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Decentralised resilient autonomous control architecture for dynamic microgrids

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Abstract: Microgrids serve as an integral part of future power distribution systems. Typically, microgrids are managed by centralised controllers. There are two major concerns about using a single centralised controller. The controller can become a performance and reliability bottleneck for the entire system, where its failure can bring the entire system down. Excessive communication delays can also degrade the system performance. As a solution, a true decentralised control architecture for microgrids is proposed, designed, developed, and tested here. Distributing the controls to local agents decreases the possibility of network congestion to occur. Decentralisation will also enhance the reliability of the system since the single point of failure is replaced by a distributed architecture. The proof-of-concept of true decentralisation of microgrid control architecture is implemented using Hardware-in-the-Loop Platform. Device level and system level controller and interaction models are defined for a self-coordination. Also, microgrid energy management system (EMS) and control case scenarios are demonstrated. The experimental results show the robustness of the proposed architecture.

1 Introduction

As the electric grid continues to modernise, distributed energy resources (DERs) such as energy storage and advanced renewable technologies can help facilitate the transition to a smarter grid islanding capabilities [1]. Microgrids also support management of critical and non-critical loads to available generation. Other microgrid requirements involve secure operations, deploying secure communications network that guarantee distributed and resilient supervisory control architecture.

Microgrid control methods can be classified into many categories, depending on the availability of master controllers, slave controllers, communications, and load-sharing strategy. Centralised and distributed (decentralised) control methods differ in many aspects. Generally, if the DGs can generate its own commands locally, it is considered as distributed control.

The distributed control is a variant of the master/slave control. A central control block controls the reference voltage and influences the output current of the units. The voltage magnitude, frequency and power sharing are centrally controlled. Hence, in distributed control, only low-bandwidth communication is required, opposed to the master/slave control scheme. Voltage regulation and fundamental power sharing are controlled centrally

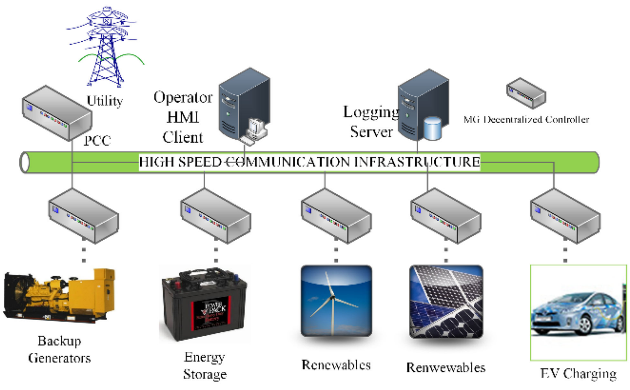

Fig. 1 *Microgrid structure with decentralised communication infrastructure*

and requires high bandwidth due to the high amount of traffic required. The distributed control method is distributed in the sense that the critical control components are dealt with local controllers. Fig. 1 shows an example of decentralised control system of a microgrid.

Centralised methods of operation are more susceptible to single point failures. Reliability is an essential since microgrids concept which is defined as solution for distribution system reliability improvement [2], therefore, emerging smart-grid concept compels microgrids to adopt decentralised methods due to the high dynamic behaviour of the microgrids. Two research areas are pursued in decentralised control architecture for microgrids: (1) The distributed control algorithm, including the control hierarchy. (2) Data exchange for decentralised control systems [3, 4]. Some efforts targeted the primary control layer, as it relates to the autonomous operation at the device level [5]. Local frequency control [6] and voltage regulation [7] at the primary control level are the major drives for decentralised controls of microgrids. Other controlled variables include active and reactive powers that are managed by the energy management system (EMS) at the secondary and tertiary control levels [8]. The variation of decentralised primary control techniques for different microgrid components as grid-forming and grid-feeding sources relies on the behaviour of the component and the controllability of microgrid variable at the source terminal. As microgrid topologies vary, the control methods consider inverter-based power sources only [9], or a combination of AC and DC sources [10, 11]. Other methods have been proposed which use real-time management of microgrids involving energy storage units over a decentralised secondary control architecture [26, 12].

Despite the vast literature on distributed microgrid control that target specific issues in the microgrid operation, a renowned need to a systemic perspective is required. The literature focuses on partial operations for microgird components, or an overall system operation. However, communication delays are often neglected and assumed as no failures in the system [4] which is contradicting the real situation for decentralised control systems. Other efforts on the microgrid controls focus on the theoretical aspect of the concept and may not address the complexity of the physical implementation of the framework [4, 11, 13]. Finally, the concept of decentralised controls in microgrids yet requires major standardisation efforts, these efforts are driven by demonstrating the proposed architectures.

This paper introduces a microgrid control architecture that characterises decentralisation as a future trend of microgrid controls. The proposed architecture merges the three microgrid control layers into one cyber-physical layer. This paper intends to bring the following main contributions to the existing literature: (1) Advocating the role of decentralised microgrid architectures as a solution for microgrid resiliency. (2) Introducing the practical complexity of decentralised architecture in comparison with the conventional systems, such as communication delays and failure management. (3) Demonstrating the collaboration of the three-level control hierarchy in a commercially viable system. (4) Proposing a novel complete architecture of decentralised microgrid controls, adopting state-of-the-art research efforts.

The rest of the paper is organised as follows: Section 2 introduced the microgrid control hierarchy and describes the interactions between the control layers. Section 3 defines three models necessary for the design of the proposed architecture. EMSs are discussed in Section 4, followed by system resiliency and coordinated failure management. The rest of the sections introduce the microgrid configuration were the proposed approach is implemented and tested. The paper concludes with the main points and future work.

2 Proposed system architecture

Microgrid control hierarchy [8] identifies three levels of controls, where each level satisfies certain requirements and roles in maintaining power reliability, quality, and economical constraints. Details of each layer are as follows:

2.1 Primary control (device level)

Device level control entails interacting with the local DER itself to perform certain functions including: physical isolation, on/off, fault clearing (device switching), fault sensing, fault controls, and re-synchronisation (device protection). For inverter: power conversion, power control, voltage and frequency regulation, primary frequency control (inverter droops, governor droops), island detection, and re-synchronisation. Most device level controls are performed through tightly coupled communication media, guaranteeing command delivery and signal delay mitigation [14].

The proposed system adopts virtual droop control (VDC) [15], which is based on natural droop control [16]. In natural droop, voltage and frequency stabilities are achieved by drooping the voltage and frequency according to active and reactive power requirement for this control level. In VDC [15], a virtual frequency and voltage are created to regulate the active and reactive power output of the sources. The active power output of the energy storage inverter determines the virtual frequency from virtual droop curve. The droop curve is defined between energy storage active power output and virtual frequency. The virtual frequency will determine the active power commands for natural gas generators from a droop relationship, defined between the virtual frequency and active power command of each source. The same concept applies to the system voltage. A virtual voltage is determined according to reactive power output of the energy storage inverter. The virtual voltage will determine the reactive power command for natural gas generators from a droop relationship, defined between the virtual voltage of the system and reactive power command of each source. It should be noted that since energy storage inverter is placed in a voltage mode, it supplies the difference between load active and reactive power and other sources in the microgrid. It behaves as a slack bus in a power system concept. Power commands of backup generators are updated only when load variation is greater than defined value. Load variation less than defined value is taken care of by the energy storage inverter.

2.2 Secondary control (system level)

Primary control level is responsible of frequency regulation. During transient operation, deviation of voltage and frequency may occur due to the load power demand fluctuations or intermittency of renewable DGs. In microgrid systems, an advantage of energy storage is enabling the microgrid to compensate for frequency and voltage deviations in a fast manner. The role of secondary control comes at a slower response to frequency fluctuations in comparison with the primary control.

The secondary layer represents the DER Management Systems (DERMS) [17]. From the utility perspective, DERs can be in a form of a microgrid (sharing the same bus), or distributed over multiple different feeders in the distribution system. The following sections explain the operations of this layer, and how they relate the concept of DERMS as a part of microgrid controllers.

Although the proposed architecture stresses the concept of decentralisation of the control algorithm, it also guarantees the general awareness of the whole system among all distributed controllers. This type of architecture is often referred to as distributed control, which does not contradict the concept of decentralisation since the system is physically distributed, and the algorithm is virtually centralised.

Fig. 2 shows the function of the secondary control that works collaboratively to achieve optimisation, protection, power calculations (considering predefined system constraints), and failure management unit (FMU) (see Section 5). Recently, efforts referred to the secondary control as the EMS, where it continuously monitors the microgrid parameters, going through data verification, and interacting with the FMU (see Figure V-5). EMS dispatches microgrid components such as energy storage or backup generators for active and reactive power and commands the primary level.

2.3 Tertiary control (grid level)

Generally, the tertiary control level manages the bidirectional power flow between the microgrid and the grid at the point of common coupling (PCC). This level also ensures optimal economical operation of the microgrid through data analytics, machine learning, optimisation, and forecasting techniques [8].

3 System design

Decentralised microgrid control system eliminates the single point of failure (central controller). Decentralisation of microgrid operations requires certain feature in the controlling components. For example, the controller should have certain level of embedded intelligence to maintain the decentralised controllers operating as one virtual unit. Coordination and additional control logic is essential; therefore, three models have been defined as key requirements to proposed architecture.

3.1 Controller model

The proposed design of the decentralised controller is shown in Fig. 3. For simplicity, the design is virtually divided into three main units: Processing unit, where the main control logic algorithm is running, with the interrupt handling routines in case of any system failures (See Section 5). The processing unit is comprised of data verification and consistency algorithms. These two units are collaboratively responsible of analysing the inputs from the peer controllers. Faults diagnostic and detection algorithm are required for this design, triggering the interrupt handling routine.

The memory unit interacts with the processing unit that manage buffered data and temporary log. It also provides peer controllers information as inputs to the control algorithm. Dynamic DER directory holds the object model of the power components (Table 1).

3.2 Data exchange model

This model defines three aspects: (1) The necessary data to be exchanged between peer controllers; (2) The way they interact; and (3) The frequency of data transmission. Data traffic starts from the electrical component system layer, where the components transmit their status data and measurements through the communication layer. Status data can be breaker status, device warnings or flags, measurements of voltage, active and reactive power, and frequency

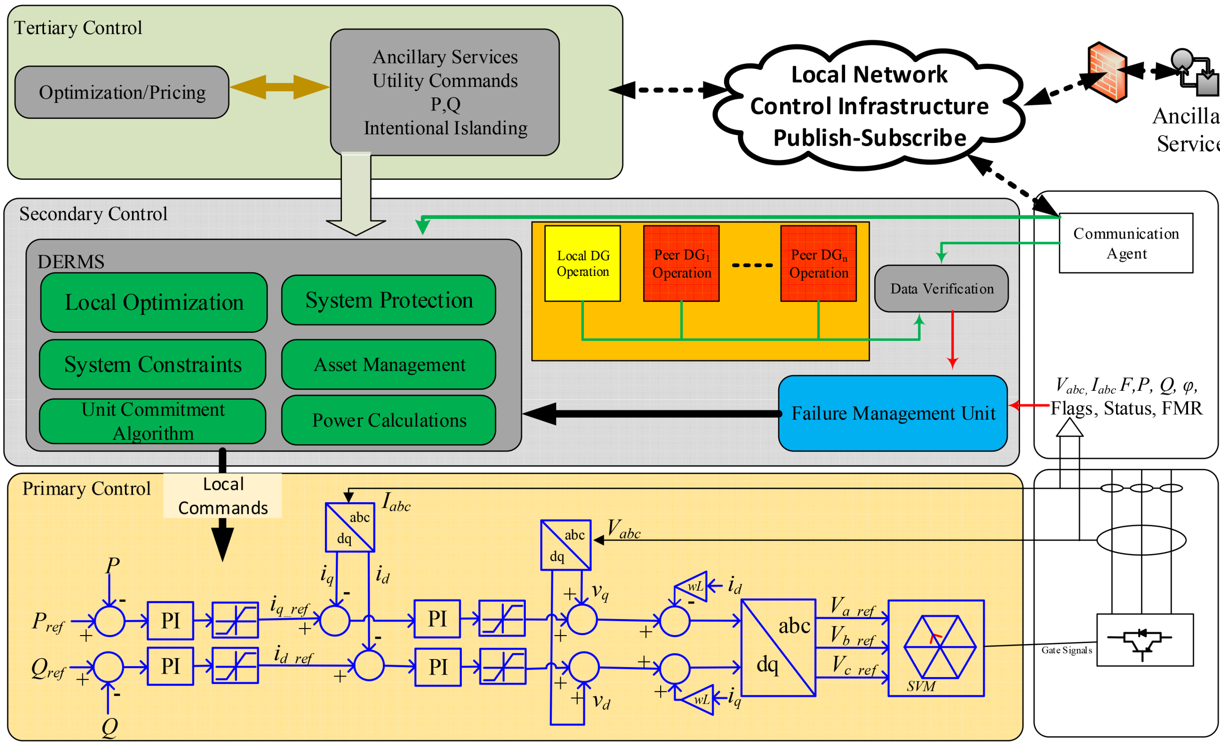

Fig. 2 *Proposed decentralised microgrid control architecture implemented for one inverter-based device*

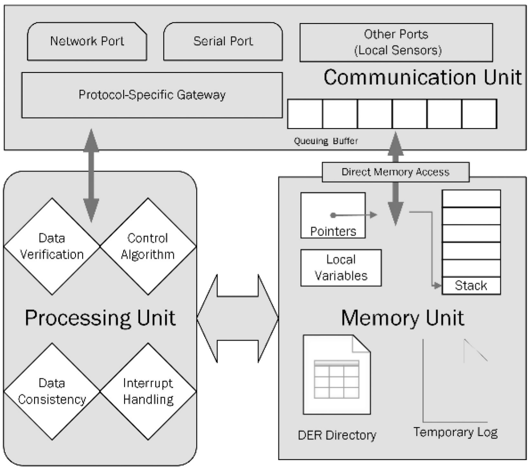

Fig. 3 *Conceptual controller design for decentralised controls applications*

of each power component (Fig. 2). Each controller receives data from its designated DER, validates the received information, and synchronises clocks considering possible delays or lost data packets during transmission over the network. Unit commitment and control algorithm utilises the most recent data inputs and sends back commands through the communication layer, which is responsible of the routing commands to the designated DER.

Recently, many efforts have been initiated and led by research institutions, industry partners, and utility companies to achieve interoperability [17]. For that purpose, many communication frameworks were implemented, adopting certain communication protocols such as DNP3, Modbus, IEC 61850 standard. From a distribution system perspective, DERMS is required to manage a group of DERs. The local controllers are required to communicate with each other to achieve uninterrupted operation. With the evolution of the Industrial Internet of Things (IIoT), utility companies are suggesting using lightweight Publish/Subscribe protocols. The proposed system implements a Publish/Subscribe protocol, which requires low-bandwidth communications, and allows more efficient utilisation to the bandwidth serving the data exchange frequency. Description of the protocol is provided in Section (7).

Table 1 Low-bandwidth demanding data exchange model

DG Type	Wind, solar, energy storage, generator…etc.
identifier	Unique IP address within the control subnet/Unique ID
attributes	status, active power, reactive power, bus voltage, frequency, breaker status, commands.

The control system layer is a combination of the distributed controllers, communication lines, and switching/routing devices in between. Communication agent in Fig. 3 handles the data exchange between peer controllers and ensures minimum data loss due to high traffic and network congestion. However, it is tangential to choose the optimal network topology with high connectivity [18]. The proposed system adopts a complete connectivity graph between peer controllers and applies the concept of the consensus cooperative control [9]. Other connectivity graphs are acceptable if the system guarantees more than one path between all controllers. Assuming five DERs in a microgrid, the adjacency matrix A in (1) will be assumed to represent the connectivity between the five DERs. Due to the limitations in space and scope, detailed study of this subtopic will be conducted in future work. The network topology in this case will not affect the overall system reliability.

$$A = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix} \quad (1)$$

3.3 Failure model

Failure model contains aspects that relate to the system reliability and availability. Most importantly, designing a self-healing distributed control system relies mainly on the robustness of the recovery algorithm in the interrupt routine. We propose a failure model for this type of control architectures. Detailed description of this model is in Section 5.

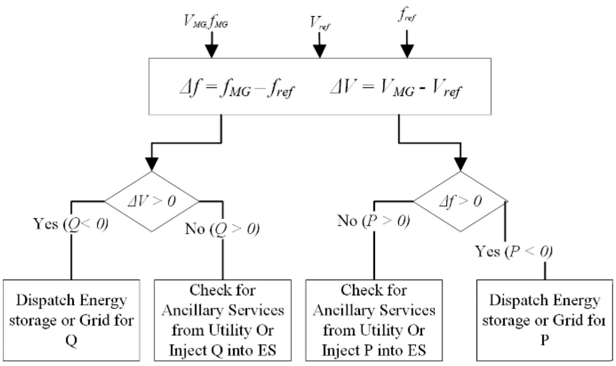

Fig. 4 *Voltage/Frequency deviation and DER dispatch flowchart*

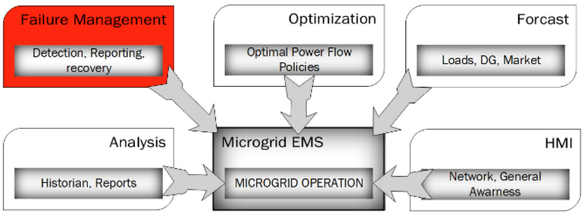

Fig. 5 *Microgrid Energy Management System sources of optimisation data. (Red) is the proposed failure management Unit*

4 Decentralised energy management system

As shown in Fig. 1, the proposed decentralised architecture is a structure of decentralised controllers that has the capability to manage their designated DER. The architecture suggests deploying multiple local controllers to achieve a continuous operation. The control system appears as one central controller. In the proposed architecture, each controller shares the status of its own DER with other controllers in real time. This requires naming scheme that guarantees unique identification of each controller and its local DER (see Table 1). Each controller must have a concurrent status of the overall system, especially for the inputs to the microgrid control algorithm running in each controller. This is a key requirement to protect the integrity of the system from being violated, otherwise, inconsistent algorithm outputs and control commands may arise, which can lead to disturbance in the microgrid operation.

The proposed architecture allows the microgrid to be scaled up or down in terms of the number of power components without affecting the operation or re-engineering the control algorithm. This also includes the recovery process in case of faults and possible redundancy that boosts the reliability of the microgrid [2].

Primary and secondary control layers are coupled into one physical layer. Tertiary control layer will be a responsible for the controller located at the PCC. Each controller must be aware of its peers and their status. This will form general awareness of the microgrid status. Each controller will be responsible of publishing its own data, the peer controllers subscribe to these data points. Renewables are operated using maximum power point tracking (MPPT). Energy storage forms the grid when backup generators are offline.

Assuming a microgrid system with n components, at any time, every local controller C_i should have a consistent general awareness of the overall system, following the equations:

$$P_{\text{net}}|_t = \sum_{i=1}^{n} (e_P P_{C_i}) = 0 \text{ p.u} \tag{2}$$

$$(Q_{\text{net}}|_t = \sum_{i=1}^{n} (e_Q Q_{C_i}) = 0 \text{ p.u} \tag{3}$$

$$V_{\text{Bus}}|_t = e_V V_{C_i} = 1 \text{ p.u} \quad i = 1, 2, \ldots, n \tag{4}$$

$$F_{\text{Bus}}|_t = e_F F_{C_i} = 60 \text{ Hz} \quad i = 1, 2, \ldots, n \tag{5}$$

where e_x is the sensitivity factor to remain in normal operating state, and its value is adjusted according to the system design and the sensitivity level of the decentralised failure management system. P, Q, V, f are active power, reactive power, voltage, and frequency of DER i, respectively. The active and reactive power calculations of the load are performed at each controller based on data updates.

$$P_{\text{load}}|_t = \sum_{i=1}^{n} (e_P P_{C_i}) \pm P_{PCC} \tag{6}$$

$$Q_{\text{load}}|_t = \sum_{i=1}^{n} (e_P Q_{C_i}) \pm Q_{PCC} \tag{7}$$

In this architecture, only the designated controller should be able to command the DER (generator, ES) and its breaker to close. This represents one of the major advantages for the true decentralised control system over the centralised control architecture; as it alleviates the delay consequences in case of a fault by commanding the DER locally. For example, the start command of a generator (before the breaker closes) is governed by the updates from the ES, i.e. State of Charge (SoC) as in (8).

$$\text{NG}^{+}_{\text{cmd}} = \begin{cases} 1, & \text{SOC} < \text{SOC}_\text{L} \cup \text{NG}^{-}_{\text{cmd}} = 0 \\ 1, & \text{SOC} < \text{SOC}_\text{H} \cup \text{P}_{\text{load}|\text{t}} > \text{ES}_{\text{CAP}} \\ 0, & \text{SOC} \geq \text{SOC}_\text{H} \end{cases} \tag{8}$$

where $\text{NG}^{+}_{\text{cmd}}$ is the start command to NG generator and $\text{NG}^{-}_{\text{cmd}}$ is the current command. SOC_L and SOC_H represent the lower and the upper limits of SOC. P_{LOAD} and ES_{CAP} are the actual load active power consumption, and the energy storage capacity, respectively. For the generator case, reconnection to the microgrid bus is delayed due to the synchronisation process, breaker closes when the following synchronisation conditions in (9) are met.

$$\begin{aligned} |f_{\text{NG}} - f_{\text{MG}}| &< 0.05 \text{ Hz} \\ |V_{\text{a\_NG}} - V_{\text{a\_MG}}| &< 0.05 \text{ p.u} \\ |V_{\text{b\_NG}} - V_{\text{b\_MG}}| &< 0.05 \text{ p.u} \\ |V_{\text{c\_NG}} - V_{\text{c\_MG}}| &< 0.05 \text{ p.u} \\ |\delta_{\text{c\_NG}} - \delta_{\text{c\_MG}}| &< 2^\circ \end{aligned} \tag{9}$$

Fig. 4 illustrates the coupling of the primary and the secondary layer (DERMS), while the bus voltage and frequency are monitored for any possible deviations at the primary level, the secondary layer responds to any deviation by dispatching DERs, shedding loads (if any). Since the control system is decentralised, dispatch commands are performed only by the designated controllers, and the rest of the system which are running the same algorithm, use the published status of that controller to intelligently match the updates with the local algorithm output. Examples of such operation are in Section 8.

5 System resiliency

One of the challenges that needs to be addressed in any decentralised or distributed system is the resiliency to any component failure that may occur. To consider a system as a fault-tolerant system, each distributed component must have failure model that contains aspects that relate to system reliability and availability (Fig. 5). Most importantly, designing a self-healing distributed control system relies mainly on the robustness of the recovery algorithm in the interrupt routine.

If the power system fault is detected, the controller moves to system fault handling routine. Based on the status flags which is reported by peer controllers, faulted DER is removed from the dynamic directory of the available DERs. After the fault clears, the controller state goes back to normal operation. Same transitions for detecting communication faults applies to the controller state. The

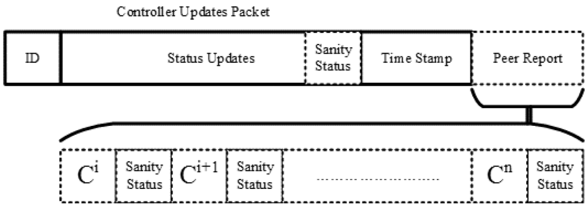

Fig. 6 *Status update packet with proposed peer report technique*

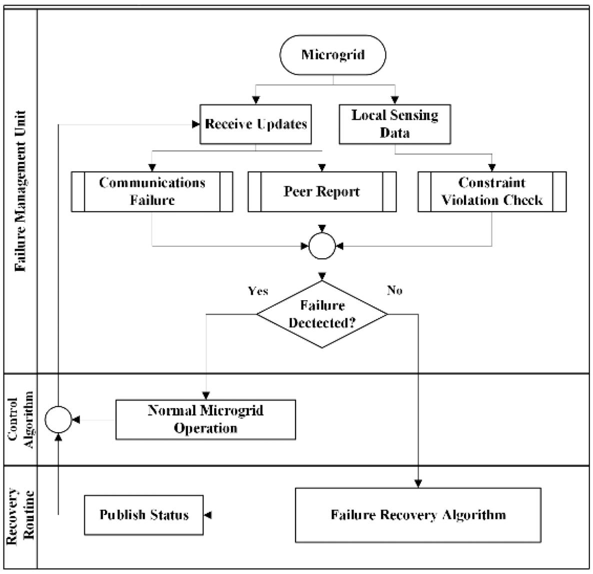

Fig. 7 *Failure detection and response flowchart [19]*

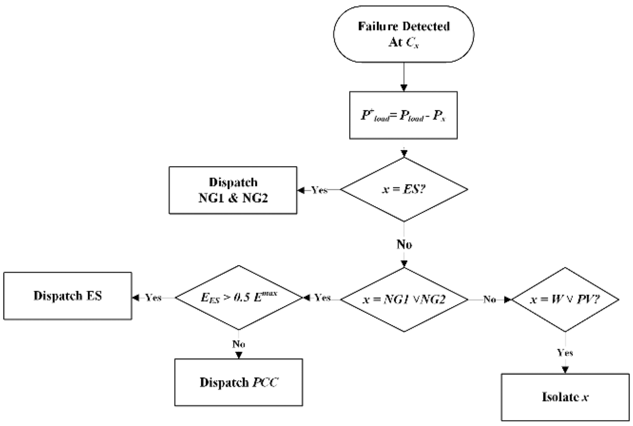

Fig. 8 *Proposed failure recovery algorithm flowchart*

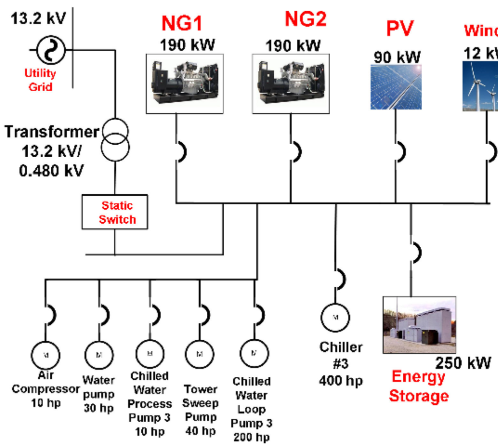

Fig. 9 *Microgrid case study schematic (fort sill microgrid)*

following methods are proposed to achieve the goal of fast system recovery:

5.1 Local sensing

Sensing local microgrid parameters is essential for microgrid operation control. Leveraging the data collected via local sensing, disturbances can be analysed to foresee any possible failures in the system. Voltage or frequency changes are interpreted as a failure in one power component. Assuming a microgrid with n distributed controllers, for a controller C_i at time t, local voltage and frequency sensing are governed by (10) and (11), respectively.

5.2 Communications

Decentralised architecture dictates the presence of a reliable communication network that is connecting all peer controllers. Various communication protocols can be applied to such system. Decentralised controllers are designed to have some level of intelligence, delays and timestamping mismatch can be interpreted as a failure of a controller, which triggers the rest of the system to react accordingly. In TCP/IP [5], the lack of acknowledgment for the three-way handshake with any peer controller can be interpreted as a failure and must be reported.

5.3 Peer reports

We propose a technique for failure detection based on reporting from peer controllers. Since all controllers update their own status and local measurements, a peer report segment as shown in Fig. 6 is allocated to broadcast any detected failure. This overcomes delay of the aforementioned techniques and helps propagate the failure incident among all controllers. This technique speeds up the system fault handling as all controllers are informed about any occurring failures.

6 Coordinated failure management

The system is considered in normal operation when the following conditions are met: (1) Constraint rules are not violated, where the bus voltage and frequency are within limits. (2) Sanity check which is performed locally results a valid condition. (3) Peer reports are all valid stating that all controllers are working properly, and the system is stable. Failure analysis are performed continuously after the updates are received from all peers. In the case of no violations were detected, nor any failure have been reported, the control algorithm maintains at normal operation. If the output from failure analysis and detection is a failure code, the fault handling and recovery takes over and the normal operation algorithm halts [19].

Unlike other EMS operations, failure management is an essential component of the unit commitment algorithm or the economic dispatch function when decentralised control architecture is deployed. At any time t, active and reactive power output of sources and the consumption of loads follows (2) and (3). FMU follows algorithms for failure response and recovery, as illustrated in Figs. 7 and 8.

7 Case study microgrid specifications

The case study for the proposed system is a microgrid that consists of various power components. Renewables (PV, wind), Energy Storage (ES), and two backup natural gas generators. The schematic of the microgrid is shown in Fig. 9. Figs. 10 and 11 show the PV, wind, and load profiles of the test system. At $t = \mathrm{T}$, the instantaneous load power at each controller is calculated using (10), which is derived from (6) and (7) (see Table 2).

$$P_{\mathrm{LOAD}}|_{t=T} = P_{NG1}(T) + P_{\mathrm{NG2}}(T) + P_{\mathrm{ES}}(T) + P_{\mathrm{Wind}}(T) + P_{\mathrm{PV}}(T) \tag{10}$$

Each controller is responsible of managing the output power of the DER, considering the constraints in (11–14). These constraints can lead to economic and environmental optimisation challenges that are out of the scope of this paper.

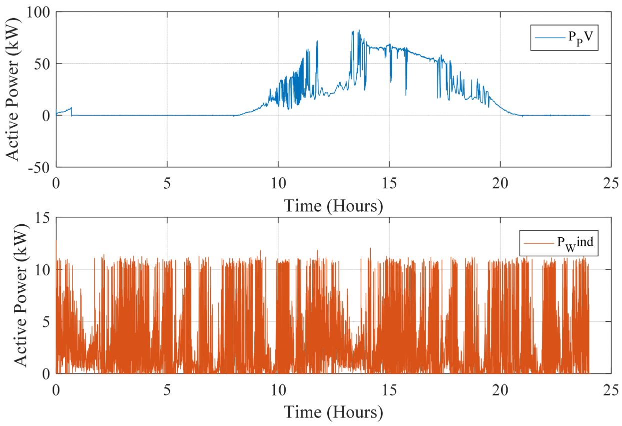

Fig. 10 *Simulated PV(top) and wind (bottom) profiles (24-h profile)*

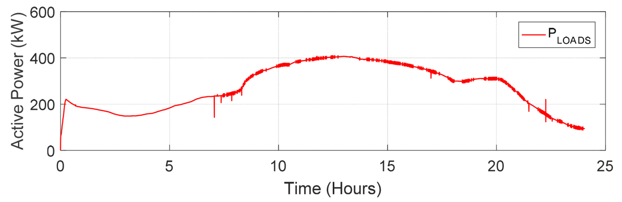

Fig. 11 *Microgrid Load profile (24 h)*

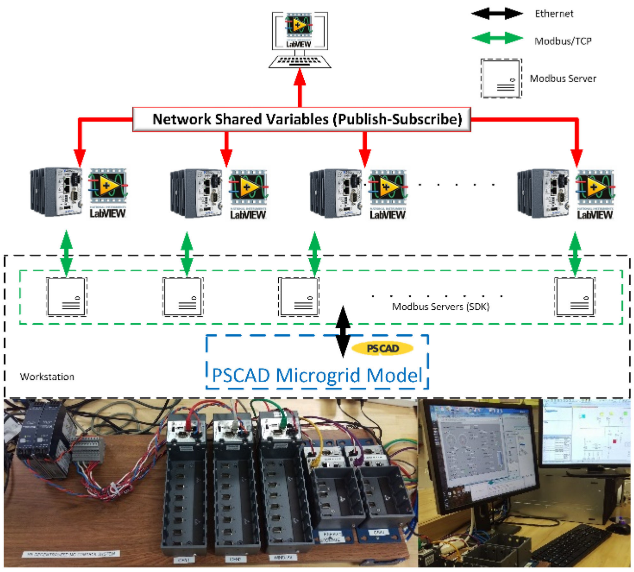

Fig. 12 *Lab experimental HIL setup for decentralised control architecture*

$$P_{\rm NG}^{\min} < P_{\rm NG}(t) < P_{\rm NG}^{\rm rated} \tag{11}$$

$$0 < P_W(t) < P_W^{\rm rated}(t) \tag{12}$$

$$0 < P_{\rm PV}(t) < P_{\rm PV}^{\rm rated}(t) \tag{13}$$

$$\left.\begin{array}{c} P_{\rm ES}^{\min} < P_{\rm ES}(t) < P_{\rm ES}^{rated} \\ E_{\rm ES}^{+} = E_{\rm ES}(t) + P_{\rm ES}(t)\ \Delta t \\ E_{\rm ES}^{+} > E_{\rm ES}^{\min} \end{array}\right\} \tag{14}$$

8 Experimental results

For testing purposes, a Hardware-In-the-Loop (HIL) platform were developed to study microgrid operations with real physical communication layer [11]. Fig. 12 shows the schematic of the platform applying the decentralised control architecture in Fig. 2. Three different experiments were performed in this section: (1) Proof-of concept of a 24-h microgrid operation under a decentralised control system; (2) microgrid transient operations such as intentional islanding; and (3) demonstration of the proposed FMU in the recovery algorithm by injecting a controller failure.

Table 2 Microgrid case study specifications

DER	Symbol	Rated power	Dispatchable
natural gas gen	$P_{\rm NG1}^{\rm rated}$	190 kW	Y
natural gas gen	$P_{\rm NG2}^{\rm rated}$	190 kW	*Y*
energy storage	$P_{\rm Es}^{\rm rated}$	250 kW	*Y*
PV	$P_{\rm PV}^{\rm rated}$	90 kW	*N*
wind	$P_{\rm Wind}^{\rm rated}$	12 kW	*N*

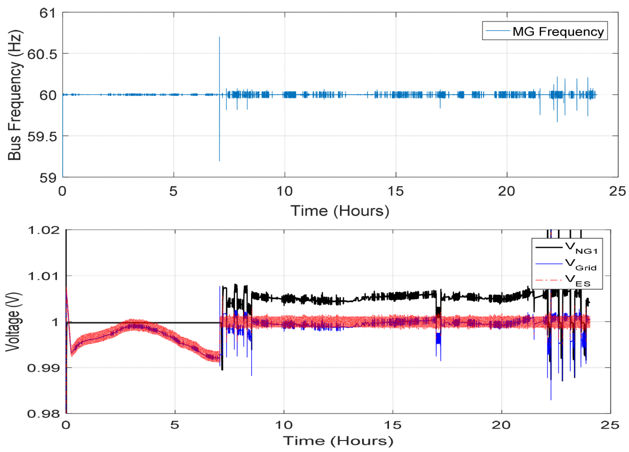

Fig. 13 *Microgrid voltage and frequency profiles over 24-h operation period*

8.1 Microgrid normal operation

Fig. 13 shows the microgrid normal curves over a 24-h period of operation. The microgrid operates in a grid tie mode, where the utility supports the load with the power demand in addition to the PV and wind. NG1and NG2 are not operating at this point, and ES is in standby mode, island mode. At $t = 7.55$ h, an intentional islanding command is issued by the PCC controller. The grid power support ramps down as the energy storage inverter ramps up the output power and forms the microgrid bus during the transition period.

8.2 System transients

Fig. 14 shows active and reactive curves of the microgrid during islanding. System simulation starts with fully charged ES. NG1 and NG2 are off and their breakers are open. The nature of the loads varies with time starting with 60 KW and increasing. ES provides the power to the loads for 16 s the decentralised controller at the ES unit measures 50% SOC remaining on the battery and publishes the update. The controller at NG1 commands to NG1 to start and synchronise with the bus and commands the breaker after 6 s providing 190 KW (NG rated power). Since the load demand is greater than the capacity of NG1, the controller of NG2 detects the current situation and connects it to participate in providing power. Also, the controller of ES detects that NG1 and NG2 are active and switches to charging mode

8.3 Failures and recovery

One of the advantages of using HIL platform is the capability of configuring and injecting failures at the hardware and/or software levels. Failing a controller is performed by powering down the controller or resetting the controller manually. Decentralisation of a control system comes with additional algorithm in response, the algorithm is introduced in Section 6. The responses of the decentralised controllers insure fast transition to a steady state after the failure occurs (see Fig. 15).

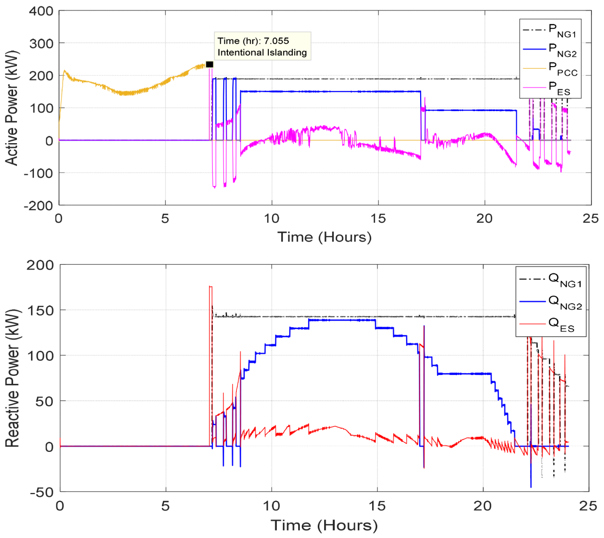

Fig. 14 *Active and reactive power curves over 24-h operation period*

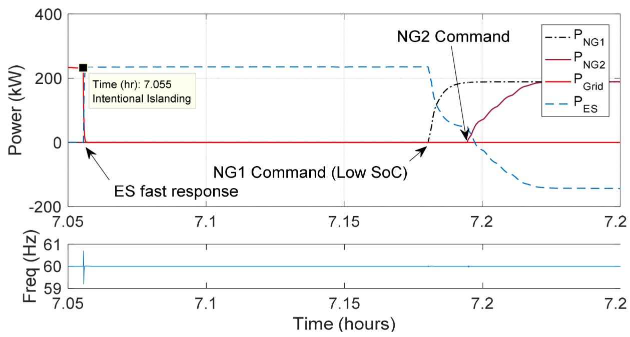

Fig. 15 *Frequency response and system interaction during islanding operation*

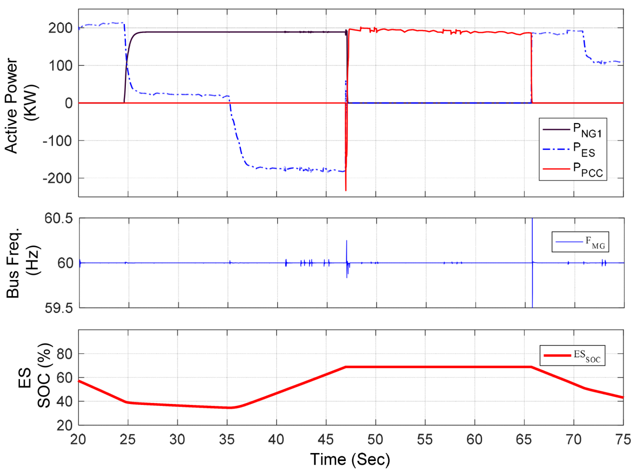

Fig. 16 *Failure management Unit response demonstration, with controller failure*

Fig. 16 illustrates the case for failure of one decentralised controller, the chosen controller for this test is NG1, which could be one of the extremist cases since the generator could be regulating the bus voltage/frequency. At $t = 47.5$, the controller of NG1 fails while both generators are running, and the ES is in charge mode. Two controllers can respond fast to this change, ES controller can command ES to take over, or the PCC controller can command emergency grid connection. For this case, PCC responded since the SOC of the battery is critically low. NG1and NG2 are shut down.

9 Conclusions

Here, a true decentralised control architecture for microgrids is proposed. Distributing the controls to local agents decreases the possibility of network congestions to occur. Decentralisation will also enhance the reliability of the system since the single point of failure is being replaced with a distributed architecture. Three different models have been defined to achieve a complete practical control architecture. The proposed system ensures reliable data exchange between controllers and microgrid components. The control concept does not also require a master or central controller. Load and generation forecasting can be integrated as well as energy storage operation, improving unit commitment, and performance. Future work of this effort includes: accurate modelling of microgrid frequency versus the change in demand and generation and including forecast for DG generation in the controls to increase reliability and improve performance.

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