered for (13), the following ESO can be used as an ultra-local model to predict the leakage current.

$$\hat{i}_{\alpha\beta k+1} = \hat{i}_{\alpha\beta k} + t_s \left(\hat{F}_{\alpha\beta k} + \alpha_1 v_{\alpha\beta k} - \beta_1 e_{\alpha\beta} \right) \quad (15a)$$

$$\hat{F}_{\alpha\beta k+1} = \hat{F}_{\alpha\beta k} - t_s \beta_2 f(e_{\alpha\beta}) \quad (15b)$$

$$\hat{i}_{leak k+1} = \alpha_2 \hat{F}_{leak k+1} - t_s \beta_3 e_{leak} \quad (15c)$$

$$\hat{F}_{leak k+1} = \hat{F}_{leak k} - t_s \beta_2 e_{leak} \quad (15d)$$

where $\hat{F}_{\alpha\beta}$ is the disturbance of the difference equations of the grid current. $\hat{F}_{leak}$ is that of the leakage current. $\alpha_1, \alpha_2, \beta_1, \beta_2$, and β_3 are the local parameters. The last two equations of this model are the novelties of the proposed model. Note that the applied observer for the leakage current is a first-order one, while (2b) shows that the leakage current

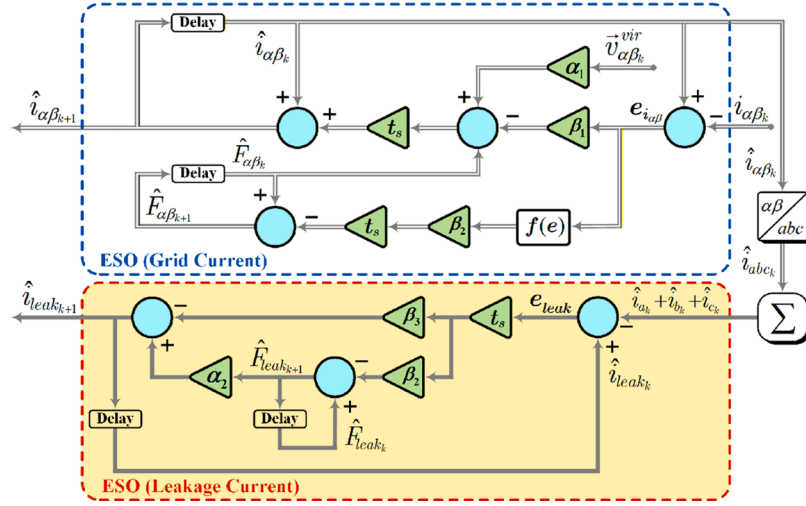


Fig. 3. Block diagram of the proposed observer.

flows in a second-order circuit. However, the effect of the capacitor is dominant in this circuit, and a first-order observer works properly.

The errors are calculated as shown:

$$e_{\alpha\beta} = \hat{i}_{\alpha\beta} - i_{\alpha\beta} \quad (16a)$$

$$e_{leak} = \hat{i}_{leak} - \sum_{x=a,b,c} \hat{i}_{xk} \quad (16b)$$

The block diagram of the ESO used in this paper is depicted in Fig. 3. The complete suggested algorithm is implemented as illustrated in Fig. 4. The voltage vector candidates indirectly affect the leakage current by the estimated grid current.

3.3. Applying virtual-odd-voltage vectors method

Based on (2b), a DC common mode voltage will effectively reduce the leakage current. Therefore, the CM voltage remains constant if the vectors of group 2 are applied as finite set candidates in the predictive method. The drawback of this method is that it reduces the number of candidates, which deteriorates the THD of the grid current.

A solution for this issue is using virtual voltage vectors. Fig. 5 shows the concept of virtual odd vectors. As shown in Fig. 5(a), in this method, the switching interval is divided by three. Each time portion contains an odd vector. The resultant vectors would be as shown in Fig. 5(b). This technique increases the number of candidates and helps to improve the THD of the grid current.

A virtual odd vector in Fig. 5 formulated as below:

$$\vec{v}_{\alpha\beta}^{vir} = x\vec{V}_n + y\vec{V}_m \quad (17)$$

where x , and y are the time portions.

$$x, y \in \left\{ \frac{1}{3}, \frac{2}{3} \right\} \quad (18)$$

and, n , and m are the odd vector number

$$n, m \in \{1, 3, 5\} \quad (19)$$

Note that the switching technique is finite set model predictive control. All virtual vectors are fixed vectors that would be examined in the cost function along with the physical vectors.

3.4. Tuning the local parameters

The parameters α_1 , and α_2 of the local model are designed based on the a rough estimation from the physical model. Thus, $\alpha_1 = 1/L_f$, and $\alpha_2 = 1/|Z_{eq}|$ are chosen.

An analytical method is applied to tune the local parameters of the ultra-local prediction model to achieve the most reliable performance of the model-free prediction.

In [34], the following suggestion is proved by the Lyapanov criterion to choose parameters β_1 and β_2 .

$$\beta_1 = 2\sqrt{M}, \beta_2 = \frac{4}{3}M \quad (20)$$

where M should be the maximum value of the disturbance's derivative. The following approximations are used to find an approximation of $M = \max(\frac{d}{dt}F)$ in a 2L3P-VSI:

$$\begin{aligned} & \max\left(\frac{d}{dt}|i_{\alpha\beta}|\right) \\ &= \max\left(r_f \alpha_1 \frac{d}{dt}|i_{\alpha\beta}| + \alpha_1 \frac{d}{dt}|v_{\alpha\beta}| + \alpha_1 \frac{d}{dt}|V_{sa\beta}|\right) \end{aligned} \quad (21)$$

Considering $\max(\frac{dy}{dt}) = 2\pi f_n y_n$, where y is an arbitrary variable, f_n is the nominal frequency and y_n is the nominal value of the variable y , M is obtained.

$$M = 2\pi f_n \alpha_1 (r_f i_{\alpha\beta_n} + v_{\alpha\beta_n} + V_{sa\beta_n}) \quad (22)$$

Based on the nominal values, $\beta_1 = 3453$, and $\beta_2 = 3.97 \times 10^6$ would be calculated for the test system.

To design the value of β_3 , the transfer function ($\frac{\hat{i}_{leak}}{i_{leak}}$) is applied.

$$\frac{\hat{i}_{leak}}{i_{leak}} = \frac{\alpha_2 \hat{F}_{leak} + \beta_3 i_{leak} - \beta_3 \hat{i}_{leak}}{\alpha_2 F_{leak}} \quad (23)$$

Considering the difference equations of the ESO, the transfer functions between the estimated and real leakage disturbances $\frac{\hat{F}_{leak}}{F_{leak}}$, and the

transfer function from the estimated and real current $\frac{\hat{i}_{\alpha\beta}}{i_{\alpha\beta}}$ can be derived.

$$G_i = \frac{\hat{i}_{\alpha\beta}}{i_{\alpha\beta}} = \frac{\beta_2 + \beta_1 s}{s^2 + \beta_1 s + \beta_2} \quad (24)$$

$$G_f = \frac{\hat{F}}{F} = \frac{\beta_2}{s^2 + \beta_1 s + \beta_2} \quad (25)$$

Using (24) and (25) in (23) results in the following transfer function.

$$\frac{\hat{i}_{leak}}{i_{leak}} = G_f + \frac{\beta_3 s}{\alpha_2 (s^2 + \beta_1 s + \beta_2)} \quad (26)$$

The value of β_3 is designed based on the Bode diagram of the transfer function (26). Fig. 6 shows the Bode diagram of the leakage current.

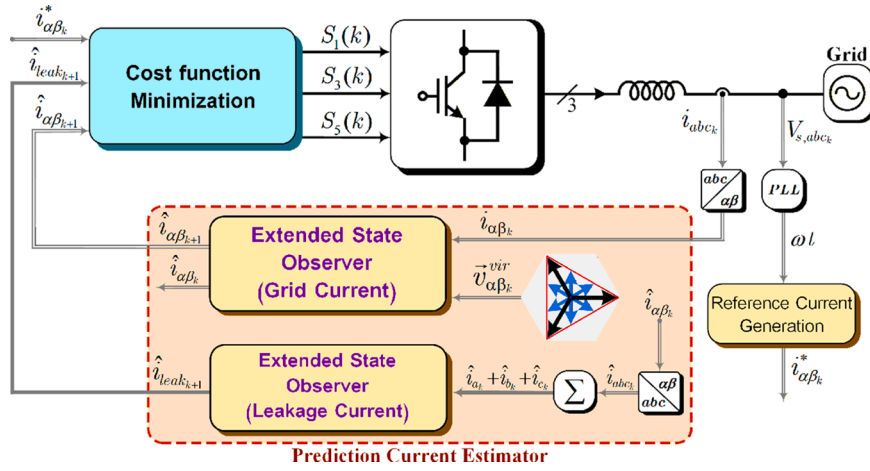


Fig. 4. Complete block diagram of the proposed method.

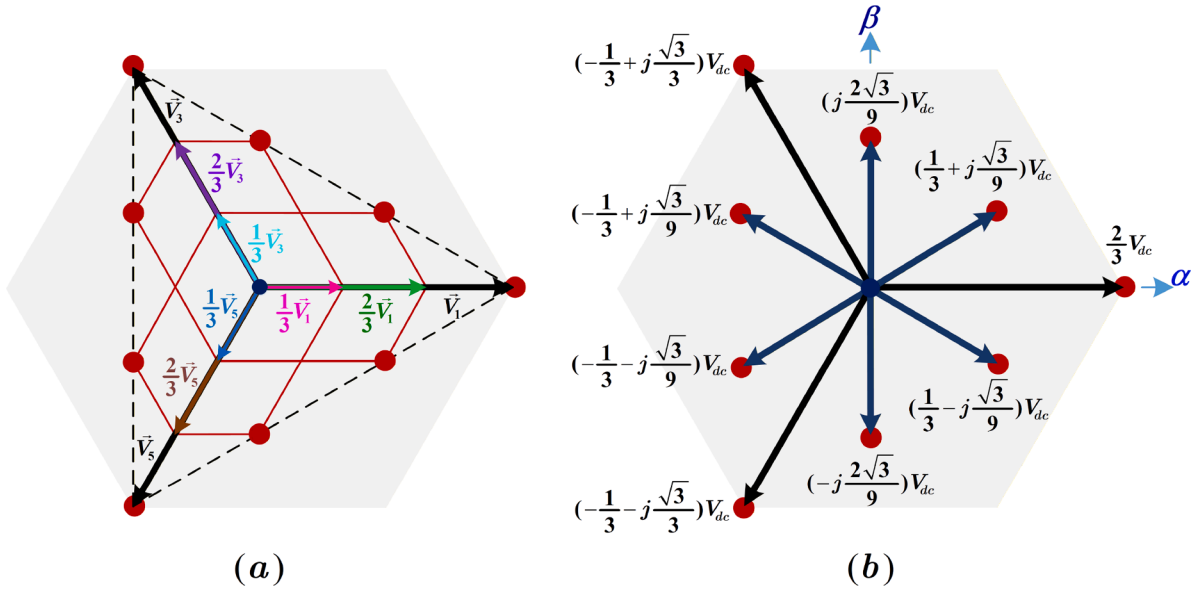


Fig. 5. Compensating the lack of voltage vectors by the virtual odd vectors.

It is clear that if the value of $\beta_3=10$ is chosen, the bandwidth is at the maximum possible value without a phase shift for the estimated value.

3.5. Lyapunov analysis

In order to ensure the stability of the observer with the designed parameters, the Lyapunov analysis is applied.

First, the errors of the observation are defined.

$$e_1 = \hat{i}_{\alpha\beta} - i_{\alpha\beta} \quad (27)$$

$$e_2 = \hat{F} - F \quad (28)$$

$$e_3 = \hat{i}_{leak} - i_{leak} \quad (29)$$

The dynamic equations of the errors will be obtained from the main observer equations:

$$\dot{e}_1 = e_2 - \beta_1 e_1 \quad (30)$$

$$\dot{e}_2 = -\beta_2 e_1 \quad (31)$$

$$\dot{e}_3 = \alpha_2 e_2 - \beta_3 e_3 \quad (32)$$

Thus, the equations can be simplified as follows:

$$\dot{e}_1 = \frac{1 + \beta_3}{\alpha_2} e_3 - \beta_1 e_1 \quad (33)$$

$$\dot{e}_3 = \frac{-\beta_2 \alpha_2}{1 + \beta_3} e_1 \quad (34)$$

Now, the Lyapunov function is defined.

$$V = \frac{1}{2} (E^2 + \beta_2 e_1^2) \quad (35)$$

$$E = \frac{1 + \beta_3}{\alpha_2} e_3 - \beta_1 e_1 \quad (36)$$

The derivative of the Lyapunov function should be negative.

$$\frac{dV}{dt} = E \left(\frac{1 + \beta_3}{\alpha_2} \times \frac{-\beta_2 \alpha_2}{1 + \beta_3} e_1 - \beta_1 E \right) + \beta_2 e_1 E = -\beta_1 E^2 \quad (37)$$

Therefore, for any positive β_1 the observer is stable.

3.6. Discrete time stability analysis

Since the implementation of the control method is in the discrete time, this kind of stability analysis is also studied, although the continuous stability of the system is already proved. If (26) is transferred

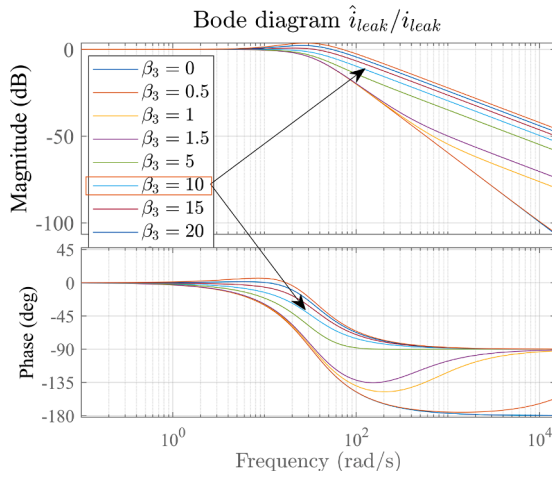


Fig. 6. Bode diagram of the transfer function of the leakage current.

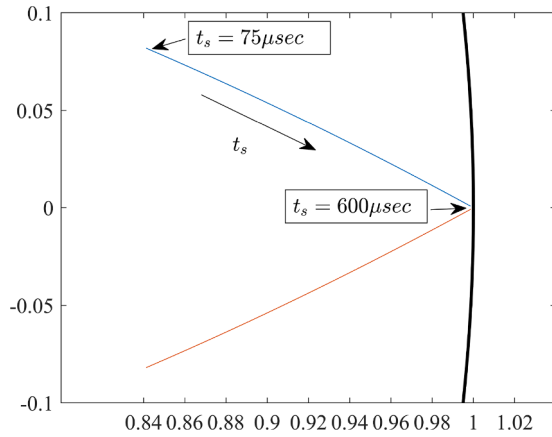


Fig. 7. Discrete poles related to the control interval.

into the discrete time domain with the tuned parameters, the following transfer function is achieved for $t_s = 75 \mu\text{sec}$.

$$\frac{\hat{i}_{leak}}{i_{leak}} = \frac{0.001499z^3 - 0.004491z^2 + 0.004484z - 0.001492}{z^4 - 3.994z^3 + 5.983z^2 - 3.983z + 0.9944} \quad (38)$$

The poles of the discrete transfer functions are depicted in different control intervals in Fig. 7. Note that there are four poles for each t_s . Only one pole pairs are depicted in the figure because the other pair is identical. It can be seen that all poles lie inside the unit circle across all tested control intervals. As the control interval increases, the poles move closer to the unit circle. When $t_s = 600 \mu\text{sec}$, the poles reach the edge of stability.

4. Experimental results

The experimental results verify the proposed method. Table 2 shows the test system specification. The applied inverter is a normal two-level inverter, the experimental setup of which is shown in Fig. 8. In addition to the proposed method, the model-free method based on the remote state modulation, taken from [10,42], and conventional model-free methods are also tested. These tests clarify the contribution of the proposed method. The second method is called fixed common-mode voltage model-free predictive control (FCMV-MFPC). This model does not include the leakage current prediction.

Figs. 9 and 10 show the CM voltage and the leakage current for the three tested methods. The results show that the CM voltage is constant

Table 2

Experimental specifications.

Parameters	Value	Parameters	Value
V_{dc}	75 [V]	r_f	0.5 [Ω]
C_{dc}	1000 [μf]	L_f	10 [mH]
v_{grid}	30 [V_{rms}]/50 [Hz]	t_s	75 [μs]
$t_{dead-time}$	3 [μs]		

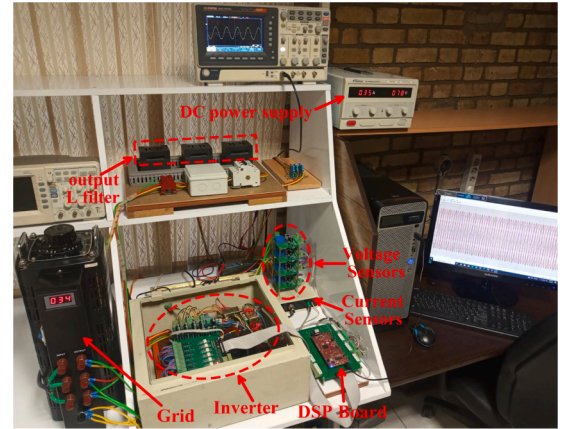


Fig. 8. Experimental setup with voltage source inverter.

for the FCMV-MFPC and the proposed method. Also, the leakage current is meaningfully decreased for these two methods compared to the conventional method. However, the current reduction in leakage is more significant for the proposed method. In addition to the leakage current reduction, the proposed method contributes to the grid current THD.

Fig. 11 shows the performance of three methods in two operating points. It shows that the current control accuracy of the conventional method is the best among the tested methods because there is no term regarding CM voltage and leakage current, and the cost function is only dedicated to the current control. However, when the remote state predictive method is applied to the model-free control, the grid current's THD (total harmonics distortion) is affected drastically. The proposed method could return the THD to a close value to that of the conventional method while the leakage current is even less than the FCMV-MFPC. The quantitative comparison of the tracking error is performed in Table 3. These results also confirm the contribution of the proposed method.

Fig. 12 shows the transient response of three tested methods. The results show that the settling time of the proposed method is as fast as the conventional model-free method, while the terms regarding the leakage current reduction are also applied. Table 4 summarizes the settling time of tested methods. The table proves that the dynamic response of the fixed CM method is slower than the normal model-free method because of fixing the CM voltage. However, the proposed method is not meaningfully slower than the normal method.

The sensitivity to the local parameters is also examined. In Fig. 13, the parameter α is intentionally changed. This parameter is decreased by 60% and increased by 100%. The results show that the reduction or increase of this parameter does not effectively influence the reference tracking behavior. Also, in Fig. 14, the parameter β is analyzed. It can be seen that an increase of this parameter by 300% does not deteriorate the results. Fig. 15 shows the leakage current during the sensitivity analysis of the α and β parameters. The figure shows that these parameters do not significantly affect the proposed method or the fixed CM model-free. The difference between the proposed method and the fixed CM model-free is kept while the local parameters are changed.

The effect of measurement noise is studied in Fig. 16. A noise with a 30 dB signal-to-noise ratio is intentionally injected into the measured

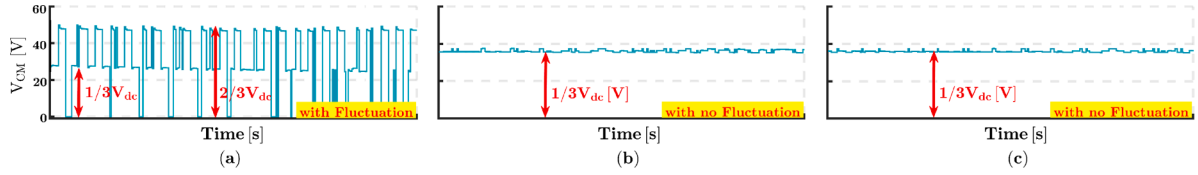


Fig. 9. Common-mode voltage: (a) conventional model-free, (b) fixed CM voltage model-free (c) Proposed Method.

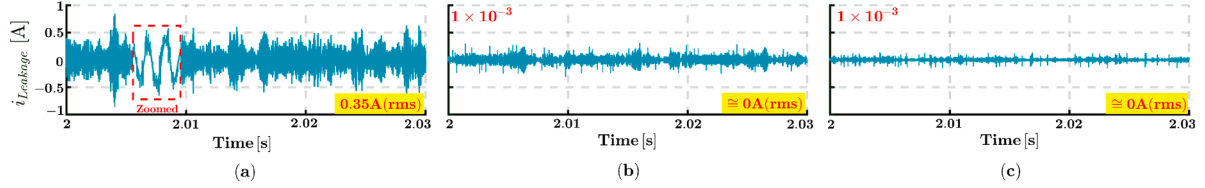


Fig. 10. Leakage current: (a) conventional model-free, (b) fixed CM voltage model-free (c) Proposed Method.

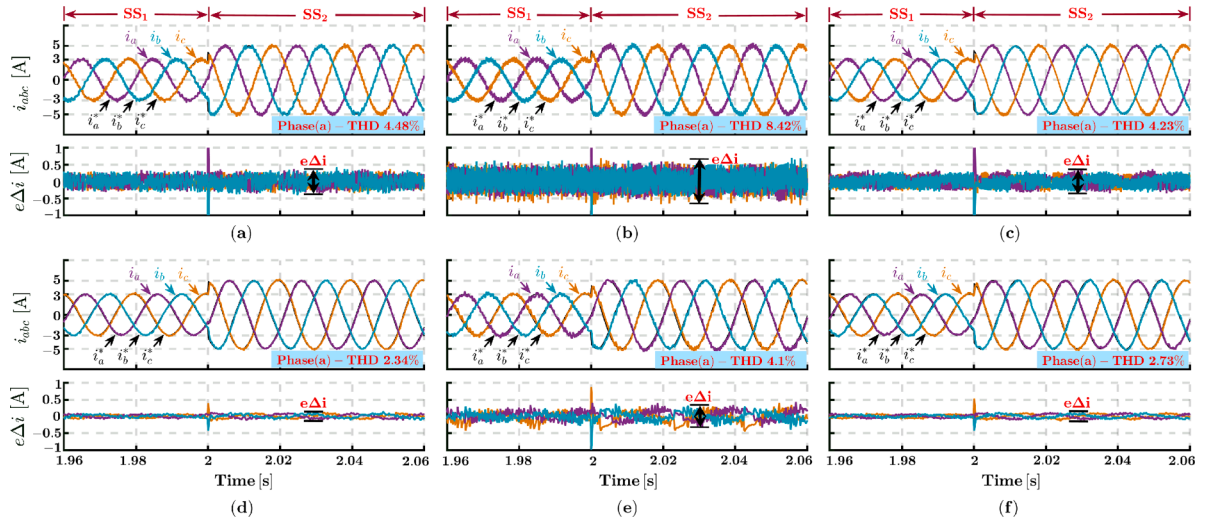


Fig. 11. Steady-state current control response: (a) conventional MPC, (b) fixed CM voltage MPC, (c) proposed method with MPC, (d) conventional model-free, (e) fixed CM voltage model-free (f) Proposed Method with model-free.

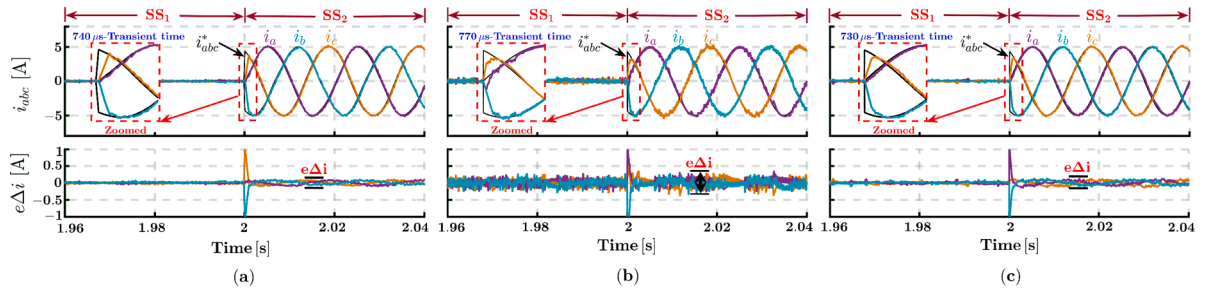


Fig. 12. Transient current control response: (a) conventional model-free, (b) fixed CM voltage model-free (c) Proposed Method with model-free.

Table 3
RMSE of grid current for three different methods.

Methods	conventional MF	FCMV-MFPC	Proposed
RMSE of i_a (%)	7.35	14.63	7.57
RMSE of i_b (%)	7.55	15.04	7.48
RMSE of i_c (%)	7.33	14.83	7.72
avg (%)	7.41	14.83	7.59

Table 4
Settling time (ST) comparison.

Methods	conventional MF	FCMV-MFPC	Proposed
ST of i_a (μs)	0	740	0
ST of i_b (μs)	720	770	730
ST of i_c (μs)	740	760	735

current, and three methods are tested. All methods show a slight increase in ripple, but the effect is negligible.

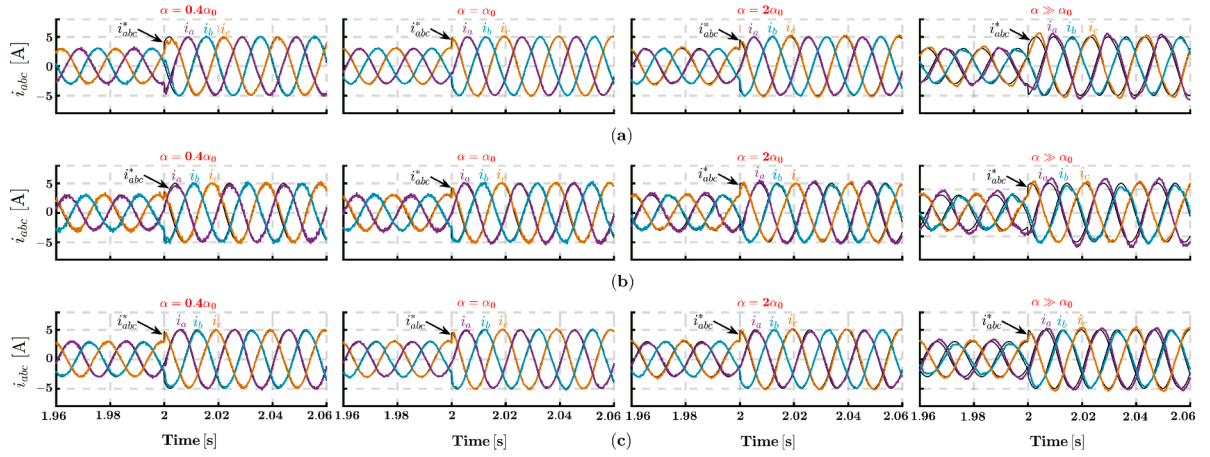


Fig. 13. Sensitivity test to the local parameter (α): (a) conventional model-free, (b) fixed CM voltage model-free (c) Proposed Method.

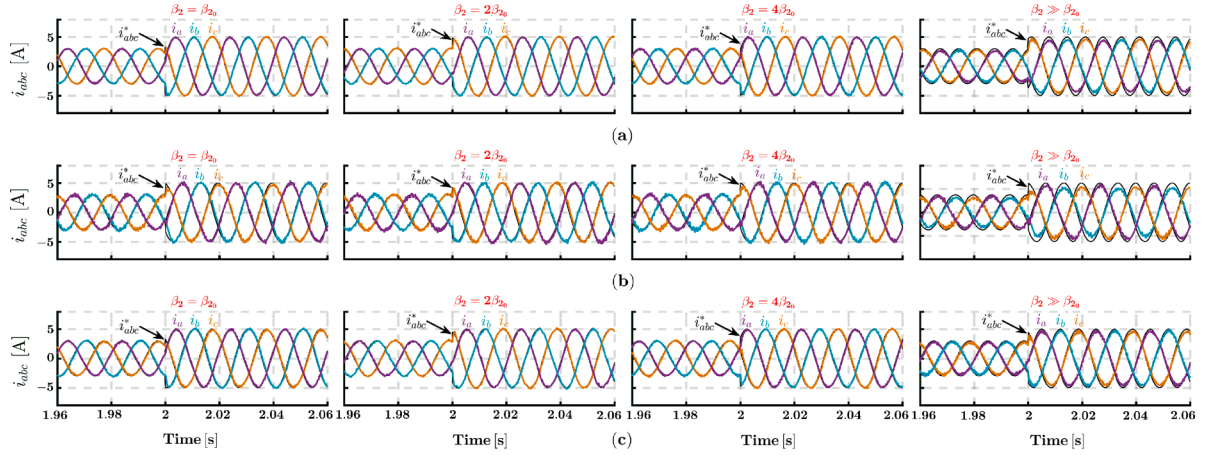


Fig. 14. Sensitivity test to the local parameter (β): (a) conventional model-free, (b) fixed CM voltage model-free (c) Proposed Method.

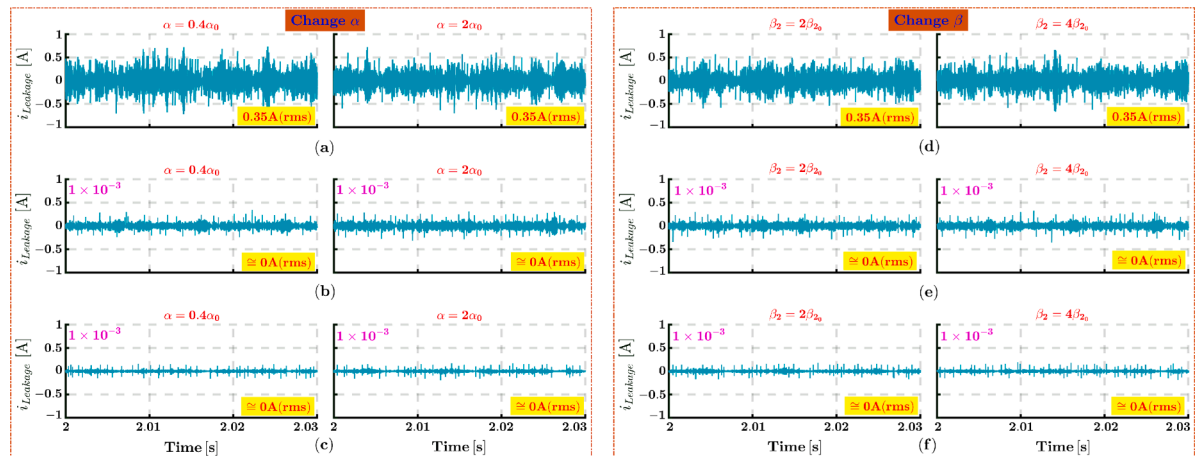


Fig. 15. The leakage current under the sensitivity test to the local parameter (α): (a) conventional model-free, (b) fixed CM voltage model-free (c) Proposed Method, (β): (d) conventional model-free, (e) fixed CM voltage model-free (f) Proposed Method..

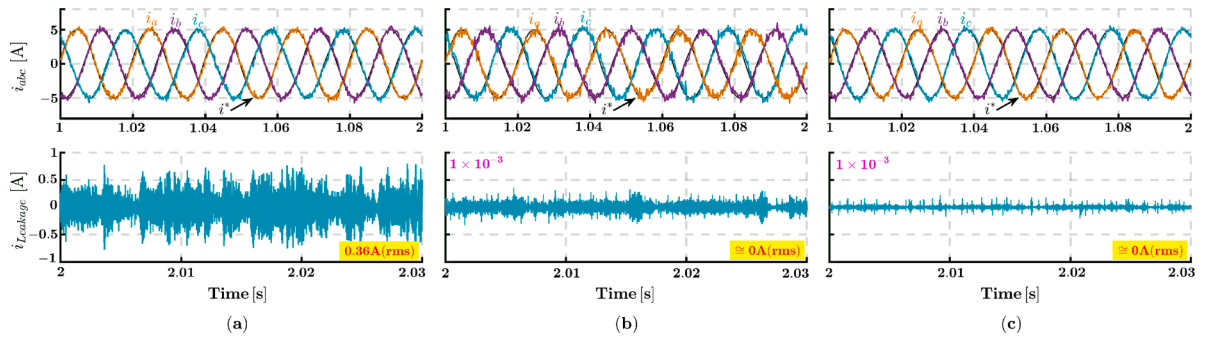


Fig. 16. Steady state response with maesurement noise injection. .

5. Conclusion

This research proposed a method to achieve three goals simultaneously, i.e., fixing the CM voltage, reducing the leakage current, and maintaining the accuracy of current tracking. The remote-state switching technique for CM voltage fixing is combined with virtual vectors to compensate for the lack of accuracy of the current control. The model-free predictive method is applied to improve the accuracy and reduce the parameter sensitivity. The leakage current estimation is added to the state observer, which contributes to the uncertain reasons for leakage current generation. It also improved the accuracy of the current control. The added part to the state observer changes its transfer function. The Bode diagram analysis is applied to prove the stability of the observer. The proposed method is experimentally verified. The results showed that the proposed method is as accurate as the normal model-free method, while the leakage current reduction is better than the fixed CM model-free technique. The applied ultra-local model for current prediction needs a rough estimation of the grid inductance which is a slight dependency on the physical parameter while the method is robust until $\pm 100\%$ change for this parameter.

CRedit authorship contribution statement

Majid Akbari: Software, Methodology, Investigation; **S. Alireza Davari:** Software, Project administration, Methodology, Investigation, Data curation; **Reza Ghandehari:** Methodology, Investigation; **Mahdi S. Mousavi:** Methodology, Investigation; **Freddy Flores-Bahamonde:** Software, Methodology, Investigation; **Jose Rodriguez:** Investigation.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jose Rodriguez reports financial support was provided by Agencia Nacional de Investigación y Desarrollo Chile. Freddy Flores reports financial support was provided by Agencia Nacional de Investigación y Desarrollo Chile. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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