Direct Interconnection of Offshore Airborne Wind Energy Systems

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Abstract

In this paper, direct interconnection of offshore pumping-mode AWE systems has been investigated. Direct interconnection is an approach to reduce the installation of power electronic sub systems in the field because of the high expenses of repair and maintenance for offshore systems. An offshore AWE park with three units has been modeled and simulation results and discussion are presented.

Keywords- Offshore Airborne Wind Energy (AWE), Direct Interconnection, Permanent Magnet Synchronous Generator (PMSG).

I. Introduction

In conventional offshore wind energy, the maximum height of a turbine is limited by technical and economical limitations. Offshore airborne wind energy systems are an innovative way to harness the winds at higher altitude, allowing greater electrical energy generation. Owing to the high expenses of maintenance for offshore plants, reliability and cost are two important factors in designing a power system to transmit offshore generated power. In offshore AWE devices, unlike steam or gas plants, the prime mover is not readily dispatchable and generated power and electrical frequency vary with the wind. Power converters are often used but they are expensive and because of long distances from the shore, the repair and maintenance expenses are very costly. In this paper direct interconnection of offshore AWE systems without individual offshore power converters has been investigated.

II. Airborne Wind Energy

An airborne wind energy system may consist of a kite, glider or horizontal wind turbine which is connected to ground through a tether and is flying freely in the air [1]. The first study for airborne wind energy has been done in 1930 in California USA though the first attempt to produce electricity from airborne wind energy might be an installed device in Northfield, Minnesota. A generator was installed on a balloon and was capable of producing 350W electrical power [2].

Since the first attempts many different AWE power systems have been investigated and tested. Windlift developed 12kW AWE system which utilizes a 40m^2 airfoil and is tethered by a ground electrical power take off station [3]. A 30kW prototype has been tested by EnerKite. This prototype has been driven by a three line ground actuated kite power system [4]. A 12kW prototype has been built by Ampyx Power in 2013. This system used a glider aircraft with a rigid wing which was tethered to a ground station. The use of a rigid wing in this approach increases the aerodynamic efficiency, meaning this system can provide the same mechanical power with a smaller wing area in comparison with soft wing AWE system. Using glider aircraft also simplifies the control challenge [5]. The electrical power take off for the Ampyx Power prototype is a single direct driven electrical machine which is connected to grid through a power converter [6]. Makani Power has tested two 10kW and one 30kW rigid wing AWE systems which utilize high voltage brushless DC motor/generators mounted on the wing [7]. A rotorcraft AWE device is under development by SkyWindPower. This system consists of a quad rotorcraft, which can use electrical power to reach the appropriate altitude for operation. It then inflects itself to the wind at a specific angle to allow the rotor to be driven by the wind, consequently generating power from the wind [8]. The use of an airborne horizontal turbine is another approach for harnessing wind energy at high altitudes. Altaeros Energies introduced a horizontal buoyant turbine which is capable of operating at 600m [9]. In this system an airborne turbine is installed within a duct formed by a helium-filled balloon like structure. The system is tethered to a ground station and the generated power is transmitted through the tether at high voltage. No performance or testing data is provided by the company. In TU Deft, University of Limerick, KU Leuven, Politecnico de Torino, University of Sussex, and Swiss Kite Power prototypes have been developed and are under investigation [5].

In this paper an offshore AWE farm has been modeled, consisting of three pumping mode AWE systems which are using tethered flying wings. In the developed system, a pumping mode AWE system uses a tethered wing flying in a crosswind pattern. The wing is connected to a ground station which is mechanically hauled by the wing. The ground station consists of a tether drum, a clutch, and electrical motor and synchronous generator, connected to each other through a common shaft. The mechanism of pumping mode airborne wind energy system has been demonstrated and is shown in figure 1[1, 5]. The operation of the airborne system has two phases, a power haul out phase and a tether/kite recovery phase. The combined cycle is called a pumping-mode cycle. A kite is the prime mover of the system and produces lift and hence tether tension from the cross wind flight motion. The kite is controlled by a control pod tethered to the ground station. During the power phase, mechanical power is delivered to the power take off system by the overrunning clutch. This clutch is on the generator side of the tether drum and thus bypasses the generator during the recovery phase, allowing tether drum reversal powered by electrical motor without reversal of the generator.

III. Direct Interconnection of offshore AWEs

Direct interconnection is a new approach to dispatch generated power to shore with less use of intermediate power electronic devices, which is especially applicable to offshore energy. In figure 2(a) the conventional method for transmitting offshore energy is demonstrated. In this approach the output power of each unit is changed to DC within a power converter and recovered to gird compliant AC.

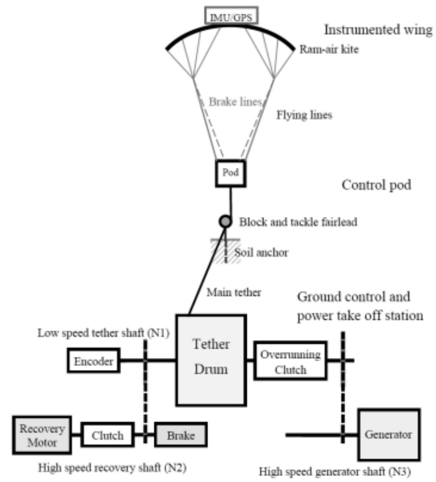


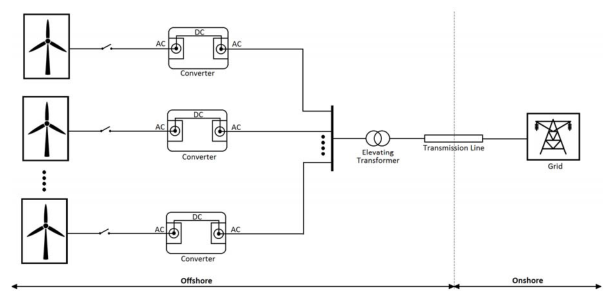
Fig1. Pumping-mode airborne wind energy system, with non-reversing generator [1, 5]

Generated power is dispatched to on shore station using submarine AC cable. Because of high expenses of offshore systems this methodology is very expensive from a maintenance, repair and availability perspective [10].

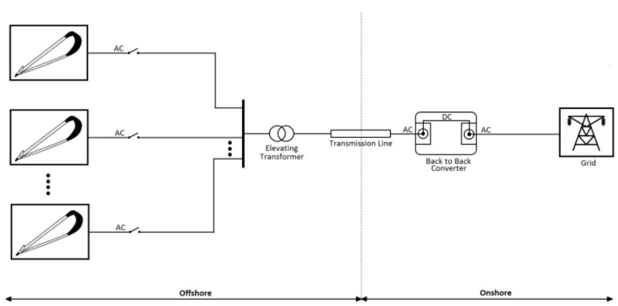
Figure 2(b) shows the proposed approach for direct interconnection of offshore AWE devices. In this system the power converters are removed from the offshore environment and all of the units are electrically interconnected to each other directly via breakers. Generated power is transmitted to shore through an underwater ac line. A back to back power converter is used at the onshore station to adjust frequency and voltage for interconnecting with the grid. Onshore the power converter is removed from the harsh marine environment and is easily serviceable, without vessel deployments and weather window delays.

Synchronization and controlling voltage are two main challenges in dealing with direct interconnection of airborne wind energy devices. The AWE devices in this paper use permanent magnet synchronous generators. The synchronization algorithm has been explained in figure 3. After launching the synchronization process, to interconnect an offline unit to the bus, at first the synchronizer system compares the frequency of offline unit with bus frequency. If the frequencies are equal, the synchronizer will go to the next stage, checking the amplitude and phase of the unit's voltage. If these parameters are not correct, the synchronizer will send a signal to the kite control system to change the tether speed in order to change the electrical frequency and voltage phase and amplitude. The kite control system is similar to the pitch controller of conventional wind turbines. This controller is trying to control input power and torque of the AWE system by changing the maneuvers and lift profile of the kite [5].

After finding voltage phase and amplitude compliant with bus the synchronizer system will send an operation signal to the unit's breaker to interconnect it with bus.



(a)



(b)

Fig2: Interconnection of offshore devices,
(a) Conventional approach, (b) Proposed approach

Another challenge in dealing with direct interconnection of offshore AWE devices is voltage drop after synchronization. As mentioned, the operation of pumping-mode AWE has two phases. For a synchronized AWE device in the kite recovery phase it will still be synchronized with the other units on the bus but will behave as a motor instead of generator. In this situation the reversing AWE system will be seen as a dynamic load to the bus and it will cause a voltage drop in the bus. A voltage controller has been designed to monitor voltage dynamically and in the case of any voltage drop this controller increases the input toque of the other units by sending signal to the relevant kite controllers.

Pole slip is another concern for direct interconnected AWE devices. In the motoring condition if the load angle of the machine exceeds 90□ the rotor will start to accelerate and it will rotate faster than the magnetic field of the armature. This condition is called "pole slip" and will lead to damage to the machine. To prevent this condition a controller monitors the load angle and if it is going to exceed the maximum value, that synchronous machine must be disconnected from the bus if it is not possible to reduce the load. However, the overrunning clutch ensures no significant load is present during the motoring condition, minimizing the load angle.

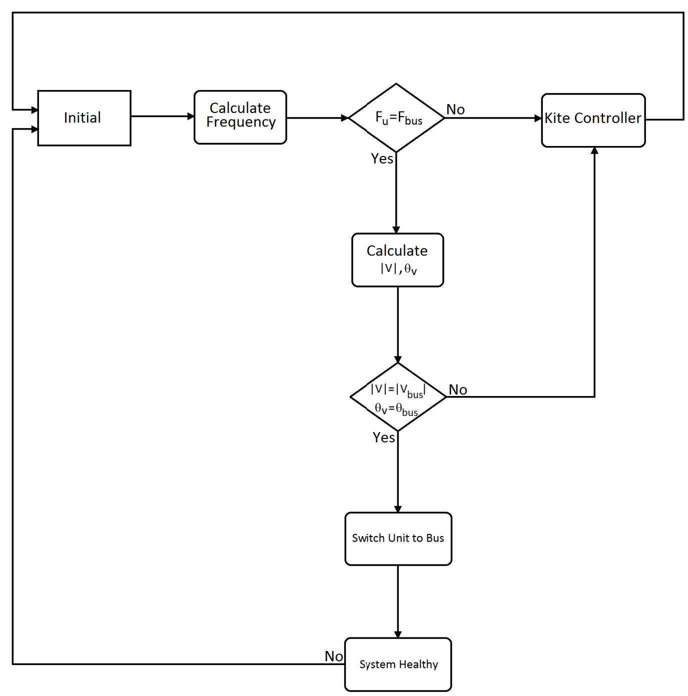


Fig3: Synchronization Algorithm

IV. Modeling and Simulation

The offshore farm model used in this analysis is illustrated in figure 4. This system consists of three pumping mode AWE units. Each unit utilizes permanent magnet synchronous generators (PMSG) to produce electrical energy. The first unit is considered as a reference for synchronization. Each unit is feeding a dump load (DL) while reaching synchronization criteria and after synchronization, joins the farm bus feeding the main load (ML) (i.e. the power converter onshore). In the case that the farm is stopped entirely, the generators may be directly connected together without requiring synchronisation.

A. Tethered wing modeling

In a simplified aerodynamic model of an AWE system, the nominal mechanical power produced is given by (1) [1,5].

$$P_m = F_t V_t \tag{1}$$

The lift and drag forces produced by tether tension are calculated by (2), (3).

$$L = \frac{1}{2}\rho S C_L V_a^2 \tag{2}$$

$$D = \frac{1}{2}\rho S C_D V_a^2 \tag{3}$$

Where in (1)-(3) F_t is tensile force, V_t is tether velocity, L and D are lift and drag forces, C_L and C_D are the coefficients of lift and drag of the wing, ρ is the density of air, S is the area of wing and V_a is the air speed.

The resultant aerodynamic force vector during steady flight is:

$$R = \sqrt{L^2 + D^2} \tag{4}$$

Similarly, the resultant aerodynamic coefficient is:

$$C_R = \sqrt{C_L^2 + C_D^2} \tag{5}$$

If we assume that the wing is in crosswind motion perpendicular to the wind vector and neglect the weight of wing according to [11], if L/D is large then V_a can be described as:

$$V_a = (V_w - V_d)E \tag{6}$$

Where V_w is wind speed, V_d is downwind velocity of the wing and E is the lift to drag ratio (L/D).

V_d of the wing is determined by tether velocity V_t and tether angle of elevation θ:

$$V_d = V_t cos\theta \tag{7}$$

As outlined in figure 5 the tensile force F_t is:

$$F_t = \frac{1}{2}\rho S C_R (V_w - V_d)^2 E^2 \tag{8}$$

Then the mechanical power produced by the wing will be:

$$P_m = F_t V_t = \frac{1}{2}\rho S C_R (V_w - V_d)^2 E^2 V_t \tag{9}$$

According to [11] at the power optimal, downwind velocity of wing is one third of wind speed:

$$V_d = \frac{V_w}{3} = V_t cos\theta \tag{10}$$

At the speed ratio given in (10) force and mechanical power produced by wing are calculated by:

$$F_t = \frac{2}{9}\rho S C_R V_w^2 E^2 \tag{11}$$

$$P_m = \frac{2}{27cos\theta}\rho S C_R V_w^3 E^2 \tag{12}$$

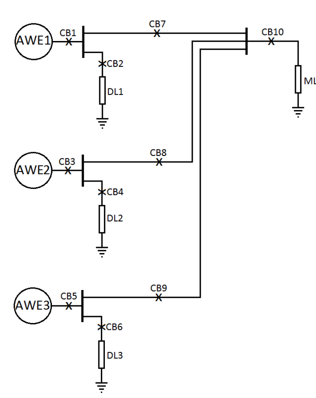


Fig4: Modeled Offshore AWE farm

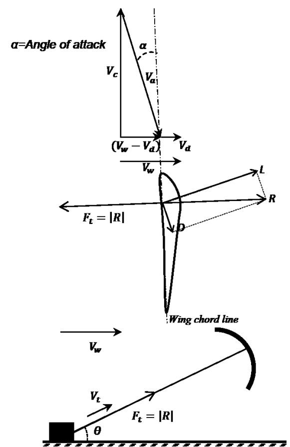


Fig5: Aerodynamic Forces during crosswind flight [1, 5]

B. Power Takeoff Model

In pumping mode AWE the kite is tethered to the ground station. The produced mechanical force by kite is delivered to the ground power take off system through the tether. The tensile force produced by interaction of kite and the wind drives the tether drum which is connected to the PMSG for electrical power take off.

The speed of tether drum relates to the tether speed by (13) [5].

$$V_t = r.\omega_d \tag{13}$$

Where ω_d is angular velocity of the tether drum. The mechanical torque produced on the tether drum due to tether tension is calculated by:

$$T_m = F_t.r \tag{14}$$

Since, the tether drum is connected directly to generator the velocity of generator rotor is equal to drum velocity:

$$\omega_d = \omega_r \tag{15}$$

The differential equation governing the system speed is given by:

$$T_m - T_e - B\omega_r - T_f = J\frac{d\omega_r}{dt} \tag{16}$$

Where T_e is the generator electromagnetic torque, B is the combined viscous friction coefficient of generator rotor and drive, T_f is the drive friction torque and J is the combined inertia of generator and drivetrain.

C. Permanent Magnet Synchronous Generator Model

It is considered that PMSG is a round rotor machine. The electromagnetic force of generator is defined in rotor dq reference frame [12] as:

$$T_e = \frac{3}{2}\, n_p.\psi_{PM}.i_{sq} \tag{17}$$

Where n_p is number of pole pairs, $\psi_{PM}$is the flux linkage produced by magnets and i_{sq} is the stator current in the dq reference frame. The induced internal voltage in stator windings of PMSG is given by (18).

$$|E| = 2\pi.f_e.\psi_{PM} \tag{18}$$

In (18) f_e is electrical frequency and is related to rotor velocity by (19)

$$f_e = \frac{\omega_r.n_p}{2\pi} \tag{19}$$

The stator voltage in dq frame is delivered from (20), (21).

$$u_{sd} = -R_s i_{sd} - 2\pi.f_e\psi_{sq} + \frac{d\psi_{sd}}{dt} \tag{20}$$

$$u_{sq} = -R_s i_{sq} - 2\pi.f_e\psi_{sd} + \frac{d\psi_{sq}}{dt} \tag{21}$$

Where u_{sd} and u_{sq} are the stator terminal voltages, R_s is stator resistance, i_{sd} and i_{sq} are the stator currents in the dq frame.

The induced flux linkages in the stator are calculated by (22), (23).

$$\psi_{sd} = -L_d i_{sd} + \psi_{PM} \tag{22}$$

$$\psi_{sq} = -L_q i_{sq} \tag{23}$$

Where L_d and L_q are the stator inductances.

The active and reactive powers of synchronous generator are computed by:

$$P_{gen} = \frac{3}{2}\left[u_{sd}i_{sd} + u_{sq}i_{sq}\right] \quad (24)$$

$$Q_{gen} = \frac{3}{2}\left[u_{sq}i_{sd} + u_{sd}i_{sq}\right] \quad (25)$$

D. Simulation

To achieve continuous power output from pumping-mode devices, the strategy proposed in [5] for timing the starting of each unit has been implemented. Since, the power of a standalone airborne wind energy system is not continuous imposing this delay is useful to have a continuous total power. This delay is explained in (26).

$$t_{d(n)} = \frac{t_{PMC}(n-1)}{N} \quad (26)$$

Where t_d is the n^{th} unit delay, t_{PMC} is the period of pumping mode cycle, n is unit index number and N is total number of units on a given bus.

Table 1 shows the specifications of the offshore airborne wind energy farm. For each unit, the pumping cycle and recovery phase duration is 90 and 10 seconds respectively. Modeling has been done in Matlab software by the Dormand-Prince numerical analysis method.

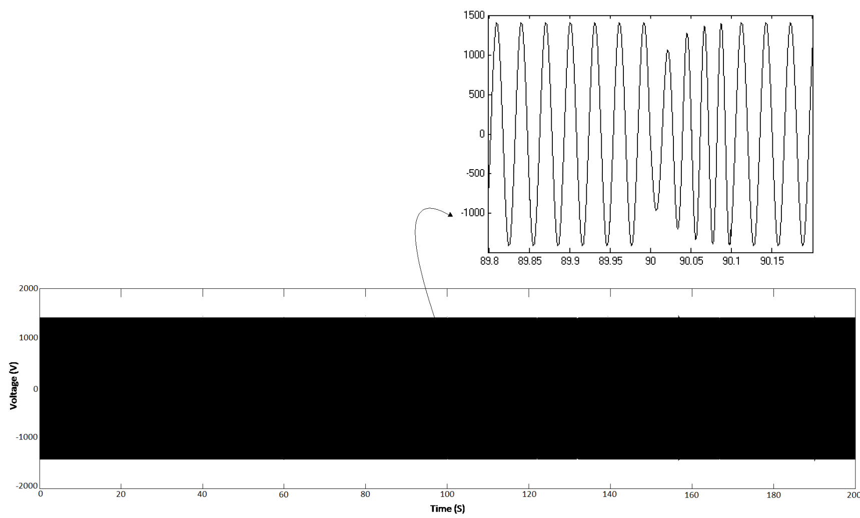


Fig6: Generated Voltage

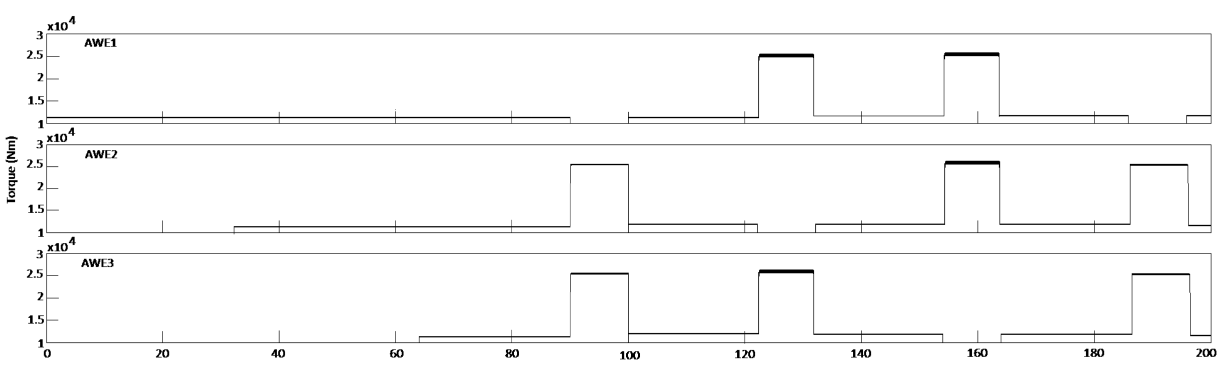


Fig7: Mechanical Torque

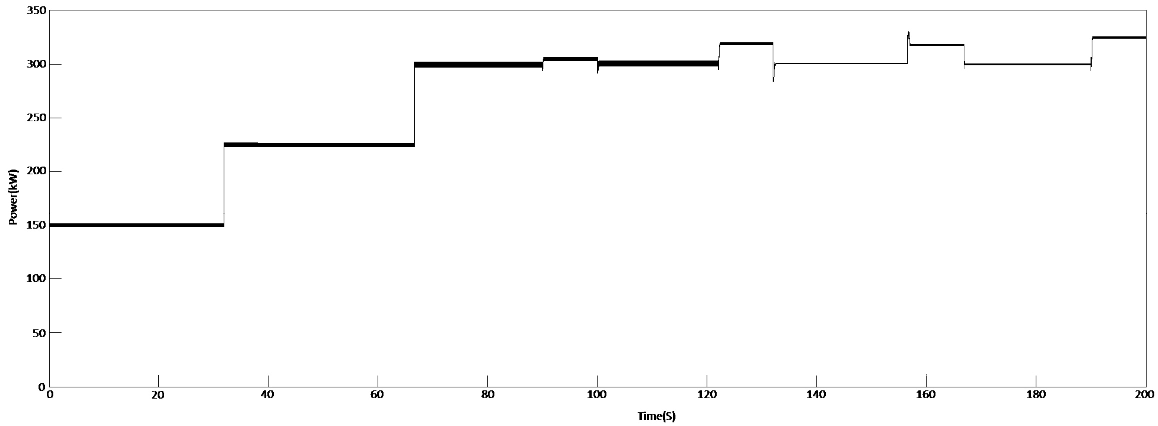


Fig8: Generated Power

Table1. Simulated system specifications

	Mechanical	
$S(m^2)$	219	Wing area
C_r	1	Aerodynamic coefficient
E	4	Lift ratio
r(m)	0.5	Drum radius
$\rho(kg/m^3)$	1.225	Air density
θ(deg)	45	Tether angle
	Electrical	
L_d(mH)	1.78	d-axis stator inductance
L_q(mH)	1.78	q-axis stator inductance
ϕ_s(V.s)	6.86	Flux Linkage of stator
P_{DL}(kW)	5	Dump load power
P_{ML}(kW)	25	Main load power
P	45	Number of pole pairs

E. Simulation Results

Figure 6 shows voltage of farm for 200 seconds. Unit one has been considered as the reference for synchronization. Unit two and third are synchronized at t=38, t=71.9 respectively. In t=90 unit one has been changed to recovery phase for 10 seconds. During the recovery phase duration this unit remains synchronized with the other units on the bus although it is in motoring mode. Since, in this situation unit one is performing as dynamic load, system voltage will be faced with a voltage drop. A PI controller has been designed to increase the input torque from the other units through the kite controller during the recovery. It can be seen that at t=90 the voltage begins to reduce due to a recovery phase beginning, however, the voltage regulator quickly brings the voltage back to normal condition (1000Vrms). This action is also taken at t=121.95 and t=156.68 when unit two and three respectively have been changed to motoring mode.

Figure 7 shows mechanical torque diagram of each unit. It can be seen when a unit is its recovery phase the voltage controller increases the mechanical torque of other units and when that unit has returned to the power phase the torque is decreased to the normal value. This action is shown in figure 8. When a unit is in motoring mode the generated power of system is increased to compensate for the increase in load and when that unit has been returns to generator mode the power is decreased to the normal value.

V. Conclusion

Direct interconnection of offshore wind energy systems was investigated. In this method, power converters have been removed and all of the units are electrically interconnected directly. Owing to the high expense of offshore repair and maintenance this approach for interconnection may prove to be a more economical implementation of offshore wind farms. The challenges in direct interconnection have been discussed and it has been shown that by using appropriate controllers and a suitable link between electrical and mechanical controllers it is possible to overcome on synchronization and voltage drop challenges. Dispatched power of interconnected AWE systems will be delivered to the onshore back to back converter to make it compatible with frequency and voltage of the grid for interconnection. Interconnecting with the grid and modelling of the onshore back to back converter is another important issue which will be considered in future works.

Acknowledgement

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