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An Adaptive Virtual Impedance Control for Reactive Power Sharing in Microgrids

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Abstract—In multi-inverter parallel connected islanded microgrids, reactive power sharing is challenged by the differences in feeder impedance and various controller parameters. In order to address this issue, a virtual impedance reshaping strategy based on the consensus algorithm is proposed in this paper. The proposed method facilitates adaptive modulation of virtual impedance to ensure that it is consistent with the desired value. Notably, the method has the advantage of accurate reactive power sharing even in the presence of communication delays and interruptions. Furthermore, the proposed strategy exhibits resistance to malicious cyber-attacks by integrating an auxiliary controller that reconstructs the propagated information in the face of cyber threats that challenge the integrity of the original signal. Furthermore, this paper introduces an exit strategy that enables data exchange during the system construction phase and subsequently fixes the virtual impedance proportionally. This feature significantly reduces the communication burden. The effectiveness of the proposed control strategy is evaluated through several experimental cases, including accurate reactive power sharing and plug-and-play capability.

Index Terms—distributed control, virtual impedance, power sharing, cyber attack, microgrid

I. INTRODUCTION

Microgrids have become a promising field [1] because of their significant economic and environmental benefits. An essential requirement in the islanded mode of microgrids is to determine the active and reactive power based on the converter capacity between the units involved [2]. In medium-voltage or high-voltage microgrid systems, active power sharing [3] is usually achieved using conventional P - ω and Q - V droop loops because of the inductive nature of the feeders. However, the droop control cannot compensate for the reactive errors caused by line impedance mismatch and different controller parameters [4].

Several power-sharing strategies have been posited to address this issue. Intuitively, formulating a precise virtual impedance [5] can significantly contribute to accurate power sharing. Nevertheless, obtaining the actual physical line impedance for each feeder is often unattainable in practical applications. To alleviate the impedance mismatch, a substantial virtual impedance has been recommended in [6]. However, this approach may lead to considerable distortion in

the bus voltage. Though the techniques proposed in [7] can be employed to compensate for the bus voltage distortions, they come at a considerable cost.

Communication-based approaches are also considered in the microgrid field [8]. In particular, a widely adopted approach involves the implementation of a centralized microgrid controller (MGCC) as the central coordinator to apply the control methods proposed in [9], [10]. The MGCC adjusts the virtual impedance in real time based on the measured power and its reference, effectively achieving the control objective of active power sharing. However, this method's reliance on the central controller makes it susceptible to communication failures, leading to a potential single point of failure. To mitigate the inherent limitations of the MGCC, the distributed philosophy has been embraced in microgrid systems to enhance their reliability. For instance, in [11], consensus-based distributed control has been recently deployed in parallel inverter systems. With this approach, individual units disseminate information to their neighbouring agents, facilitating collaborative decision-making. Notably, this method involves substantial data exchange among the inverters due to periodic data exchange with neighbouring units. Consequently, the limited communication resources become a constraint, potentially compromising the performance of the distributed system [12]. As an alternative, a discrete-time communication mechanism is proposed in [13] for updating neighbour states, which aids in conserving communication resources to a certain extent.

The communication-based event-triggered control (ETC) approach has recently garnered significant attention in the field of multi-agent systems (MAS) [14]. In contrast to the conventional periodic approach, one of its key advantages lies in its non-periodic communication nature, which further reduces the communication burden among individual units. This approach has been successfully applied in the microgrid domain as well [15].

The fundamental principle underlying the ETC triggers is to execute data sampling/transmission or decide on control assignments based on carefully designed event triggers. Consequently, communication resources under ETC are consumed only when "needed" or "necessary", enabling intelligent scheduling of sampling/transmission on the communication network [16]. A dynamic ETC architecture was recently

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introduced to alleviate the communication burden while maintaining power sharing. According to this hypothesis, the convergence law is activated only when the output power varies [17]. However, in practical applications, the substantial traffic pressure on the communication network remains unchanged as numerous loads on the AC bus switch frequently.

Furthermore, adopting communication technology can facilitate flexible and rapid control, ensuring accurate reactive power sharing. Nonetheless, it is susceptible to cyber attacks [18], which can undermine overall control accuracy and lead to instability [19], [20]. To address these issues, this paper proposes a resilient communication-based virtual impedance reshaping strategy for proportionally sharing reactive power in an inverter-connected system. The contributions of this study can be summarized as follows:

(1) It proposes a method that relaxes the requirement for knowledge of the feeder and bus voltages. (2) The proposed method employs an adaptive tuning virtual impedance, effectively minimizing the voltage drop across the impedance compared to existing techniques such as those described in [6], which embed a sizeable virtual impedance in the control loop. (3) The proposed method is fully distributed and thus not vulnerable to the "single point of failure" problem experienced by prior approaches in [9], [10]. (4) The proposed control strategy can significantly reduce the communication burden, unlike the distributed-based method outlined in [11]–[13], [15]–[17]. (5) While the impact of communication delays has been studied in distributed control systems such as [9], the present method further mitigates the impact of communication failures. (6) The proposed method addresses a gap in the existing literature on communication-based virtual impedance strategies by ensuring cyber security even during a communication cyber attack.

II. ISLAND MICROGRID CONTROL

Fig.1 shows a typical infrastructure of islanded microgrid with reactive load penetration in this paper. L_f and C_f represent the filter inductor and capacitor, respectively. The feeder comprises an inductor and resistor elements and takes on inductive characteristics [21]. i_{Li} , V_{Ci} and i_{oi} represent the filter-inductor current, filter-capacitor voltage and output current of DG_i , respectively.

III. ISLAND MICROGRID ANALYSIS

Fig.1 displays the typical configuration of an island microgrid with nonlinear and reactive load integration. The proposed control strategy ensures proportional sharing of the reactive power.

A. Configuration of droop control

The output of the droop control is utilized to generate the reference for the inner controller and therefore manage the power flow. The conventional droop control is usually used according to the P- ω and Q-V law, which can be expressed as:

$$\omega_i = \omega^* + k_{pi}(P_{iref} - P_i). \quad (1)$$

$$V_i = V^* + k_{qi}(Q_{iref} - Q_i). \quad (2)$$

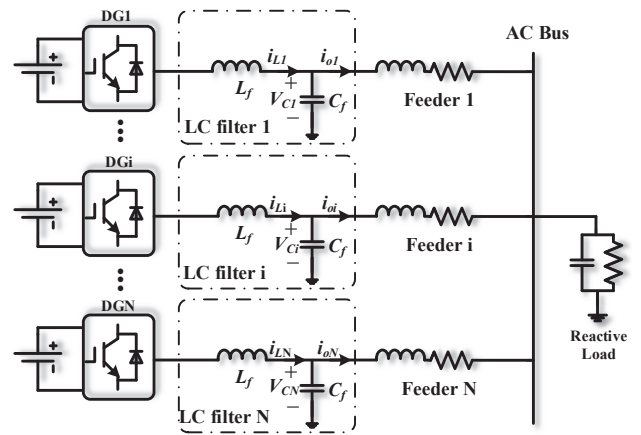


Fig. 1. The scheme of a microgrid with N inverters.

where ω_i and V_i are the output angular frequency and voltage amplitude, which are the references to regulate the output voltage; ω^* and V^* are the nominal set points of frequency and voltage amplitude. In island mode, the active power and reactive power reference values, P_{iref} and Q_{iref} , are set to zero; P_i and Q_i are the measured active power and reactive power of i th DG; The droop gains for the active and reactive power loops, k_{pi} and k_{qi} , should be designed in accordance with the maximum power ratings of the inverters.

As shown in (1), ω_i is a global variable, indicating that the output frequency among the participating converters is identical. This means that the active power can be proportionally shared. However, achieving reactive power sharing is challenging due to the mismatched feeder impedance and different droop coefficients, as will be discussed in detail in Section II-B.

The reference for the inner controller that manages the actual output voltage of the filter capacitor is derived from the outcome of the droop control. It can be written as (3):

$$V_{d,i} = V_i \sin\left(\int \omega_i dt\right) \quad (3)$$

The inner control is usually composed of a voltage controller and a current controller, in which the reference is the output of the droop controller, denoted as $V_{ref,i} = V_{d,i}$. The control block diagram of the inner loop controller can be equivalent to (4).

$$V_C = V_{ref} \cdot G_V(s) - Z_o(s) \cdot i_o \quad (4)$$

where $G_V(s)$ denotes the voltage gain of the inner controller, which should be 1 for a well-designed converter, and $Z_o(s)$ indicates the equivalent impedance of the inverter is determined jointly by the controller's parameters and the droop coefficient.

B. Reactive power sharing analysis

As in Fig.2(a), the voltage drop across the feeder in [17] can be approximated as (5):

$$\Delta V_i \approx \frac{X_i Q_i + R_i P_i}{V_C} \quad (5)$$

where P_i and Q_i are the measured active power and reactive power of i th DG, X_i and R_i represent the inductive and resistive components of the feeder, ΔV_i denotes the voltage drop, which is demonstrated by the AC Bus voltage minus filter capacitor voltage. Further, we assume that the line is inductive, i.e. $X_i \gg R_i$. This way, (5) can be rewritten as (6).

$$\Delta V_i \approx \frac{X_i Q_i}{V_o} \quad (6)$$

By appropriately designing the virtual impedance as in Fig.2(b), the voltage drop among the participating units is tuned. Thus, the proportional sharing of reactive power can be accomplished.

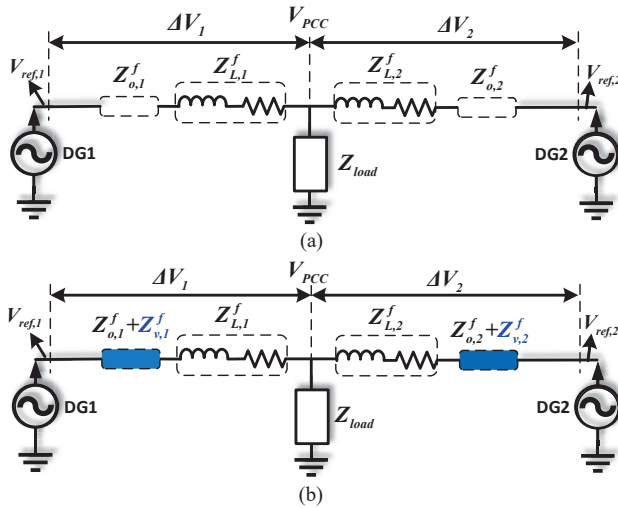


Fig. 2. (a) The effect of feeder mismatch. (b) Virtual impedance on reactive power control.

IV. PROPOSED METHOD

A. Sparse communication network

The communication network involved in the microgrid can be represented by an undirected cyber graph, which shows how the converters share data with their neighbours. For each local converter i th of the microgrid, the communication graph with its neighbours j th can be described as a directed graph with edges and links via the communication adjacency matrix $A = (a_{ij})_{N \times N}$. The communication weight a_{ij} is set to 1 if the i th and j th units are in regular communication, and 0 otherwise. The degree of vertex ζ_i is given as $d_i = \sum_{j=1}^N a_{ij}$. The corresponding degree matrix is $D = \text{diag}(d_1, \dots, d_N)$. The Laplacian matrix of the communication network, denoted by L , is defined as $L = D - A$. This paper suggests a consensus-based adaptive reshaping approach to virtual impedance. The overall control block diagram is shown in Fig.3. The proposed method allows proper proportional reactive power sharing by adaptively modulating the virtual impedance. It relaxes the knowledge of the line impedance and immunizes to cyber attacks. Note that the controller only transmits its data to its neighbours in the initial stage of system build-up. Therefore, it significantly relieves the communication burden.

B. Consensus-based impedance reshape algorithm

In Fig.3, the inverters exchange information related to reactive power ($k_{q1}Q_1^f, \dots, k_{qN}Q_N^f$) with their adjacent units to achieve a consensus state. With the consensus philosophy, the reactive power controller can be expressed by (7), (8).

$$Z_{v,i}^f = L_{0,i}^f + L_{c,i}^f \quad (7)$$

$$L_{c,i}^f = \int k_{v,i}^f [\sum_{j \in N_i} a_{ij} (k_{qj} Q_j - k_{qi} Q_i)] dt \quad (8)$$

where $k_{Q_i}^f$ and $k_{Q_j}^f$ represents the droop coefficient; The virtual fundamental impedance $Z_{v,i}^f$ are divided into two parts; The fixed virtual inductors $L_{0,i}^f$ are used to improve the system's stability. The adaptive impedance $L_{c,i}^f$ are determined by the neighbour's information and the state of the local unit is denoted as $Z_{v,i}^f = L_{0,i}^f + L_{c,i}^f$; $k_{v,i}^f$ is the impedance reshaping factor. The integral controllers are employed to eliminate reactive power-sharing errors.

With the virtual impedance reshaping, the voltage reference for the voltage controller is modified as (9):

$$V_{ref} = V_d - Z_v^f i_o^f - Z_v^h i_o^h \quad (9)$$

where V_d denotes the output of the droop controller.

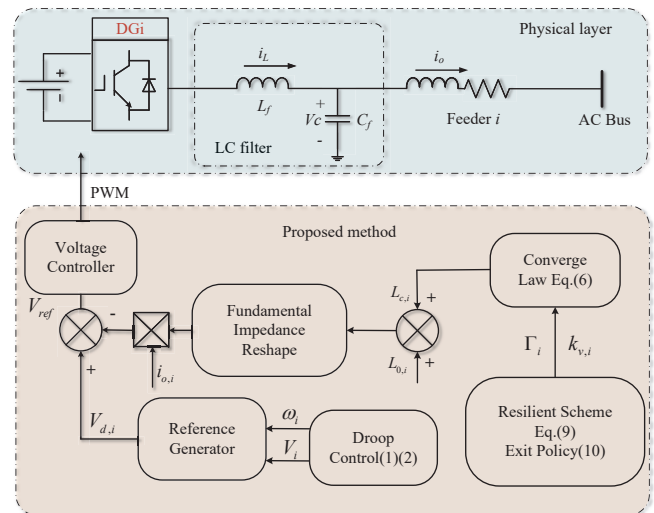


Fig. 3. Comprehensive control block diagram of the proposed method.

V. CYBER ATTACK AND COMMUNICATION RELIEF

The proposed virtual impedance effectively enables the proportional sharing of reactive power. However, its susceptibility to cyber-attacks poses a significant threat to its operation. This section introduces and models the false data injection attack (FDIA) and analyzes its impact on power-sharing performance. Then a resilient controller is designed to immunize the cyber attack by reconstructing the attacked signal. Furthermore, we introduce an auxiliary controller to alleviate communication

burdens by disabling the communication network while maintaining accurate power-sharing performance. This is achieved by modulating the virtual impedance to a desired value before the communication disables operation occurs and keeping it unchanged during the operation.

A. Cyber attack analysis

The false data injection attack (FDIA) is a highly concerning type of attack involving injecting false data into the original data [19]. This kind of cyber attack can be modelled using Equation (10).

$$x_{a,j} = x_j + \eta_j \varepsilon(t) \quad (10)$$

where x_j and $x_{a,j}$ represent the original neighbouring and attacked signal, respectively. The binary variable η_j is zero in the normal state and equals one when the false data injection attack (FDIA) is present with the malicious element $\varepsilon(t)$.

B. Resilient framework and exit policy

To mitigate cyber-attacks, we suggest a resilient enhanced auxiliary controller in this paper. An auxiliary controller is adopted to reconstruct the propagated information when a cyber-attack challenges the original signal. If we take $\Delta\delta_{i,j} = n_{Qj}Q_j - n_{Qi}Q_i$ in (3). $\Delta\delta'_{i,j}$ can be taken as (11):

$$\Delta\delta'_{i,j} = (1 - \Gamma_i)\Delta\delta_{i,j} + \Gamma_i\Delta\delta_{i,j}^* \quad (11)$$

where $\Delta\delta_{i,j}^* = \min\{\Delta\delta_{i,1}, \dots, \Delta\delta_{i,j}\}, \forall j \in N_i, j \neq i$. $\Gamma_{i,j}$ is a binary variable, $\Gamma_{i,j} = 1$ represents the exist of cyber attack.

An auxiliary controller utilized to reduce the communication burden by deactivating the proposed communication-based method can be expressed as follows:

$$k_{v,i}^f = \begin{cases} k_{v,i}^f, & \text{if } \Gamma_{i,j} \cup \Gamma_{i,2} \dots \cup \Gamma_{i,N} = 0 \\ 0, & \text{else} \end{cases} \quad (12)$$

Moreover, as analyzed in Section I, the communication burden remains a challenge in the commutation-based approach. To address this problem, after the virtual impedance has been appropriately designed, the impedance reshaping factor $k_{v,i}^f = 0$. Thus the communication-based algorithm is disabled, thus relaxing the communicating burden.

VI. EXPERIMENTAL VERIFICATION

The efficacy of the proposed adaptive control strategy has been verified through experiments conducted on a distributed AC microgrid consisting of three parallel-connected inverters, as shown in Fig.4. The system parameters are provided in Table I. The present investigation focuses on establishing the reactive power rate of inverters in accordance with a predetermined maximum capacity proportion of 1:2:3. Employing the experimental configuration depicted in Fig.4 and incorporating the proposed adaptive control scheme, a series of diverse experiments were conducted to assess the efficacy of the developed approach.

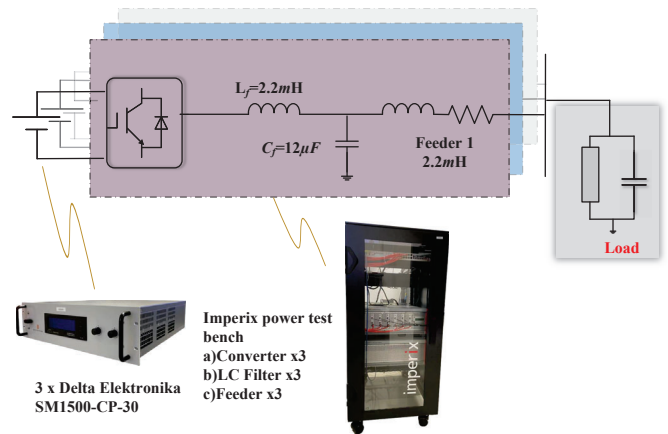


Fig. 4. Experimental setup.

TABLE I
PARAMETERS OF THE MICROGRID IN EXPERIMENT

Symbol	Interpretation	Value
U_{dc}	DC-link voltage	150V
Z_L	Line impedance	2.2 mH
L_f	Inductor of LC filter	2.2 mH
C_f	Capacitor of LC filter	12μF
f_s	Switch frequency	20kHz
k_{p1}, k_{q1}	Droop coefficient of DG1	1/1000
k_{p2}, k_{q2}	Droop coefficient of DG2	1/2000
k_{p3}, k_{q3}	Droop coefficient of DG3	1/3000
k_{ph}	Proportional coefficient	0.001
k_{rh}	resonant coefficient	50
$k_{v,i}^f$	fundamental impedance reshape factor	0.001
ω^*	Nominal angular frequency	314rad/s
V^*	Nominal voltage amplitude	110V

A. Power sharing and immunity to communication disruptions

Initially, as depicted in Fig.5(a) and (b), during stage 1, the accuracy of reactive power sharing is compromised due to disparities in droop coefficients and line impedances. Specifically, the distinct droop coefficient and feeder impedance impact the fundamental impedance while the other control parameters remain unchanged. However, subsequent activation of the adaptive control of virtual impedance enables the realization of proportional active power sharing, irrespective of the initial conditions. Notably, even in a communication delay of 15ms and an interrupted communication link from DG2 to DG1, the performance of power-sharing remains unaffected.

B. Cyber attack and resilience enhancement

Fig.6 (a) and (b) illustrate the implications of cyber attacks on inverter-connected systems and also show the effectiveness of the proposed method in mitigating such threats. During stage 2, the communication-based virtual impedance is implemented, leading to proportional sharing of active power, and no cyber attacks are present in the communication network. Subsequently, at the start of stage 5, a false data injection attack is launched on the communication line from DG2 to

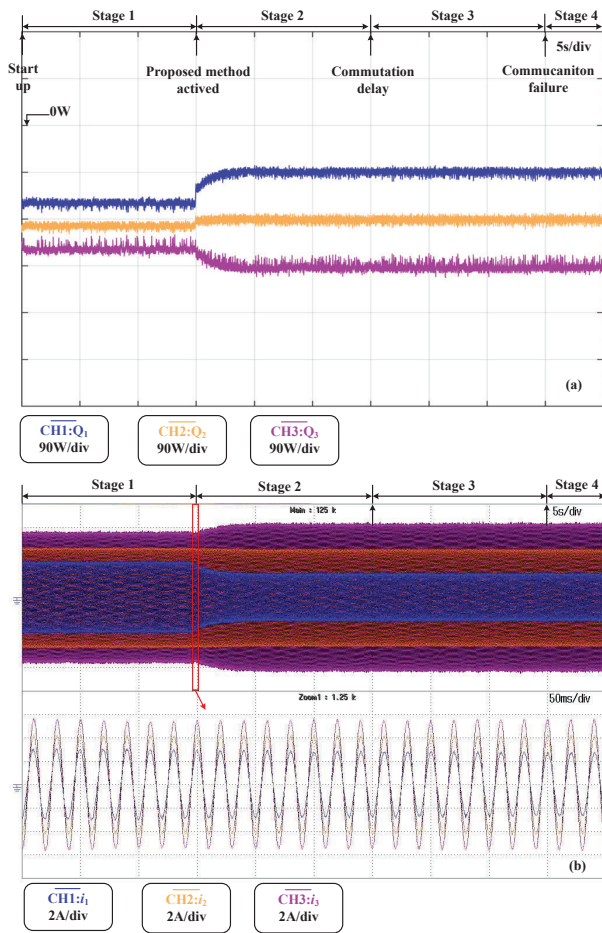


Fig. 5. Performance of the proposed adaptive virtual impedance: (a) Reactive power. (b) Fundamental current

DG1, with $\varepsilon(t) = 100$ W affecting both the active power controller. Consequently, the power-sharing ratio deviates from the optimal point. However, upon activation of the proposed resilient framework in stage 6, the corrupted data is eliminated, and the attacked signal is reconstructed, successfully restoring the power-sharing ratio to the desired 1:2:3 proportions. These results exemplify the resilience of the proposed method against cyber-attacks, underscoring its potential to enhance the security and stability of microgrids. The study showcases the ability of the adaptive control scheme to safeguard against cyber threats, thereby solidifying its relevance in the realm of microgrid protection.

C. Communication relief strategy

As previously indicated in the introduction part, the proposed methodology presents the potential to alleviate the communication burden by deactivating the communication network once all participating inverters are interconnected and successfully share active power. Fig.7 (a) and (b) illustrate the behaviour of reactive power and fundamental current, respectively. It is imperative to emphasize that at the onset of stage 7, the communication network is terminated following

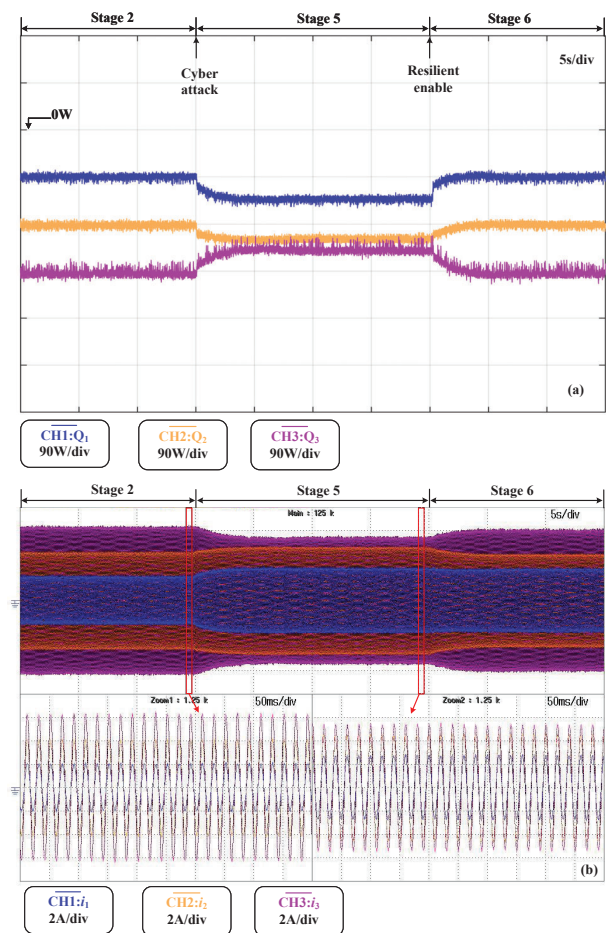


Fig. 6. The effectiveness of the cyber attack mitigation:(a) Reactive power. (b) Fundamental current.

the implementation of virtual impedance loops to facilitate power-sharing. Furthermore, ensuring plug-and-play capability for the microgrid under diverse operating conditions remains a crucial aspect of this study. When the communication is disabled after the virtual impedance is fixed, the inverter-connected system should sustain power-sharing in proportion to a ratio of 1:2:3. Proceeding to stage 8, the disconnection of DG1 and DG2 maintaining a power-sharing ratio of 1:2, with DG3 outputting 0W, as demonstrated in Figures 12(a) and 13(a). Finally, in stage 9, the reconnection of DG3 to the microgrid system effortlessly re-establishes the reactive power-sharing ratio at 1:2:3 among the three participating inverters. Notably, this is achieved without further communication, owing to the precise adjustment and fixation of virtual impedances. The study's outcomes thus underscore the system's robust ability to sustain proportional power-sharing under varying conditions while minimizing dependence on continuous communication.

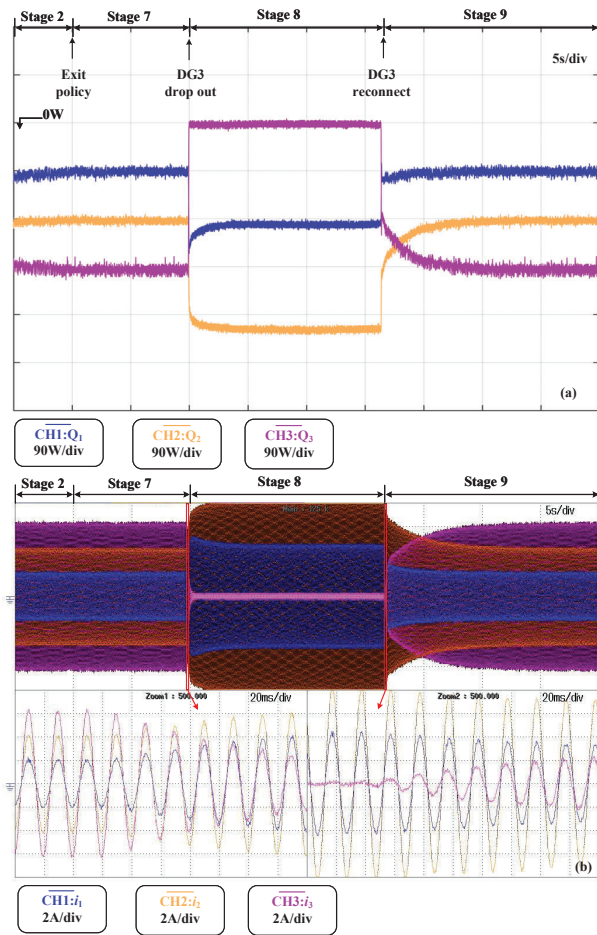


Fig. 7. The plug-and-play operation for the reactive power controller after communication is disabled: (a) Reactive power. (b) Fundamental current.

VII. CONCLUSION

This paper proposes a virtual impedance reshaping strategy for reactive power sharing in an island microgrid. The proposed control strategy takes the benefits of immunizing communication delay, communication failure, and cyber attacks. It realizes accurate power sharing while significantly reducing communication data exchange and achieving the plug-and-play feature among the DG units. Experimental results demonstrated the effectiveness of the proposed method.

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