Experimental rig investigation of a direct interconnection technique for airborne wind energy systems

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A R T I C L E   I N F O

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A B S T R A C T

Airborne wind energy is a new approach to reach the stronger and more consistent winds at higher altitudes. In this paper, the interconnection of pumping mode airborne wind energy systems inside an energy farm is investigated. An experimental rig hardware setup has been designed and built to model an AWE farm in small scale. A direct interconnection system has been developed and examined on the experimental test rig. The direct interconnection technique (DIT) is a new method developed for the interconnection of marine wind energy systems within an energy farm, without requiring offshore-based power electronic converters. DIT relocates power electronic converters from the offshore site to the shore substation by interconnecting marine generators directly to a common bus. This method makes possible significant improvements to the economy and reliability of marine renewable energy systems. In this paper, for the first time, the direct interconnection technique is investigated experimentally for physically emulated pumping mode airborne wind energy systems. The construction of the experimental rig hardware setup is described, and the laboratory test results for the direct interconnection of airborne wind energy systems are presented and discussed.

1. Introduction

Airborne wind energy (AWE) is a high-altitude wind energy system using one or more kites, gliders or horizontal flying turbines tethered to a ground station for energy production. Loyd first reported an analysis of a kite for producing electrical energy from winds in 1980. He modelled a large scale power production using an aerodynamically efficient kite. Loyd showed that a tethered wing as big as a C-5A aircraft is capable of generating 6.7 MW of electrical energy with a 10 m/s wind [16]. Since then, several prototype airborne wind energy systems have been introduced although most of them are still in the research and development stage. Nevertheless, several companies claim that they plan to offer the first commercialised AWE systems by 2020 [25,5]. Airborne wind energy systems provide a cost-effective and feasible technology to harness the wind energy at high altitudes where the wind is stronger and more consistent. AWE systems do not use a static tower and associated civil engineering infrastructure resulting in considerably less capital expenses (CAPEX) and operating expenses (OPEX), particularly for offshore wind energy systems where the price of marine operations and constructions is significantly high. Operation at high altitudes can make a remarkable enhancement in the amount of power generated as the wind power density increases with the cube of the wind speed [1,6]. Accordingly, even a small increase in operating altitude of the wind energy system can make a notable enhancement in generated power. Airborne wind energy systems can reach winds in altitudes from 100 m to 2000 m [5,25] while the highest (hub height) conventional wind turbine is 220 m high [32]. According to Archer et al. [2], at altitudes above 200 m, wind energy devices can provide a high capacity factor at a low cost.

This paper focuses on pumping mode AWE systems. Pumping mode airborne wind energy is a promising AWE technology to reach the winds at higher altitudes. Fig. 1 demonstrates the construction of a pumping mode AWE system. A flying kite or glider is tethered to a ground (or floating) station by a length of high strength, lightweight tether (often Dyneema). The ground station consists of a tether drum coupled to a generator for electrical power production. A complete operation cycle consists of two operation phases, the power phase and the recovery phase. During the power phase, the crosswind flight manoeuvre of the kite or glider provides lift force which causes tether to pay out and rotates the tether drum and generator to produce electricity. When the wing arrives at a set maximum tether length, the AWE system transitions into the recovery phase. In this phase, power is consumed to recover the tether to the initial length. Prototype systems to date often perform this phase by operating the generator as a motor.

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During the recovery phase, the flight controller sets the wing in a low lift flight condition to minimise the power consumption while recovering the tether and the wing. This results in a system where net positive power is generated over a complete cycle of operation; however, this power is non-continuous. The generator reversal process during the recovery phase introduces inefficiency and significant constraints on system operation [8]. Also, the generator reversal process utilises additional expensive four-quadrant power electronic converters with a considerable failure rate [28,33] resulting in higher cost and less reliability. The authors introduce a non-reversing alternative pumping mode AWE system in 2013 [8]. Fig. 2 illustrates the mechanism of the non-reversing pumping mode airborne wind energy system. During the recovery phase, a fractional size electrical motor is connected to the tether drum to return the wing to the initial length of the tether; meanwhile, the generator is decoupled from the tether drum by an overrunning clutch. The non-reversing mechanism eliminates the need for the four-quadrant power electronic converter and allows for optimal machine selection for both the power generation and recovery motor phases. Also, it is more suitable for large-scale AWE systems, and grid-integrated AWE devices due to the faster and more efficient transition between the operating phases.

The gearless direct-drive power-take-off system is the most popular technology for pumping mode airborne wind energy systems. Given that the direct-drive systems operate at low speeds, doubly-fed induction generators (DFIG) and Squirrel cage induction generators (SCIG) are not suitable as they need a gearbox for speed and torque adjustment [21]. Hence, synchronous generators are the best choices for the direct-drive AWE systems. As mentioned above, AWE systems are not always operating in generation mode. For instance, a pumping mode AWE system needs a motor for tether reel-in during the recovery phase of the operation, or a wing-mounted generator AWE system requires a thruster motor at some phases of operation. These AWE systems usually use the same electrical machine to operate as generator and motor. The use of Electrically excited synchronous generators (EESG) is not technically applicable for the generator/motor purposes. EESG machines have a small starting torque in motor applications so that they need assistant start-up systems [13]. Consequently, the permanent magnet synchronous machine (PMSG) is the best option for the direct-drive AWE systems due to the ability of operation in both motor and generator modes. EESG systems can be used in non-reversing AWE systems as a generator, although the PMSG is more popular in this type of AWE systems likewise. This popularity is due to not needing external power supply, brushes and DC-DC power electronic converters for a field excitation system in PMSGs. Induction machines have been utilised in some AWE systems. In [10] a SCIG is employed in a pumping mode AWE system. The machine operates as a generator in the power phase and a motor during the recovery phase. The generator/motor is coupled with a gearbox and a tether drum through a belt drive system. The presented efficiency of the SCIG in this application is 54% [10]. Also, in [31] a 20 kW doubly-fed induction generator /motor is used for a pumping mode AWE system.

Pican and Toal introduced the direct interconnection technique (DIT) in 2011 for marine wind energy systems [20,19,29]. Fig. 3 compares the conventional interconnection approach and the direct interconnection technique. Using DIT, unlike the conventional procedure, offshore generators are interconnected directly in synchronism to the main bus of the energy farm without any power electronic converter. After transmission of the generated power to the shore substation, a shore-based back to back power electronic converter(s) regulate the power in compliance with the grid codes for the grid interconnection. Moving the offshore based power electronic converters to the shore substation could make a remarkable improvement in the economy and reliability of the AWE devices. According to Spinato et al. [28] and Zhao et al. [33], power electronic converters possess a significant rate of failure among the wind turbine subassemblies. Considering the notable rate of failure for power electronic devices and the
high expenses of offshore repair and maintenance operations, DIT can notably decrease the cost of the produced power by marine renewable devices. Also, the elimination of the marine-based power electronic devices and their associated equipment such as capacitor banks and filter banks can result in a smaller offshore substation where the size of the offshore substation is highly influential on the overall cost of the offshore wind energy systems [26]. Moreover, the high accessibility of the shore-based back to back power electronic devices without any weather-window limitation for repair and maintenance can lead to a significant improvement in the reliability of the generated power.

The first investigation on DIT for offshore conventional wind generators has been reported in Pican et al. [19,20]. Coleman et al. [8,6,7] present initial research work for the implementation of a DIT algorithm for offshore AWE systems. The research is followed by Salari et al. [24,23] to develop a comprehensive DIT for marine pumping mode AWE systems considering the in-depth power control, operation and electrical performance of directly interconnected AWE generators under nominal and fault conditions.

This paper presents an experimental investigation of DIT for non-reversing pumping mode AWE systems. The research performed in this paper is the first practical study of DIT for airborne wind energy systems and is the first test rig in literature to model power take-off for scaled pumping mode AWE systems. The hardware setup can emulate pumping mode AWE systems for research applications related to the ground station. The paper starts by describing the construction of the experimental rig hardware setup for modelling of the non-reversing pumping mode airborne wind energy systems. The test bench structure is outlined. A comprehensive DIT system for an AWE farm has been designed and examined on the laboratory test rig. The test results are reported and discussed, and finally, the content of this research work is concluded, and suggestions for further research are presented.

### 2. Experimental rig hardware setup

The laboratory hardware setup emulates a miniature AWE wind farm and consists of three multi-pole permanent magnet synchronous generators (PMSG) coupled with three-phase induction motors (IM) as prime movers. The prime movers simulate the wing and tether manoeuvres as seen by the generators. Variable frequency drives (VFD) control the induction motors as variable speed prime movers. These drives are capable of controlling the motors with different speeds and torques that are necessary for the wing manoeuvre modelling. A high-speed data acquisition and real-time control system is developed to control the experimental rig and implement the various controllers discussed within this paper.

#### 2.1. Electrical system

Fig. 4 illustrates the electrical circuit diagram of the hardware setup. This design provides dump loads (DL) just for G1 and G2. G3 utilises the main load as a dump load. Dump loads are resistive loads providing generator loading before interconnection to the synchronous bus and its main load. After interconnection with the main bus, the control system bypasses the dump loads from the generator terminals and connects the generators to the main load (ML). Table 1 outlines the specifications of the electrical system. G3 is considered as the reference generator for DIT. This means that the DIT controllers consider the voltage and frequency of G3 as the reference values for the synchronisation process.

The utilised VFDs in this research work are single-phase to three-phase 7.5 kW Mitsubishi drives. VFDs can control prime mover motors with different speeds and torques. Variable frequency drives are capable of either V/f constant or vector control methods for the control of induction motors. As the V/f constant method performs with constant torque and variable speed, it is not suitable for emulating the pumping mode AWE systems where both the input torque and speed of the generator are highly variable. Accordingly, the VFDs are configured for vector control. In vector control mode, the VFDs can emulate pumping mode AWE systems with the variable torque and speed profiles of the tethered wing system. Fig. 5 and Fig. 6 show the experimental rig hardware setup.

#### 2.2. Control and data acquisition system

The test rig utilises a National Instruments CompactRIO industrial controller which is composed of a field-programmable gate array module (FPGA), real-time controller and reconfigurable IO modules (RIO). The CompactRIO along with sensors and relays provides the control and data acquisition system for the rig. An Ethernet network provides a link between the CompactRIO and a host PC where LabVIEW codes perform as the user interface system for controlling the test rig and data monitoring.

![Fig. 4. Experimental rig electrical circuit diagram.](image-url)

### Table 1: Electrical specifications of the rig equipment.

<table>
<thead>
<tr>
<th>Generators (G1, G2 and G3)</th>
<th>PMSG, 1.4 kW, 16 Poles, 3 phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>IM, 2.2 kW, 50 Hz, 400 V, 4.96 A, 3 phase</td>
</tr>
<tr>
<td>M2</td>
<td>IM, 1.5 kW, 50 Hz, 400 V, 3.45 A, 3 phase</td>
</tr>
<tr>
<td>M3</td>
<td>IM, 2.2 kW, 50 Hz, 400 V, 4.91 A, 3 phase</td>
</tr>
<tr>
<td>VFDs (VFD1, VFD2, VFD3)</td>
<td>1phase/3phase, 0–1000 V, 0–400 Hz, 0.1–7.5 kW</td>
</tr>
<tr>
<td>Dump loads (L1, L2)</td>
<td>Resistive, 6 Ω, 3 phase</td>
</tr>
<tr>
<td>Main load</td>
<td>Resistive 1.8 Ω, 3 phase</td>
</tr>
<tr>
<td>Power transformer</td>
<td>0–430 V, 50/60 Hz, 3 phase</td>
</tr>
</tbody>
</table>
Fig. 7 illustrates the architecture of the control and data acquisition system. A LabVIEW based control software has been developed and installed on the PC with a Windows operating system. The developed software provides a graphical user interface (GUI) and establishes data transfer between the computer and the CompactRIO for collecting data and passing control signals to actuators. The high speed of data processing is ideal for the synchronisation process as it provides a fast and deterministic data acquisition system for sampling and analysing the generated voltage of the generators. Two interdependent software codes have been developed for the FPGA and real-time processors. The FPGA software contains I/O, data acquisition, basic measurements and calculations that require high-speed processing. Measurements, synchronisation process, controlling VFDs and relays are performed in the FPGA mode. The FPGA intercommunicates with the real-time processor via a Direct Memory Access with a First-In-First-Out topology (DMA FIFO). The second software module has been developed for the real-time process. This software intercommunicates with the FPGA software using the DMA FIFO. The real-time software reads data from the DMA FIFO and sends them to a Windows host PC where the user interface runs. It also acquires the issued command signals by the control system and writes them to the DMA FIFO to pass them through the communication loop to the FPGA. Control loops for frequency control and load sharing control as discussed below, are implemented in the real-time software on the RT processor. Furthermore, the real-time software records the acquired data on a USB flash memory as a Test Data Exchange Stream (TDMS) file format which can be read and analysed later using tools such as Microsoft Excel and MATLAB.

3. Direct interconnection technique for AWE systems

3.1. AWE farm model

Fig. 8 shows the power circuit diagram of the emulated non-reversing pumping mode AWE farm. Three 1.4 kW permanent magnet synchronous generators operate for electrical power production. The generators are mechanically coupled with three-phase induction motors as prime movers. VFDs in collaboration with the induction motors provide the torque profile of a tethered kite. Fig. 9 illustrates the unregulated speed profile of the generators. The sinusoidal oscillations are due to the kite figure-of-eight manoeuvre as shown in Fig. 1. A 55 s delay between the operation of the generators is applied to provide a continuous power. A complete operation cycle for each AWE system is 200 s with the duty cycle of 80%. Due to the lack of recorded experimental data for non-reversing pumping mode AWE systems, it is difficult to emulate the generator speed and torque profile precisely. However, according to [30,12,22,6,31,3,11] the provided speed profile is close to the real speed profile of several prototype pumping mode AWE generators. A directly interconnected AWE generator stays interconnected with the main bus when it operates in the recovery phase. In this situation, the generator performs as a synchronous motor to remain...
synchronised with the main bus. Here in this research, when an AWE unit is in the recovery phase, the stator terminals of the prime mover motor are disconnected from the corresponding VFD via a relay. Given that the induction motors are squirrel cage machines; consequently, there is no source of a magnetic field on the rotor, and the stator terminals of the induction motors are open-circuit during the recovery phase. Thus, the induction motors do not impose any opposing magnetic force on the rotor when an AWE unit is in the recovery phase. Therefore, during the recovery phase, the inertia of the joint shaft between PMSG and the prime mover is the only load for the synchronous motor.

A load sharing controller (LSC) has been developed to control the contribution of each generator in power production. Unequal power generation leads to a circulating current between the interconnected generators and increases power losses within the farm power network [15]. Further, unbalanced power generation may load a generator more than its maximum capacity. In this case, a pole slipping fault is highly probable, causing intensive mechanical and electrical damages [14,4]. As the synchronised generators operate with the same voltages, the LSC uses the generated current by each generator to evaluate the level of load balance in the AWE farm. If the LSC detects any inequality in the contribution of a generator, it tries to regulate the mechanical input power of the generator by controlling the associated VFD. In a real AWE system, the regulation of the input power can be performed by sending command signals to the kite flight controller. Once an AFC or the LSC sends a command signal to the flight controller, it tries to change the input mechanical power of the associated generator by changing the crosswind flight manoeuvre and the wing angle of attack. Here in this work, AWE3 is the primary frequency controller of the farm and therefore it is allowed to generate slightly more or less than other generators to keep the frequency of the farm close to the assigned operating frequency. The diagram of the developed control system for the DIT is presented in Fig. 11. In Fig. 11, $I_{Bus}$, $V_{Bus}$, $f_{Bus}$ and $\theta_{Bus}$ are the current, voltage, frequency and phase angle of the main bus; and $I$, $V$, $f$, $\theta$ are current, voltage, frequency and phase angle of AWE units respectively. $P^*$ is reference power and $f^*$ is reference frequency.

### 3.2. Test results

In this section, the developed DIT algorithm for AWE systems is investigated. Different tests are performed to examine the performance of DIT controllers and AWE generators. The first test considers the operation of the test rig during the synchronisation process. The reference generator, AWE3 is already connected to the main bus and interconnection algorithm. Following the startup of an offline machine, an automatic frequency controller (AFC) regulates the speed and torque of the generator’s prime mover until the frequency of the generator is equal to the operating frequency of the energy farm. Once the AWE system launches the synchronisation process, an automatic synchronisation controller (ASC) compares the frequencies, voltages and phase angles of the generator and the main bus. In the case of any frequency difference between the main bus and the generator, the ASC communicates with AFC to regulate the mechanical torque and speed of the generator. Considering the uncontrollability of the excitation magnetic field in PMSGs and the absence of power electronic converters at the generator terminals there is no possibility for controlling the phase angle. After achieving the frequency and voltage synchronisation criteria, the ASC continuously checks the phase angles, and once they are equal, it sends a command signal to the associated circuit breakers (CB) for interconnection with the main bus.

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AWE1 uses the frequency and voltage of the main bus for the frequency control and synchronisation process. Fig. 12 shows the frequency of AWE1 and the main bus. After 3.40 s AFC1 brings the frequency of AWE1 to the operational frequency of the main bus, i.e. 50 Hz. However, the interconnection of AWE1 is carried out 3.02 s later at \( t = 6.42 \text{ s} \). The delay is due to the synchronisation process accomplished by the ASC. The ASC compares the frequencies and voltages of the main bus and the corresponding unit, and once they meet the synchronisation criteria, the AWE unit is permitted to join the main bus. Fig. 13 shows the voltage signals of AWE1 and the main bus before and after the interconnection. Two voltage signals have the same frequencies and voltage amplitudes although the DIT system must wait until the phase angle difference is zero or very small close to zero. At \( t = 6.42 \text{ s} \) the phase angle difference is small enough, and the two signals are almost overlapped. Hence the ASC1 sends the interconnection command signal to the corresponding circuit breaker and interconnects AWE1 at \( t = 6.42 \text{ s} \). The AFCs consider a 0.3% offset in the unit frequency lower than the main bus frequency as the appropriate criteria to reach the synchronisation moment with a beat (difference) frequency. Without this small frequency offset, two signals with the same frequencies would always keep a constant phase angle difference and a synchronisation moment would never be reached. Frequency and voltage of AWE2 are illustrated in Fig. 14 and Fig. 15 respectively. Figs. 12–15 show that the breaker switching along with the fluctuating torque from the prime mover can cause oscillations in the frequency and voltage of the generators and the main bus at the interconnection moment.

To study the performance of the directly interconnected generators, the authors first present the system without active controllers and then follow with active controllers operable. This allows comparison of performance with and without and also demonstrates the necessity of these controllers for desirable electrical performance of the direct interconnection technique.

Fig. 16 shows the active power of each generator and the total generated power at the main bus. Generated power during the power phase is positive, and the power consumed by the generator during the recovery phase is negative. As mentioned before, during the recovery phase a directly interconnected synchronous machine operates as a synchronous motor synchronised with the main bus.

In Fig. 16, the load sharing control is not implemented. In the beginning, AWE3 is interconnected to the main bus feeding the main load. AWE3 is also considered as the main generator of the farm for the synchronisation process of the other generators. At \( t = 3.2 \text{ s} \) and \( t = 52.1 \text{ s} \), AWE2 and AWE1 join the main bus although a few seconds after the synchronisation, at \( t = 53.1 \text{ s} \), AWE2 operation is switched to the recovery phase. AWE2 consumes about 125 W power when it is in the recovery phase. Over this time, the main generator (AWE3) and the other interconnected power-phase generator (AWE1) are in charge of providing power for the main load and the recovery phase unit. As the generators are similar, it is expected that they divide the load equally between themselves although the presented results in Fig. 16 shows an unbalanced load sharing between the generators. With the transition of AWE2 to the recovery phase, AWE1 starts to increase its generated power to about 1050 W while AWE3 declines its contribution to 800 W approximately. The main cause of the 250 W load imbalance can be justified by Millman’s Theorem [18]. According to Millman’s theorem, as the paralleled synchronous generators have a natural tendency to stay synchronised, any small voltage difference between the generators can result in a considerable current inconsistency and consequently an unbalanced load sharing. This poor load sharing can increase the risk of a pole slipping fault by overloading the generators [14,4]. Moreover, the circulating current can heat up the windings of the generators and can cause false operation of the overcurrent protection system [17]. The poor load sharing can also be observed when all generators are in the power phase. For illustration, between \( t = 233.8 \text{ s} \) and 238.6, when AWE units are in the power phase; AWE1 generates about 530 W while AWE2 and AWE3 generate about 335 W and 830 W respectively. Despite the variable and periodic power production of the individual AWE
units, the generated power at the main bus is continuous and approximately constant. However, at the operational phase transition times, power oscillations can be observed. These oscillations are due to load variations as a result of the changes in the number of generation units and the login/out of a synchronous motor (recovery phase AWE).

Considering the nominal power of the main load is 1700 W and the nominal phase voltage is 32 V, according to Fig. 16, the maximum power oscillation at the operational phase transition moments is ±380 W which is 22.35% of the nominal power.

Fig. 17 shows the main bus frequency without load sharing control. The operating frequency is 50 Hz. At the start when just AWE3 is connected to the main bus, its automatic frequency controller (AFC1) controls the frequency properly around 50 Hz by regulating the input mechanical torque of the generator. In Fig. 17 up to 1.08% fluctuations around the operating frequency are evident because of the oscillating mechanical input torque and velocity of the AWE generators. After the synchronisation of the other units to the main bus, the frequency is appropriately maintained around the operating frequency by AFCs even when an AWE unit is in the recovery phase. Similar to power, when an AWE unit is switched between the operational phases, temporal fluctuations occur as a result of the variations in the power system topology. The maximum temporary frequency oscillation is 2.99 Hz which is about ±6% of the nominal frequency. Frequency variations particularly low-frequency oscillations can threaten the power system stability [27]. These oscillations must be kept small as far as possible to keep the transient stability of the generators at the operational phase transition moments. In electrically excited generators, the frequency oscillations are controlled through a high-speed excitation system while in permanent magnet synchronous generators the excitation system is not controllable [27]. Later in this paper in section 3.2.2, it is shown that the implementation of a load sharing controller is helpful for the reduction of the frequency oscillations.

The root-mean-square (RMS) phase voltage at the main bus without LSC active is shown in Fig. 18. After the synchronisation of all AWE units to the main bus, the voltage is changing in the range of 31.40–32.50 V. Due to the expected oscillating incoming speed and torque profiles from the AWE prime movers, it is not possible to achieve a perfectly flat RMS voltage profile. Of course, detailed investigation of what generator shaft mechanical input profiles are possible is
dependent on the AWE flying system design, operation and real-time control and are beyond the scope of work in this paper that focuses on electrical power integration for AWEs. Based on this experiment run with assumed input profiles, the maximum temporary voltage fluctuation at the operational phase transition times is approximately ±14%. Due to the uncontrollability of the excitation magnetic field in permanent magnet generators and the absence of power electronic converters in the offshore field with DIT, it is not possible to control the voltage fluctuations at the main bus. Voltage variations are highly associated with the variations in the load, hence controlling the shared load between the generators can be useful in reducing voltage oscillations.

Fig. 19 illustrates the RMS current at the main bus delivered to the main load. In Fig. 19 the LSC is not active. As can be seen, the main bus current is continuous and approximately constant although, due to the oscillating torque from the prime movers, it is variable within the range of 17.43–18.11 A. Temporary fluctuations happen when a main bus interconnected unit changes its current operational phase. Given that the nominal voltage is 32 V, the nominal current of the main load is 17.77 A. According to the presented results in Fig. 19, the temporary current oscillations at the main bus can rise to ±9.3% of the nominal current. These temporary current oscillations are not desirable, particularly when they happen regularly every time that a unit is in the operational phase transition. The temporary changes in current can cause rapid voltage overshoots in inductive equipment such as power transformers and generators [9]. This is more critical for big power transformers and generators since they have a large inductance causing a significant voltage overshoot. The voltage overshoot is harmful to the power system components by increasing the voltage stress on their insulation system [9]. The regular occurrence of the voltage overshoots in the directly interconnected AWE farm causes persistent periodic voltage stress on the energy farm equipment which can negatively affect their standard performance and lifespan. Accordingly, voltage and current overshoots must be controlled for better performance of the directly interconnected AWE energy farm.

Fig. 20 illustrates the generated power at the main bus and the contribution of each unit to the power production when the load sharing controller is implemented. AWE3 is directly interconnected to the main bus and AWE2, and AWE1 join the main bus at t = 7.10 s and t = 7.80 s. Power at the main bus is continuous and flat although up to 5% consistent fluctuations around the nominal power (1700 W) are inevitable as a result of the oscillations in the input power from the prime movers. Implementation of the load sharing controller significantly reduced the temporary power oscillations at the operational phase transition times. With LSC active, the maximum power spike when a unit is in the operational phase transition is 11%, while without LSC active it is 22.35%.

Thanks to the LSC a proper load balance is evident in Fig. 20 although due to the power oscillations from the prime movers, and the AWE3 authority as the pilot generator to generate more for the frequency control of the AWE energy farm, it is not possible to achieve 100% equal load sharing. For instance between t = 33 s and t = 73 s when AWE1 is in the recovery phase, the generated power by AWE2 is
about 800 W, and AWE3 generates 950 W approximately. It means that AWE2 and AWE3 contributions during this term are about 46% and 54% respectively. Also, between $t = 164$ s and $t = 187$ s when all units are in the power phase, the share of AWE1, AWE2 and AWE3 is 32%, 32% and 36%. Table 2 compares the contribution of each generator during various operational situations of the energy farm. As can be seen in Table 2, AWE2 and AWE3 always have the same contribution while the AWE3 contribution can be up to 8% more than other generators.

Fig. 21 illustrates the AWE farm frequency at the main bus with the load sharing controller active. As mentioned before, the operating frequency is 50 Hz. It can be observed that despite the fluctuating mechanical power and speed from the prime movers (kite and tether drum emulators), AFCs can control the farm frequency close to the operating frequency. The frequency of the farm oscillates up to ± 1.72 Hz at the operational phase transition moments which is 3.44% of the operating frequency. Compared to the main bus frequency without LSC where the temporary frequency fluctuations at the operational phase transition moments rise to ± 6%, a 71.33% improvement is obtained.

The RMS voltage and current at the main bus with the LSC active are illustrated in Fig. 22 and Fig. 23 respectively. The generated voltage fluctuates in the range of 2.5% around the nominal value of 32 V although, when an AWE unit changes its operational phase, it may jump or drop up to 6%. Compared to the main bus voltage without the LSC a notable improvement in the main bus voltage is achieved. With the LSC active, the maximum temporary voltage fluctuation range at the operational phase transition moments subsides from ± 14% to ± 6%.

Fig. 23 shows a significant improvement in the generated current at the main bus with the LSC active. The maximum value of the current temporary fluctuations at the main bus has decreased from the maximum value of 9.3% without the LSC to 6.7% with the LSC active. This 27.95% improvement in the current fluctuations at the operational phase transition times can result in less thermal and electrical stress on the energy farm equipment.

Table 3 compares the variations in the main bus parameters before and after the utilisation of the LSC. According to Table 3, the load sharing control, in addition to reducing the circulating current between the generators can significantly improve the temporary fluctuations in the main bus parameters resulting in more reliability and less thermal and electromagnetic stress on the power network equipment such as power transformer, generators and cables. Despite the significant improvement in the quality of the generated power by the directly interconnected AWE generators with the LSC active, it is not yet suitable for grid interconnection. Accordingly, before grid interconnection, the utilisation of a power electronic converter is necessary to achieve smooth power.

When a directly interconnected generator is in the recovery phase, it exchanges reactive power with other generators to stay synchronised with the main bus. This reactive power can reduce the efficiency of the system by causing a circulating reactive current between the recovery phase generator(s) and other generators. Fig. 24 and Fig. 25 investigate the reactive power of the directly Interconnected AWE generators without and with LSC active. In Figs. 24-25 and Table 4, lagging and
leading power factors are indicated by “+” and “-” respectively. The LSC does not control the reactive power although Figs. 24 and 25 show that the load sharing control can improve the reactive power exchange inside the AWE energy farm. According to Fig. 24 when an AWE unit is in the recovery phase, it exchanges a significant amount of leading reactive power with other AWE units interconnected to the main bus. For instance, during the AWE2 recovery phase, AWE2 exchanges about 700 VAR leading reactive power with AWE1 and AWE3. Approximately the same amount of reactive power is exchanged when the other AWE units are in the recovery phase. Comparing Fig. 24 and Fig. 25 shows that maintaining the load balance in a directly interconnected AWE farm by LSC can considerably improve the amount of reactive power exchange. In Fig. 24 the maximum exchanged reactive power when a unit is in the recovery phase is 693 VAR while in Fig. 25 with LSC active it is 211.3 VAR.

Table 4 shows the average power factor of the directly interconnected AWE units during the different operating modes with and without the LSC active. The power factor of AWE1 when it is in the recovery phase is 0.28 leading and 0.38 leading without and with LSC active respectively. AWE2 power factor during the recovery phase is 0.23 leading without LSC and 0.31 leading when the LSC is operated. AWE3 shows the smallest recovery phase power factor of 0.13 leading although with the LSC this power factor has been improved to 0.33 leading. Table 4 indicates that within a directly interconnected AWE farm, the recovery phase operation of an AWE unit can be also destructive for the lagging power factor of the power phase AWE units. Nevertheless, the implementation of LSC can clearly decrease this negative effect of the AWE recovery phase in a DIT configuration.

However, controlling the load balance using LSC can improve the reactive power operation; still, the improved reactive power is not yet at a satisfactory level and further reactive power control and compensation strategies must be implemented. The authors have already suggested a solution for DIT reactive power compensation using computer simulation models in a prior work, [24]. More experimental studies for reactive power control of the DIT will be carried out and reported in future work.

4. Discussion and conclusion

An experimental rig hardware setup is used to investigate DIT for AWE systems. A DIT algorithm has been designed and implemented. For the implementation of the algorithm, several controllers including the automatic synchronisation controllers, the automatic frequency controllers and a load sharing controller have been developed. The DIT algorithm is examined on the hardware setup, and test results are discussed. The results prove the practicality of the DIT for pumping mode AWE systems. The critical challenge for the implementation of DIT for AWE systems is the interaction of the recovery phase AWE(s) with the main bus and other generators. Theoretically, it was anticipated that during the recovery phase the directly interconnected AWE unit operates as a synchronous motor to maintain synchronism with the main bus. The test results have confirmed the theoretical expectations for the operation of the directly interconnected generator during the recovery phase. The results also show that the transition from the power phase to the recovery phase and inverse causes significant temporary oscillations in the frequency, voltage, current and power of the AWE energy farm.
However, the temporary oscillations considerably subside with the implementation of a load sharing controller. Unbalanced distribution of the load between the directly interconnected generators can also result in a significant circulating current between the generators negatively affecting the reliability and efficiency of the energy farm power network. A reactive power and power factor study show a significant undesired reactive power exchange and a reduced power factor when a directly interconnected AWE generator is in the recovery phase. This reactive power exchange reduces the active power capacity of the energy farm and increases the farm power losses via a circulating reactive current between the interconnected AWE units. The test results show the implementation of a LSC improves the reactive power performance of the AWE units although it is still far from the desired performance.

Despite the clear benefits, the use of LSC can introduce some additional complexity to the system which is now discussed. As the AFC

<table>
<thead>
<tr>
<th>Power phase</th>
<th>Recovery phase</th>
<th>AWE1</th>
<th>AWE2</th>
<th>AWE3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWE1, AWE2, AWE3</td>
<td>-</td>
<td>32%</td>
<td>32%</td>
<td>36%</td>
</tr>
<tr>
<td>AWE2, AWE3</td>
<td>AWE1</td>
<td>0%</td>
<td>46%</td>
<td>54%</td>
</tr>
<tr>
<td>AWE1, AWE3</td>
<td>AWE2</td>
<td>48%</td>
<td>0%</td>
<td>52%</td>
</tr>
<tr>
<td>AWE1, AWE2</td>
<td>AWE3</td>
<td>50%</td>
<td>50%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Fig. 19. Main bus current without the LSC.

Fig. 20. Generated power at the main bus with the LSC active.

Fig. 21. Frequency at the main bus with the LSC active.
and LSC both regulate the input torque of the generator, the LSC can increase the complexity of the prime mover controller (flight controller) so that improper harmony between AFC and LSC might lead to destructive oscillations in the generated power by the generators. Considering one generator as the pilot generator for the frequency control which is exempted from the load sharing control is highly helpful for avoiding the inconsistency between the controllers. Further, fast regulation of mechanical torque and speed in response to the alternation of the operational phase can result in high-frequency transient oscillations in the main bus frequency and the other electrical parameters. Accordingly, proper tuning of the controllers and the implementation of the rate and amplitude limiters at the output of the LSC and AFC controllers are essential.

The fluctuating power from the prime mover potentially inherent in AWE is another challenge for the implementation of DIT for AWE systems. DIT synchronises a generator at equal frequency, voltage and load angle with the main bus. Fluctuations of the incoming power from the prime mover make it tricky to find the exact moment for the synchronisation. After synchronisation, frequency controllers are in charge of maintaining the farm frequency around the operating frequency. The results show that despite the fluctuating speed and torque from the prime movers and the transitory shocks to the system at the operational phase transition times, frequency controllers can control the main bus frequency within an acceptable range around the operating frequency.

The experimental test results of DIT prove the practicality of the direct interconnection technique for pumping mode AWE systems. It is shown that by the implementation of proper controllers this technique is entirely feasible for AWE systems. The results show that the generated electrical power is irregular such that it is not suitable for direct grid integration. Hence, the use of a power conversion station before the grid interconnection point is necessary to covert the generated power in compliance with the grid operation codes. This project at this stage focuses on the implementation and analysis of DIT for AWE devices inside an energy farm. In this regard, the directly interconnected generators are connected to a three-phase resistive load to dump the

![Voltage at the main bus with the LSC active.](image1)

![Current at the main bus with the LSC active.](image2)

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Temporary variations in the main bus parameters without and with the LSC.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without LSC active</td>
<td>With LSC active</td>
</tr>
<tr>
<td>Amplitude</td>
<td>% of the nominal value</td>
</tr>
<tr>
<td>Max. power variations</td>
<td>380 W</td>
</tr>
<tr>
<td>Max. frequency variations</td>
<td>2.99 Hz</td>
</tr>
<tr>
<td>Max. current variations</td>
<td>1.65 A</td>
</tr>
<tr>
<td>Max. voltage variations</td>
<td>4.48 V</td>
</tr>
</tbody>
</table>
generated power by the farm. In future work, research will analyse the performance of the directly interconnected AWEs when they are integrated into a grid emulator with an analysis on the grid dynamic load interaction through a power electronic converter. Furthermore, the poor reactive power operation of the directly interconnected generators show the necessity for the development and testing of a reactive power control system in future experimental studies.

**CRediT authorship contribution statement**

**Mahdi Ebrahimi Salari:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Joseph Coleman:** Conceptualization, Writing - review & editing, Supervision. **Cathal O’Donnell:** Writing - review & editing. **Daniel Toal:** Supervision, Writing - review & editing, Project administration, Funding acquisition.

**Declaration of Competing Interest**

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