Unified centralised/decentralised frequency control structure for microgrids

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Abstract
When the microgrid (MG) operates in islanded mode, the frequency adjustment is performed through the secondary control. This control can be achieved through centralised, distributed or decentralised strategies. The centralised strategies are the most applied in the MG due to the facility of the control and coordination of the distributed generations. However, due to centralisation of processing and information, these strategies depend on the continuous operation of the communication channels. The decentralised and distributed strategies are proposed in the literature to avoid the reliability issues of centralised strategies. This paper proposes a new control interface that can combine the centralised and decentralised secondary frequency control strategies in a unique control structure, merging the advantages of each technique. The proposed unified secondary frequency control structure (USFCS) can ensure the benefits of centralised control and can maintain the MG frequency regulation even during control or communication failures. The proposed USFCS is verified on an MG based on the CIGRE benchmark LV distribution network through simulation. The results have shown that the proposed control structure can guarantee the frequency regulation even during failures and can restore it to regular operation after failure.

1 INTRODUCTION
Microgrids (MG) can be considered small-scale power systems that can facilitate the integration of distributed generation (DG) into the electrical network [1, 2]. MGs are defined as an aggregation of DGs and loads operating as a single system that can provide power and heat [3]. Hybrid microgrids can be exploited at two different levels, that is islanded mode and connected to main power grids [1–4]. In the connected mode, the MG can import or export power from the main grid; the voltage and frequency regulation is maintained by the main grid. The islanding can occur intentionally or not, and in this operation mode, the dispatchable DGs of the MG must control the voltage and frequency in order to maintain the load balance [1–4].

In order to maintain the MG operating during the islanded mode, a hierarchical control structure must be employed [5, 6]. A three-level hierarchical control structure normally comprises primary, secondary, and tertiary control levels. Primary control is responsible for ensuring the stable operation of DGs and the power sharing among them. Secondary control is responsible for adjusting the MG frequency and voltages. This control acts over the primary control by setting new frequency and voltage references. At the tertiary level, the optimal management of power flow is achieved [5, 6].

The objectives of secondary and tertiary control sometimes overlap in the literature. According to [7], the secondary control aims to find the optimal dispatch of the available DG units, so it is also referred to as MG energy management system (EMS). However, reference [5] considers that secondary control is responsible for compensating the frequency and voltage deviations produced by the action of the primary control, and the optimal management and the power flow control are performed only in the tertiary control. The definition presented in [5] is considered in this work.

The primary control is typically performed by droop techniques, the same as applied in synchronous generator [2–6]. The secondary and tertiary control can be performed by many different strategies, which can be classified as: centralised, distributed and decentralised [8–11].
In the centralised strategies, the control of the MG is performed by a microgrid central controller (MGCC). The MGCC performs the control by monitoring variables such as active and reactive power, voltages and frequency which are collected from DGs and critical loads, through a communication link [5, 6, 12, 13]. This strategy can be well applied for small-scale MGs or for MGs where the owners of DGs and loads have common goals [12, 14]. These strategies can easily and rapidly achieve optimal control for the MG, due to the access to the information being concentrated in the MGCC. However, due to the centralisation of the communication, information and the control, such strategies are not very reliable, because if a local failure occurs in the communication system or in the MGCC, frequency and voltage regulation can be affected [14].

Decentralised and distributed strategies are proposed to overcome the reliability issues of the centralised control. These strategies can be well applied for MGs where the owners of DGs and loads have different goals, or for large-scale MGs, where the application of the centralised control requires a massive database and fast computational processing [9, 10, 12, 15]. The distributed strategies are characterised by the control being performed by multiple computational units that can exchange information through a communication network. These strategies can be as efficient as the centralised strategies while having a small database and fast processing in each distributed control unit. However, the performance of these strategies still depends on the communication network [15, 16].

The decentralised strategies are characterised by the control being performed only based on local measurements, presenting high reliability due to dismissing the communication network. However, these strategies cannot guarantee optimal performance due to the lack of information about the whole system [9, 10, 15, 16].

Several works in the literature deal with the improvement of secondary frequency control, the focus of this work. References [17, 18] propose a fuzzy system to automatically tune the PI gains of the frequency control in order to improve the stability and the performance of these controls. The PI gains of the frequency and voltage control are both simultaneous and automatically tuned by an artificial neural network (ANN) in [19]. The ANN provides an online modification of the control parameters. Reference [20] proposes a fuzzy logic based on secondary frequency control for MG. The membership functions are obtained through a particle swarm optimisation algorithm. A novel optimal fuzzy logic controller for wind turbines is proposed in [21, 22]. The aim is to control the frequency regulation in a system with high penetration of wind generation. The influence of the communication delay on the stability frequency regulation with PI controller is analysed in [23]. A small-signal model is used to find the delay margins that maintain the MG stable. In [24], the influence of communication multi-delay on the stability frequency regulation with PI controller is analysed. Model predictive controller to avoid communication delays in the frequency regulation is proposed in [25].

For decentralised secondary control (DSC), many strategies are proposed. Local measurement-based control is proposed in [26], where each decentralised controller regulates the frequency only with local frequency measurement. The strategy proposed in [26] presents a frequency deviation in steady state. A proportional control with a low-pass filter for frequency regulation is proposed in [27]. Again, a frequency deviation in the steady state is observed. Reference [28] shows the equivalence between secondary control and the washout filter-based power-sharing strategy for frequency and voltage regulation. A fully decentralised leaky integral controller for frequency regulation derived from a classic lag element is presented in [29]. Strategies based on state estimators can be found in [30–32]. Reference [30] proposes a linear model-based state estimator, considering a cost function to the voltage regulation. A cooperative control of frequency and voltage by using a Luenberger observer is proposed in [31]. Decentralised sliding mode estimator with a frequency and voltage cooperative control is proposed in [32].

Several researchers adopt a distributed control strategy. Most of this research involves the concept of a multiagent system [11, 28]. In [33], a novel distributed control for frequency and voltage regulation and reactive power sharing is proposed. In this strategy, each controller communicates with each other. Cooperative secondary control is proposed in [34], where each controller needs to communicate only with its neighbour. The feedback linearisation is applied in the voltage control to transform the voltage regulation problem into a second-order tracker synchronisation problem. Reference [35] uses a distributed averaging PI control to regulate the frequency and voltage. In [9], an optimal distributed control for frequency and voltage regulation is proposed. In this reference a finite-time controller provides frequency regulation and active power sharing.

The event-trigger-based strategies are being adopted in the MG frequency regulation [11]. These strategies can drastically decrease the number of actuator updates and communication burden. In this sense, reference [36] proposes a cooperative event-trigger controller in centralised and decentralised control strategies. Both strategies are based on the Lyapunov method, ensuring the stability and convergence of the method. A distributed event-triggered control is proposed in [37]. The frequency regulation and the economic dispatch is achieved through a consensus algorithm. A distributed event-triggered control is proposed in [38]. The pinning-based protocol is used to the frequency and the voltage regulation, and a consensus-based optimal power-sharing control protocol is considered for the economic dispatch. A detailed overview of secondary control strategies is presented in [11, 28].

The centralised Secondary Control (CSC) strategies still are the most applied in the bulk power system. Nowadays, distributed secondary control and the DSC are the most adopted control strategy in MGs. Despite the widespread use of distributed secondary control and the DSC, the CSC has been the subject of study by researchers, as it can easily and rapidly achieve optimal control. However, no studies have been found that address MGCC failure, which impacts the reliability of the CSC of the MG. Thus, this paper aims to propose a unified secondary frequency control structure (USFCS) capable of maintaining the MG frequency regulation even during MGCC or communication network failure. In the proposed USFCS, both centralised and DSC strategies operate simultaneously,
TABLE 1 Comparison of the proposed structure to the state-of-art

|                    | USFCS | CSC [17–25] | DSC [26–32] |
|--------------------|-------|-------------|-------------|
| Frequency regulation can be performed without the MGCC? | Yes   | No          | Yes         |
| Frequency regulation can be performed without communication? | Yes   | No          | Yes         |
| Can achieve optimal performance through communication? | Yes   | Yes         | No          |
| Smooth transition during the switching of the strategies? | Yes   | No          | No          |

which makes it possible to take advantage of the potential of each strategy. In this proposal, during regular operation, each decentralised controller unit (DCU) acts only as an interface between the MGCC and the DG. During a failure, the DCU acts as a backup for the MGCC, assuming the frequency regulation. When the failure ends, the control can return to CSC mode without the frequency reaching harmful values. This structure can achieve the benefits of centralised control during regular operation, and still maintaining the frequency regulation during failures of MGCC or the communication network. The mathematical model for the proposed control structure using fixed PI gains [5] for the centralised controller and proportional with low-pass filter [27] for the decentralised controller is presented in this paper. The new control structure strategy is tested in the adapted low voltage distribution network CIGRE benchmark MG [39] through simulations in Matlab/Simulink. The main benefits of the proposed method in comparison with the CSC and DSC strategies are presented in Table 1.

Thus, this paper aims to contribute in MG investigation by:

- Introducing a new USFCS that allows the centralised and DSCs to operate together, which contributes to the reliability of the MG frequency control, because if a failure occurs that makes DGs unable to respond to the MGCC, the frequency control is performed by the DSC. In additional, this control structure is capable of maintaining a smooth transition between the DSC and CSC, which contributes to the stability of the MG;
- Presenting an MG model for dynamic studies, where distinct generations sources and controllers are considered (synchronous generators, converted-based sources and storage devices).

2 PROPOSED SECONDARY FREQUENCY CONTROL STRUCTURE

As discussed previously, the frequency regulation can be compromised if a failure occurs in the MGCC or in the communication link. A new control strategy is developed to regulate the frequency during failures. The structure of the proposed control is shown in Figure 1, where both centralised and decentralised control operates simultaneously. In this strategy, each DCU sends and receives information from the MGCC through a communication system structure. Thus, the MGCC knows the states of all DCUs, and each DCU knows the state of the MGCC.

Considering an islanded AC MG consisting of \( N \) dispatchable DGs, each DG unit is composed of the droop control represented in (1).

\[
\omega_i = \omega^* + m_i (P_i - P^*) + \Delta \omega_{Dij},
\]

where \( i \) is the index of the \( i \)th DG, \( \omega_i \) is the angular frequency, and \( \omega^* \) is the angular frequency reference for the droop control. \( m_i \) is the frequency droop coefficient. \( P^* \) stands for active power reference for the droop control, and \( P_i \) is the active power output. \( \Delta \omega_{Dij} \) is the frequency reference processed through the DCU.

The proposed USFCS can be summarised in the diagram of Figure 2. Three operational conditions can be presented:

- Normal operation: the DCUs and the MGCC have no communication or control failures, thus the DCUs and the MGCC can communicate;
- Total failure: all the DCUs cannot communicate with the MGCC. Then, all DCUs change to DSC mode;
- Partial failure: one or more DCUs cannot communicate with the MGCC. Then, only the DCUs that present failure change to DSC mode.

In normal operation condition, the MGCC will regulate the frequency by setting the reference values and sending them to
each DCU through the communication channel. In this paper, the messages sent by a controller are denoted without an apostrophe. The messages received by a controller are denoted with an apostrophe. The communication link is represented as:

\[ \text{State}_i = \begin{cases} 0 & \text{Disconnected,} \\ 1 & \text{Broadcasting} \end{cases} \]

(3)

with State_i representing the state of the i-th communication channel. As shown in (3), State_i receives 1 or 0 depending on whether the communication channel is operational or not.

The MGCC generates the references (Δ𝜔_k,T) through the PI controller and sends them to each DCU when in regular operation (fail = 0 & State_i = 1, ∀i ∈ N) using the communication channel. Along with the references, the MGCC sends more variables to the DCUs, the CmC = 1 to indicate whether the MGCC is operational and the CmT = 0 to inform the DCU to operate in DSC mode.

Each DCU receives the message from the MGCC, and if the variable CmT indicates to operate in CSC mode (CmT = 1), the DCU will send the received reference to its respective DG. The reference sent to the droop controller of a DG is denoted Δ𝜔_k,D. Thus, for regular operation, the references of the secondary control sent to a DG denoted with index i will be Δ𝜔_k,D = Δ𝜔_i,P. Each DCU after receiving the messages from the MGCC sends a new message to the MGCC reporting the reference Δ𝜔_k,D sent to the droop controller, the variable CmC_k = 1 indicating that the DCU is operational, and the variable CmK_k = 0 indicating that the DCU is operating in DSC mode.

If a total failure occurs in the MGCC or in the main communication link (fail = 1 | State_i = 0, ∀i ∈ N), resulting in the MGCC being unable to send the frequency references and its states, the DCUs will no longer receive the information from the MGCC. Thus, each DCU will change to DSC mode. In other words the DCUs assume the frequency regulation using only local frequency information. When the DCUs change to DSC mode the references generated by the DSC strategy (Δ𝜔_k,D) must be initialised with the last reference sent by the MGCC, thus avoiding the abrupt variation of the references.

If the MGCC or the communication link returns to operate, the MGCC and the DCUs can exchange information again. The MGCC sends a message containing the variables CmC = 1, CmT = 1 and Δ𝜔_k,D = 0 to all DCUs that have their communication channels operating. The variable CmT = 1 warns the DCU to maintain its operation in DSC mode. Thus, each DCU maintains the DSC mode and sends a message to the MGCC containing the variables CmD = 1, CmK = 1 and the value of Δ𝜔_k,D generated by the DSC strategy.

The MGCC, when receives the messages from the DCUs, can know which communication channels are operating (CmD_k = 1). After that, the MGCC will arbitrarily select a DCU (denoted as index k) to start the tracking process represented by the diagram shown in Figure 3. The tracking process is carried out to ensure that the initial condition of the PI controller is equal to the frequency reference generated by the selected DCU (Δ𝜔_k,D). Thus, when the MGCC assumes the frequency regulation, the initial condition of the PI will have the same value as the last frequency reference generated by the DCU when operating in DSC mode.

The switches SW1 and SW2 operate interconnected during the tracking process. Both switches change to position ‘a’ at the same time, and the PI controller does not receive the frequency error between the reference and the measured frequency in the PCC. In this configuration, the integrator of the PI controller will converge to the value Δ𝜔_k,D − K_p(𝜔_ref − 𝜔_PCC). When the control output (ETF) is nearby to converge, the tracking process is finished, so the switches SW1 and SW2 change to position ‘b’, and frequency error is applied again in the PI controller. Then, the PI controller returns to its normal configuration, the
generated reference will be the sum of the converged value of the integrator and the value of the proportional gain multiplied by the frequency error, which is equal to the value of the reference generated by the selected DCU ($\Delta\omega_{iD}$).

The MGCC must adjust the initial value of frequency reference for each DCU after the tracking process. That adjustment is carried out through the sum of the PI controller output and a variable denoted as ‘initialisation variable’. The initialisation variable is calculated by the difference between the last references generated by the DCU and the last reference generated by the PI controller before changing to CSC mode. Thus, applying the PI controller before changing to CSC mode. Thus, applying

$$\Delta\omega_{iD} = sPI_i + K_p \omega's_i$$

At first, the MGCC will inform the DCU to continue operating in DSC mode; then, with the received frequency reference generated by the DSC ($\Delta\omega_{iD})$, the MGCC will calculate the new initialisation variable and send it to the DCU with the message to operate in CSC mode. Once the DCU receives the message from the MGCC, it will switch to CSC mode and send back to the MGCC a message containing the variables $CmD = 1$, $CmK = 0$ and the frequency reference value sent to the primary control of the DG.

The proposed USFCS can be summarised in the diagram of Figure 2. It is possible to represent the control actions mathematically for the USFCS, when the PI fixed gains controller strategy [5] is applied to the CSC of the MGCC, and the proportional with low-pass filter controller strategy [27] is applied to the DSC of the DCUs, as presented in the following subsections.

### 2.1 Centralised control

The $\Delta\omega_{iD}$ frequency reference provided by the MGCC to each DCU can be expressed as

$$\Delta\omega_{iD} = \begin{cases} 
\text{Fail} = 1 & | \text{PCCS} = 1 \\
0 & \text{if } CmK_i = 1 \text{ and } CmD_i = 0 \\
\text{Rst} = 1 & \text{if } \text{Fail} = 0 \text{ and } \text{PCCS} = 0 \\
Tr + IH_i & \text{if } CmK_i = 0 \text{ and } CmD_i = 1 \text{ and } \text{Rst} = 0,
\end{cases}$$

where $\text{Fail}$ indicates the operating state of the MGCC ($1$ = failure and $0$ = no failure), $\text{PCCS}$ represents the operation mode of the MG ($1$ = connected mode and $0$ = islanded mode). $CmD_i$ is the DCU message received by the MGCC that indicates the DCU operating state or communication channel state ($1$ = no failure and $0$ = failure). $CmK_i$ is the DCU message received by the MGCC indicating the operation mode of the DCU ($1$ = DSC mode and $0$ = CSC mode). $Tr$ is the output of the PI control function, as in (6). $\text{Rst}$ indicates whether the MGCC is in the tracking process or not, as in (8). $IH_i$ is the initialisation variable for each DG, as in (5), this variable is calculated by the MGCC only when a DCU changes from DSC to CSC mode.

$$IH_i = \begin{cases} 
0 & \text{if } \text{Fail} = 1 | \text{PCCS} = 1 \\
L\text{Rst} = 1 | CmD_i = 0 \\
\text{Fail} = 0 \text{ and } \text{PCCS} = 0 & \text{if } \text{Fail} = 0 \text{ and } \text{PCCS} = 0 \\
\Delta\omega_{iD} (t_i) & \text{if } \text{Fail} = 0 \text{ and } \text{PCCS} = 0 \\
\text{Rst} = 1 & \text{if } \text{Fail} = 0 \text{ and } \text{PCCS} = 0 \\
CmK_i = 1 \text{ and } \text{Rst} = 0, \\
\text{Rst} = 1 & \text{if } \text{Fail} = 0 \text{ and } \text{PCCS} = 0 \\
CmD_i = 1 \text{ and } \text{Rst} = 0, \\
\text{Rst} = 1 & \text{if } \text{Fail} = 0 \text{ and } \text{PCCS} = 0 \\
CmK_i = 1 \text{ and } \text{Rst} = 0,
\end{cases}$$

where $t_i$ is the time when the MGCC calculates the initialisation variable.

Many CSC strategies can be adapted to the proposed control, such as the automatically tune PI strategies [17, 19, 23]. However, for this work, the PI controller of fixed gains was chosen because of its simplicity [5]. The output ($Tr$), of the PI controller with fixed gains applied in the proposed strategy can be represented mathematically in (6).
Decentralised control where the tracking process. Mathematically, $\Delta \omega_{D ji} = \omega_{ref} - \omega_{i}$ where $\omega_{ref}$ is the reference frequency and $\omega_{i}$ is the frequency read from the DG. During failures, the DCU changes from CSC to DSC mode, in this mode the DCU begins to regulate the frequency locally. These frequency references are expressed as:

$$\Delta \omega = (\omega_{ref} - \omega_{i})$$

where $\omega_{ref}$ is the reference frequency and $\omega_{i}$ is the frequency read from the DG.

During the tracking process, all DCUs must operate in DSC mode, so the MGCC sends the message with the variable $CmC_i$ to each DCU. $CmC_i$ can be expressed as shown in (10).

$$CmC_i = \begin{cases} 0 & \text{if } Rst = 0 \\ 1 & \text{if } Rst = 1 \end{cases}$$

The MGCC sends the message with the variable $CmC = 1$ to all DCUs during all its operation. If the MGCC fails, the variable will no longer be sent ($CmC = 0$). $CmC_j$ is defined as shown in (11).

$$CmC_j = \begin{cases} 0 & \text{if } Rst = 0 \\ 1 & \text{if } Rst = 1 \end{cases}$$

2.2 Decentralised control

As described before, the DCU can operate in two modes: CSC and DSC. During CSC mode, the DCU operates only as an interface between the MGCC and the DG. In this mode, the DCU sends the MGCC's frequency reference to its respective DG. During failures, the DCU changes from CSC to DSC mode, in this mode the DCU begins to regulate the frequency locally. These frequency references are expressed as:

$$\Delta \omega_{D ji} = \begin{cases} 0 & \text{if } PCCS = 1 \\ \Delta \omega'_{ref} & \text{if } PCCS = 0 \& CmC'_{ji} = 1 \end{cases}$$

$$\Delta \omega'_{ref}(t_f) = \begin{cases} 0 & \text{if } PCCS = 0 \& CmC'_{ji} = 1 \end{cases}$$

where $\Delta \omega'_{ref}(t_f)$ is the last reference sent to each DCU by the MGCC before the failure. $t_f$ is the time when the DCU identifies the system failure or when the variable $CmC'_{ji}$ sent from the MGCC changes its state to 1 while the MGCC is in regular operation ($CmC = 1$). $CD_i$ is the DSC strategy implemented in the DCUs.

For the proposed approach different DSC strategies can be applied, in this paper the proportional with low-pass filter controller [27] is applied, as shown in (13).

$$CD_i = \frac{a_i \cdot (\omega_{ref} - \omega_i)}{1 + s \cdot t_{2i}},$$

where $a_i$ is the DSC proportional gain. $t_{2i}$ is the time constant for the low-pass filter. $\omega_{ref}$ is the DSC frequency reference. $\omega_i$ is the frequency read from the DG_i bus.
During the DSC mode, if the MGCC or the communication channel returns, the DCU sends the message $CmK_j$ to the MGCC to indicate that the DCU operates in DSC mode. $CmK_j$ is expressed as shown in (14).

$$CmK_j = \begin{cases} 
0 & \text{if } PCC_S = 1 \land (CmC_j' = 1 \land CmT_j' = 0) \\
1 & \text{if } PCC_S = 0 \land (CmC_j' = 0 \land CmT_j' = 1) 
\end{cases} \tag{14}$$

All DCUs send the message $CmD_i = 1$ to the MGCC during regular operation, which can be represented mathematically by (15).

$$CmD_i = 1. \tag{15}$$

### 3 | MG MODEL

The proposed USFCS is tested in an islanded MG based on the CIGRE benchmark LV distribution network [39] using Matlab/Simulink. The MG is shown in Figure 4, and its electrical parameters are presented in Table 2. The nominal frequency of 60 Hz is adopted.

The voltage source converters for the Batteries 1 and 2, photovoltaic system and wind turbine were modelled using the average model [40], and the primary sources of the DGs were considered as ideal. The control block diagrams used in the converters are shown in Figure 5. The parameters and control gains for the converters are presented in Table 3.

The control of the converters is modelled in dq0 frame. The photovoltaic system and wind turbine operate in power control mode. In this control mode, the control block in Figure 5 is represented only by the current control, which is presented in Figure 6. The references for the current control are generated according to (16) and (17), and a phase lock loop (PLL) must generate the reference angle.

$$I_{dref} = \frac{V_{kd}P_{ref} + V_{kg}Q_{ref}}{V_{kd}^2 + V_{kg}^2}, \tag{16}$$

$$I_{qref} = \frac{V_{kd}P_{ref} - V_{kg}Q_{ref}}{V_{kd}^2 + V_{kg}^2}, \tag{17}$$

where $I_{dref}$ and $I_{qref}$ are the current references for the current control. $V_{kd}$ and $V_{kg}$ are the direct and the quadrature converter voltages. $P_{ref}$ and $Q_{ref}$ are the active and reactive power references.
The batteries operate in voltage and frequency control mode with droop. In this control mode, the control block, in Figure 5, represents a voltage control in series with the current control. The voltage control is shown in Figure 7. The references of the voltage controller $V_{dre f k}$, $V_{qre f k}$, and the angle $\theta$ are set by the reactive and active droop control.

The adopted gains for the MG secondary control are obtained through a heuristic algorithm. The method applied is based on the method applied in [41], where different operation points and contingency are considered. Thus, the values adopted for the gains are: $a = 5$ and $t2 = 10$ for the DSC. $K_{TRK} = 50,000$ and $ER = 1E - 6$ for the tracking process.

## TEST RESULTS

In order to assess the effectiveness of the proposed control strategy, two cases are evaluated, as follows:

**FIGURE 6** Converters current control [40]

**FIGURE 7** Converters voltage control [40]

**FIGURE 8** Diesel governor and actuator parameters
i. The first case evaluates the proposed USFCS when a failure occurs in the MGCC. In this case, all DCUs operating in CSC mode switch to DSC mode. When the MGCC returns the tracking process is started;

ii. The second case evaluates the proposed USFCS when a communication failure occurs between the MGCC and a specific DCU. In this case, only one DCU switch to DSC mode when the failure occurs. The tracking process is not performed in this case.

In each case, the proposed USFCS is compared with two other strategies: (i) the conventional PI proposed in [5], that comprises the CSC; (ii) the operation of both CSC and DSC without applying the tracking process and the initialisation variable of the DSC during switching between controls. In the figures below, approach (i) is called ‘only CSC’, and approach (ii) is called ‘Switching: CSC and DSC’. In addition, the robustness of the proposed USFCS is assessed in the face of communication delay.

4.1 Case 1: Performance of the USFCS when the MGCC fails

Initially the MGCC is operating normally in the CSC mode with only 15% of the load and in the sequence the following events occur:

i. at \( t = 0.5 \text{s} \), the Load R15 increases to 9 kW and 5 kvar;
ii. at \( t = 1 \text{s} \), a failure occurs in the MGCC (\( \text{Fail} = 1 \));
iii. at \( t = 3 \text{s} \), the Load R16 increases to 20 kW and 13 kvar;
iv. at \( t = 5 \text{s} \), the MGCC returns to regular operation.

As can be seen in Figure 9, for the three strategies can regulate the MG frequency, since for all of them the MGCC is operating normally with CSC strategy. At \( t = 1 \text{s} \), when the failure occurs, the frequency reaches 59.68 Hz if the CSC switch to DSC mode without the proposed initialisation variable (‘Switching: CSC and DSC’), as shown in dashed line with square markers. If the MG is operating only with the CSC strategy (‘Only CSC’), it is not possible to restore the frequency, as shown in dotted line with a plus sign. On the other hand, the proposed USFCS is capable of maintain the frequency regulation during the MGCC failure and guarantees a smooth transition between the CSC and DSC mode, as shown in solid line. With the proposed USFCS there is no drop in frequency during the MGCC failure. It is also important to notice that the DSC strategy cannot fully restore the frequency in steady state to the nominal value (60 Hz), which can be seen right before the Load R16 is increased and right before the MGCC returns to normal operation, when the frequency reaches 59.99 and 59.95 Hz, respectively. At \( t = 5 \text{s} \), when the MGCC returns to normal operation, the frequency for the proposed USFCS remains above 59.95 Hz and falls below 59.4 Hz in the other two strategies.

The low frequency values observed at \( t = 5 \text{s} \), when the MG is not operating with the proposed USFSC, are due to the fact that the CSC starts the frequency regulation considering only the frequency error. If the MG switches to CSC mode when the MGCC returns but not applying the tracking process, the PI of the MGCC will be initialised with the value \( K_p (\omega_{\text{ref}} - \omega_{\text{PCC}}) \). Thus, the frequency reference sent to the droop control of each DG will change drastically when the DCUs change to CSC mode, causing an abrupt frequency variation.

The behaviour of communication variables for the USFCS is shown in Figure 10. During the MGCC failure, the \( C_{\text{mC}} \) and \( C_{\text{mT}} \) variables are zero, and \( C_{\text{mK}} \) variable changes its value to 1. After the MGCC returns, the values of the \( C_{\text{mC}} \) and \( C_{\text{mT}} \) variables become 1, and the tracking process is started with the Battery 1 being the DCU selected for the tracking process, which lasts for 0.015 s in this case. The variable \( C_{\text{mK}} \) becomes zero after the end of the tracking process, at \( t = 5.015 \text{s} \), and the variable \( C_{\text{mT}} \) also becomes zero. The frequency references sent by the MGCC to each DCU are initialised to the last value of the DCUs when they were operating in DSC mode, ensuring that the frequency reference does not suddenly change, as shown in Figure 10.

The frequency references generated by the DCUs of Batteries 1 and 2 during the MGCC failure are different from those generated by the DCU of the diesel generator. This behaviour is associated with the dynamics of each device. Thus, the diesel generator’s initialisation variable calculated by the MGCC will be different from that calculated for Batteries 1 and 2, when the DCUs switch from DSC to CSC mode. From Figure 10, the difference in the reference of the batteries and the diesel generator is 0.11 rad/s, from (5) the initialisation variable of the Battery 2 is zero (\( H_{\text{g2}} = 0 \text{ rad/s} \)) and the initialisation variable of the diesel generator is 0.11 rad/s (\( H_{\text{g1}} = 0.11 \text{ rad/s} \)).

The active power for each DG in the MG when the USFCS is applied is presented in Figure 11. The batteries and the diesel generator do not show sudden changes in the active power generation after the occurrence of the failure (\( t = 1 \text{s} \)) and in the return of the MGCC (\( t = 5 \text{s} \)). Due to the implemented

![FIGURE 9 Frequency of MG when a failure occurs in the MGCC](image-url)
centralised and decentralised strategies, the DGs must achieve the active power sharing in steady state. However, in DSC mode, the references generated by the DCU of the diesel generator during the transient state are different from the references generated by the DCUs of the Batteries 1 and 2. These differences impact the active power sharing when the MGCC returns before the system reaches the steady state. Thus, the reference differences are maintained in the CSC operation. At the end of the simulation, \( t = 7 \) s, the batteries have the same active power generation, 7.34 kW, and the diesel generator presents 15.39 kW; however, for this case the active power sharing should be 7.16 kW for the Batteries 1 and 2 and 15.75 kW for the diesel generator.

4.2 Case 2: Performance of the USFCS when the communication channel of Battery 1 fails

As in Case 1, the MGCC is operating normally in the CSC mode with only 15% of the demand, and in the sequence the following events occur:

i. at \( t = 0.5 \) s, the Load R15 increases to 9 W and 5 kvar;
ii. at \( t = 1 \) s, the communication channel between Battery 1 and MGCC goes out of operation;
iii. at \( t = 3 \) s, the Load R16 is increases to 20 kW and 13 kvar;
iv. at \( t = 5 \) s, the communication channel returns to regular operation.

The results of the proposed USFCS in Figure 12 show that the DCU of the Battery 1 switches to DSC mode when the communication channel goes out of operation (\( t = 1 \) s). Then, the DCU can initialise the DSC strategy using the last value of the frequency reference received from the MGCC (\( \Delta \omega_{r_{1}} = 1.16 \) rad/s). Although the MG frequency can still be regulated without the proposed USFCS, when the communication channel goes out of operation, the frequency reference (\( \Delta \omega_{r_{1}} \)) of the DCU of the Battery 1 becomes zero for both strategies, leading to low-frequency values, as shown in Figure 12 in dotted line with plus markers when the MG is operating with only the CSC.
strategy and in dashed line with square markers when the MG switches from CSC to DSC mode without applying the initialisation variable.

When the communication channel returns operating, the proposed USFCS guarantees a smooth transition due to the initialisation variable $IH$. If the proposed USFCS or the initialisation variable $IH$ is not applied, when the communication channel returns, the frequency reference sent to the Battery 1 changes drastically, causing a high-frequency variation, as shown in Figure 12 (dashed line with square markers and dotted line with plus markers). The frequency reaches 60.42 Hz.

The DCU of the Battery 1 and the MGCC set their respective $CmK$ and $CmT$ variables to 1 when the communication channel goes out of operation, as shown in Figure 13 at $t = 1$ s. When the communication channel returns at $t = 5$ s, the MGCC sets the new initialisation variable of Battery 1 ($IH = -1.16$ rad/s) and sets the variable $CmT$ to zero. The DCU changes to CSC mode when it receives the message with the variable $CmT' = 0$ from the MGCC.

The tracking process is not performed in this case because the DCUs of the Battery 2 and the diesel generator still operate in the CSC mode. Thus, the references generated by the PI controller of the MGCC are still applied to these DCUs.

The active power for each DG when the USFCS is applied is presented in Figure 14. When Battery 1 is no longer able to communicate with the MGCC, at $t = 1$ s, and when the communication is restored, at $t = 5$ s, Battery 1 does not present abrupt variation in the active power generation. The behaviour of the active power will follow the secondary control references provided by the DCUs. Thus, when the DCU of Battery 1 changes to DSC mode, the secondary control references and the active power of the Battery 1 begin to decrease causing a difference in

4.3 Influences of the communication delay

In order to show the influence of communication delay on the USFCS when the MGCC fails, the same events as in Cases 1 and 2 are simulated, but communication delays of 50, 100 and 150 ms are now considered.

Figure 15 shows the MG frequency for each value of communication delay. The same events of Section 4.1 are considered.

the active power between Battery 1 and Battery 2. This difference is 0.8 kW.
FIGURE 16 Tracking references for different communication delays when a failure occurs in the MGCC.

FIGURE 17 Frequency of MG for different communication delays when the communication channel of Battery 1 fails.

FIGURE 18 Initialisation variable of the Battery 1 for different communication delays when the communication channel of Battery 1 fails.

(Case 1). As can be seen, for $5 \, \text{s} < t < 6 \, \text{s}$ the tracking process is influenced by the communication delays, presenting a different duration for each delay value. Thus, for this case the longer the communication delay, the longer the tracking process takes.

From Figure 16 is possible to notice that tracking process duration will be affected by communication delays. The tracking process duration is: 0.1 s for 50 ms delay; 0.2 s for 100 ms delay; 0.3 s for 150 ms delay.

Figure 17 shows the MG frequency for each value of communication delay, when the same events of Section 4.2 are considered (Case 2). The communication delay does not considerably affect the MG frequency. When the communication channel of Battery 1 returns, at $t = 5 \, \text{s}$, the frequency behaviour for each communication delay is slightly different. This is due to the difference between initialisation variable’s selected value and the reference generated by the DSC strategy when the communication delay is present. When the DCU switches to CSC mode, the value of the new reference is slightly different from the last one, as shown in Figure 18. The value of the initialisation variable for each communication delay is: $IH_{1} = -0.99 \, \text{rad/s}$ for no delay; $IH_{1} = -1.10 \, \text{rad/s}$ for 50 ms delay; $IH_{1} = -1.24 \, \text{rad/s}$ for 100 ms delay; $IH_{1} = -1.40 \, \text{rad/s}$ for 150 ms delay.

5 | CONCLUSION

This paper proposed a new control interface that can combine the centralised and decentralised secondary frequency control strategies in a unique control structure, which can guarantee the frequency regulation during MGCC or communication failures.

In this strategy, each DCU acts as an interface between the MGCC and the DG. In regular operation, the MGCC sends frequency references to each DCU that forwards to its DG, and the DCUs and the MGCC exchange information to know the states of each other. Whether a failure occurs in the MGCC or in the communication channel, the DCUs will no longer receive messages from the MGCC, and each DCU will change to DSC mode. In the DSC mode the frequency regulation is performed locally without communication. If the communication channel or the MGCC returns, each DCU will switch to CSC mode and send the new references of the MGCC to its respective DG.

Compared with the PI strategy, the proposed USFCS can ensure frequency regulation during the MGCC or communication failures. Additionally, the proposed strategy can guarantee a smooth transition between control modes. However, the proposed structure affects the active power sharing in the MG when the DCUs return to CSC mode.

Through simulation, the influence of communication delays on the USFCS was verified, where the tracking process and the variable of initialisation were affected by the communication delays. The communication delay influences the duration of the tracking process when the MGCC returns after a total failure and also the value of the initialisation variable when a communication channel returns after a partial failure. Future work will analyse the mitigation of the influence of the communication delays on the USFCS.

The USFCS can be adapted to be used in conjunction with other CSC and DSC strategies. In this sense, the results obtained can be further improved, allowing future research. In addition, stability analysis of the MG operating in DSC and CSC modes, and experimental implementation of the proposed strategy in an MG laboratory could be studied in future work.
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Nomenclature

\[ t \] Time
\[ i \] Index of each DCU and DG
\[ N \] Number of DGs in the secondary control
\[ \omega \] Angular frequency
\[ V \] Voltage magnitude
\[ P \] Active power output
\[ Q \] Reactive power output
\[ \omega^* \] Angular frequency reference for the droop control
\[ V^* \] Voltage reference for the droop control
\[ m \] Frequency droop coefficient
\[ n \] Voltage droop coefficient
\[ P^* \] Active power reference for the droop control
\[ Q^* \] Reactive power reference for the droop control
\[ \Delta \omega \] Frequency reference processed through the PI secondary control
\[ \omega_{ref} \] Angular frequency reference for the secondary control
\[ \omega_{PCC} \] Angular frequency in the PCC
\[ K_p \] Proportional secondary control gain
\[ K_i \] Integrative secondary control gain
\[ \Delta \omega_{MGCC} \] Frequency reference processed through the MGCC
\[ IH \] Variable for the initialisation of the frequency reference processed through the MGCC
\[ \Delta \omega_{DCU} \] Frequency reference processed through DCU
\[ CD \] Frequency increment processed through DSC
\[ a \] DSC proportional gain
\[ t_2 \] Time constant for the low-pass filter
\[ CmC \] MGCC operation variable sent to the DCUs
\[ CmT \] DCU operation command sent by the MGCC
\[ CmD \] DCU operation variable sent to the MGCC
\[ CmK \] DCU operation mode variable sent to the MGCC
\[ Rt \] Auxiliary variable for the MGCC tracking process
\[ K_{TRK} \] Tracking gain
\[ ETR \] Tracking error
\[ ER \] Tracking minimum error
\[ X' \] Received message
\[ X \] Message sent
\[ Z_{cm} \] Communication channel delay
\[ State \] Communication channel operation
\[ PCCS \] PCC operation
\[ Cf \] Converter filter capacitance
\[ L_f \] Converter filter reactance
\[ R_f \] Converter filter resistance
\[ K_{pC} \] Proportional control gain for converter voltage control
\[ K_{IC} \] Integrative control gain for converter voltage control
\[ K_{pK} \] Proportional control gain for converter current control
\[ K_{iK} \] Integrative control gain for converter current control
\[ I_{dc} \] Direct current reference for the converter current control
\[ I_{qu} \] Quadrature current reference for the converter current control

\[ V_{dc} \] Direct converter voltage
\[ V_{qu} \] Quadrature converter voltage

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