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***Abstract*—The share of renewables in the power system is increasing rapidly. Large offshore wind power plants (OWPPs) are developed at a high pace and conventional fossil fuel-based plants are decommissioned. If the OWPP gets islanded due to any contingency or in the event of a blackout, the whole OWPP will be shutdown. This paper proposes a STATCOM with a battery storage that is located at the point of common connection to an OWPP to enable OWPP energization from a fully discharged state to operate in islanded mode. The STATCOM functionality provides fast and dynamic reactive power management and the battery unit provides active power balancing capability to regulate the frequency in the island. The concept is demonstrated through time-domain simulations on an OWPP model in PSCAD. The results confirm the technical feasibility of the system.**

***Keywords*—battery storage, STATCOM, offshore wind power plant, islanded operation, frequency control, voltage control, grid forming converter.**

I. Introduction

A number of large offshore wind power plants (OWPPs) have been developed especially in Europe and many more are under development worldwide [1]. According to Global Wind Energy Council (GWEC), the total offshore wind power capacity will rise to over 235 GW by 2030 from 29 GW in 2019 [2].

Wind power is inherently non-dispatchable by nature. The power changes with the wind speed and is zero when the wind speed is below the cut-in speed. Wind is a meteorological phenomenon resulting in varying wind power all the time. The power variations can be smoothened to some extent with the help of a battery storage. Often a STATCOM is used to provide fast and dynamic reactive power management and hence contribute to the reactive power regulation and handle voltage variation at the point of common connection.

A STATCOM with integrated battery storage, referred to as IBESS has been proposed [3],[4]. It can provide fast, dynamic and bidirectional control of both the active and reactive power exchange and hence it can be used to energize the electrical infrastructure in the OWPP grid. Once a stable voltage has been established the wind turbine units can be connected and start operating. Thereafter, power generation can be resumed depending upon the availability of wind at the instant.

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This paper uses the IBESS to energize the OWPP from a completely deenergized state in the absence of any connection to the onshore grid and enables its operation in the islanded mode. Such a system will be able to meet not only the auxiliary consumption of the OWPP, but also maintain it in a standby state ready for the restoration of the power system after a blackout. The concept is demonstrated through time-domain simulation in PSCAD. The IBESS controller is using a grid forming strategy based on the power synchronization control proposed in [5],[6]. The benefits of installing an IBESS at the PCC of an OWPP are listed as follows:

- Soft-charging to energize the offshore grid;
- Maintain the battery state of charge (SOC) at the optimum level;
- OWPP can meet the power demand for its own auxiliary loads;
- Run the OWPP in an island mode, thereby harnessing the wind power that would be wasted otherwise, provided that the battery is not fully charged already;
- In case of blackout maintain the OWPP in standby mode to be ready for immediate power production and delivery of control functions after the grid is restored;
- The OWPP is ready to perform black-start immediately.

Islanded operation of the OWPP with stable voltage and frequency profile is a pre-requisite for providing the black-start functionality to the power system [7]. Gryning et al. have presented a battery-sizing method based on historical wind data and availability requirement to perform black start [8].

The paper is organized as follows. The test network is described in Section II. The IBESS topology and its grid forming controller has been described in Section III. Section IV presents the simulation results for the sequence of events necessary for the energization and operation of the OWPP. The results are finally concluded in Section V.

II. Test OWPP Model

A. OWPP Network

The test OWPP model is based on the 1386 MW Hornsea Two OWPP [9]. A third of the plant has been modelled here as shown in Fig. 1. The model grid comprises of the 220 kV export cable system, associated shunt filters and reactors, and 2x270 MVA, 220/66 kV transformers at the collector bus. The export cables comprise of 40 km long 3-core underground

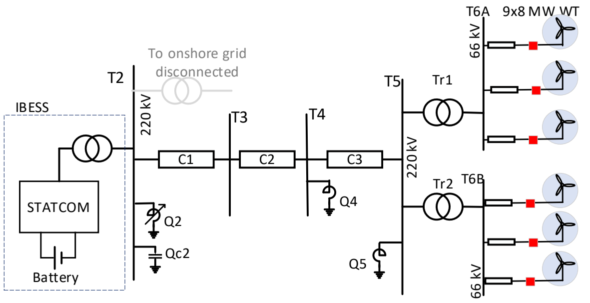

Fig. 1. Schematic diagram of the test OWPP network.

TABLE I. NOMINAL RATINGS OF IBESS AND 8 MW WT UNIT.

Base values	Unit	IBESS	8 MW WT unit
Active power (P)	MW	50	8
Reactive power (Q)	Mvar	100	-
Power factor		-	0.9
Nominal MVA (Base)	MVA	111.8	8.889
Nominal rms voltage	kV (l-l)	33	0.69
Base voltage (peak)	kV (l-g)	26.94	0.5634
Nominal rms current	kA	1.956	7.4377
Base current (peak)	kA	2.766	10.518
Base impedance	Ω	9.740	0.05356
Base frequency	Hz	50	50

cables laid in flat formation and two sections of piped cable cores, each section 60 km long, in trefoil layout. For reactive power compensation (120 – 300) Mvar variable shunt reactor at the bus T2, 170 Mvar reactor at the bus T4, and 90 Mvar shunt reactor at the bus T5 have been connected. There is 80 Mvar capacitive shunt filter connected at the bus T2.

The nominal ratings and the selected base values for the IBESS and the wind turbine (WT) are given in Table I. While the OWPP has 55 WT units, here only 37 units have been considered. These 37 units are aggregated into 6 groups, comprising of 4, 5, 6, or 9 units. The ratings of the WT group equivalent are accordingly scaled up. The 66 kV collector feeders are represented by a series combination of 0.68 Ω resistor, 5.2 mH inductor and 5.1 µF shunt capacitor on the turbine side.

B. WT Model

The WTs are modelled in terms of the average model of the grid-side converters along with their converters. An ideal dc link is assumed that implies sufficient wind power is available at all instants. The grid following control tracks the active and reactive power references together with the ac voltage magnitude regulation. The controller is implemented in the synchronously rotating *dq*-coordinate frame. In this study, the WT is in the voltage regulation mode, which is realized by injecting the reactive current in proportion to the voltage deviation from the nominal value. A droop frequency regulation of 5% in the steady state is implemented.

III. IBESS TOPOLOGY AND ITS CONTROL

Modular multilevel converter (MMC) is the preferred topology for high voltage and high power STATCOM applications. For the IBESS, a 20 kVdc battery unit is integrated with the STATCOM, which is connected to the 33 kVac bus. Since the dc voltage is too low for the MMC using the double star half-bridge (DSHB) topology, the double star full bridge MMC with centralized energy storage (DSFB-CES) has been selected as described in [10].

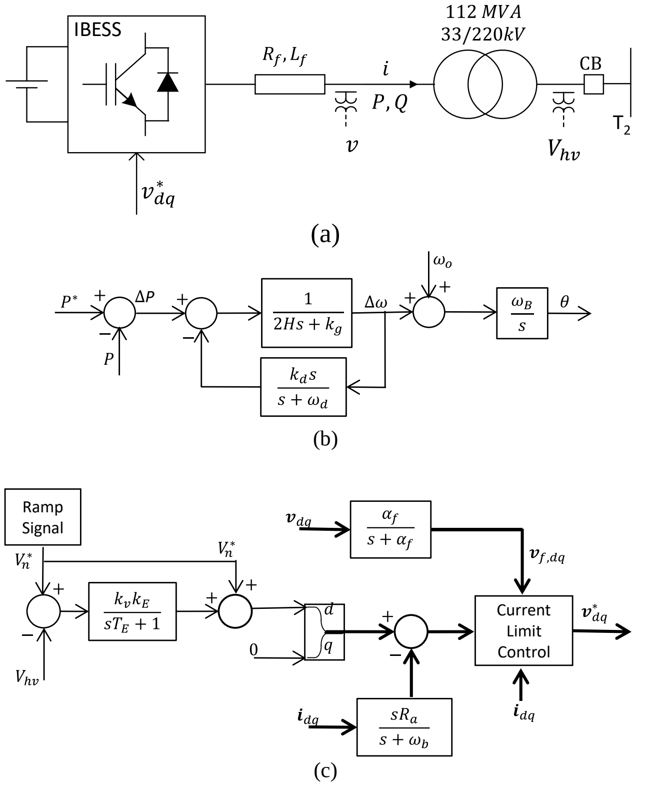

Fig. 2. (a) Schematic diagram of IBESS. (b) Power synchronization control (PSC). (c) Voltage magnitude controller (VMC).

TABLE II. PARAMETERS OF IBESS CONTROLLER.

Parameter	Symbol	Value
Parameter k_g	k_g	62.5 pu
Base frequency	ω_B	100π rad/s
Mechanical inertia constant	H	5 s
Damping controller gain	k_d	62.5 pu
Damping controller bandwidth	ω_d	16 rad/s
Voltage regulation gain	$k_v k_E$	1.25 pu
Voltage regulator time constant	T_E	0.05 s
Active damping resistance	R_a	0.05 pu
Cut-off frequency	ω_b	0.2 rad/s
Current magnitude limit	$\lvert I_{max}\rvert$	1.1 pu
Equivalent inductance	L_f	0.05 pu
Current control bandwidth	α	5000 rad/s
Current control gain	αL_f	0.7958 pu
Voltage filter bandwidth	α_f	2500 rad/s
Voltage magnitude limit	$\lvert V_{max}\rvert$	1.1 pu

A single-line diagram of the IBESS and its controllers are shown in Fig. 2. All the control parameters are defined in Table II. The grid forming controller of the IBESS has two parts – (i) power synchronization control (PSC) and (ii) the voltage magnitude controller (VMC).

A. Power Synchronization Control

The PSC was proposed in [5] to emulate the swing equation of the synchronous machine. Tuning of the controller for grid connected applications is described in [6]. From the block diagram in Fig 2(b), the IBESS frequency deviation, $\Delta\omega$, corresponds to the deviation in IBESS power, ΔP, and is given by,

$$\Delta\omega(s) = \frac{1}{2Hs + \frac{k_d s}{s+\omega_d} + k_g} \Delta P(s). \quad (1)$$

Here, the parameter, H, indicates the inertia constant as defined in the conventional power system. It tends to resist the frequency deviations. The damping parameter k_d tends to damp out the high frequency oscillations if any in the power deviation. In steady state (1) can be written as,

$$\Delta P = k_g \Delta\omega. \quad (2)$$

Thus, the reciprocal of the parameter, k_g, indicates the droop frequency response of the IBESS. In this study, 1.6% frequency regulation droop has been considered by setting $k_g = 62.5$ pu.

The PSC determines the frequency and phase angle, θ, of the IBESS in the grid forming control mode. The angle which is used in all the Park's transformations and inverse transformations.

B. Voltage Magnitude Control

The VMC determines the magnitude of the ac voltage to be generated by the IBESS. The VMC comprises of the nominal voltage reference, V_n^*. It is augmented by inputs from the voltage regulation and reactive power regulation. Only the voltage regulation loop has been shown in Fig. 2(c). In addition, there are active damping terms given by,

$$\Delta \boldsymbol{v}_{dq} = \frac{sR_a}{s+\omega_b} \boldsymbol{i}_{dq}. \quad (3)$$

The active damping terms are subtracted from the voltage references so as to damp out the oscillations in the IBESS output current. Finally, the current magnitude limiter is implemented to ensure that the IBESS current limits are not exceeded.

IV. Energization and Islanded Operation of OWPP

Simulation studies are carried out to demonstrate that the IBESS is capable of energizing the offshore OWPP grid and support stable islanded operation.

A. Test Cases and Success criteria

The following test cases are envisaged:

- Energizing the offshore grid;
- Synchronizing the WT units;
- Power ramp up of the WT units.

The success criteria for the islanded operation were defined as follows:

- Steady-state frequency remains within the range of 47 – 52 Hz all the time;
- Voltage profile should be within the ±10% band around the nominal voltage;
- The IBESS current limits shall not be violated.

B. Energizing Offshore Grid

Initially, the OWPP is in the deenergized state, i.e. the whole OWPP grid is islanded and dead. The offshore grid can be energized in two ways – (i) by hard switching or (ii) by soft-charging.

Hard switching for the grid energization involves running up the IBESS to the nominal voltage and then connecting the grid components one by one. Fig. 3 shows the current and

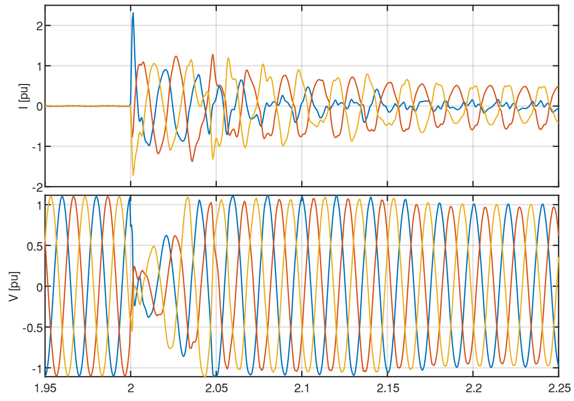

Fig. 3. IBESS three åhase current and voltage waveform when IBESS transformer is connected to export cables.

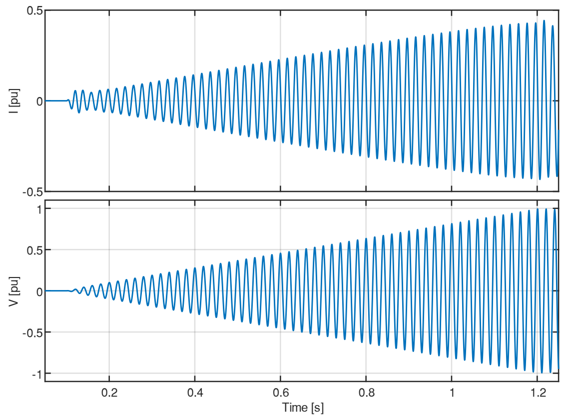

Fig. 4. IBESS current and voltage during the soft-charging of the export cables. Only phase A is shown here.

voltage transients when the IBESS transformer is connected to the offshore grid. The de-energized cables behave like a short-circuit in the first cycle and the instantaneous current rises to 2.34 pu violating the IBESS current limit. Such large transients would not be acceptable for power electronic solutions, like IBESS.

While the hard-switching may not be fully eliminated, it can be minimized to a reasonable extent in the OWPP, by using soft-charging when it is energized. In this process, all the circuit breaker in the OWPP grid remain connected and the voltage is slowly ramped up to 1 pu. Thus, the transient currents can be avoided to a large extent.

In the simulation study, the IBESS voltage is ramped up from 0 to 1.0 pu in the period from 0.1 s to 1.2 s. The IBESS current and voltage waveform for the phase A are shown in Fig. 4. Both the current and the voltage increase smoothly and they remain balanced throughout the soft-charging process. This energizes the export cable system and the collection grid. During the energization, the IBESS supplies the maximum active power of 8.7 MW, while it absorbs the maximum reactive power of 48.3 Mvar, which is generated by the high voltage export cables. This is the excess reactive power considering that all the shunt reactors in the OWPP are connected. In steady state, at 2.5 s, the IBESS supplies 5.2 MW and absorbs 47.5 Mvar at 49.92 Hz. According to 1.6% droop characteristic of the IBESS, the IBESS should be supplying, 0.1 pu power, i.e. 5 MW. The terminal voltages are

TABLE III. SYNCHRONIZATION OF AGGREGATED WT MODELS.

Connection time	WT group	No. Of units	Power ramp* starts at
4 s	WTB1	9	21 s
7 s	WTB2	4	22 s
10 s	WTB3	5	23 s
13 s	WTA1	4	22 s
16 s	WTA2	9	23 s
19 s	WTA3	6	24 s

*WT power is ramped up from 0 to 0.15 pu in 1 s.

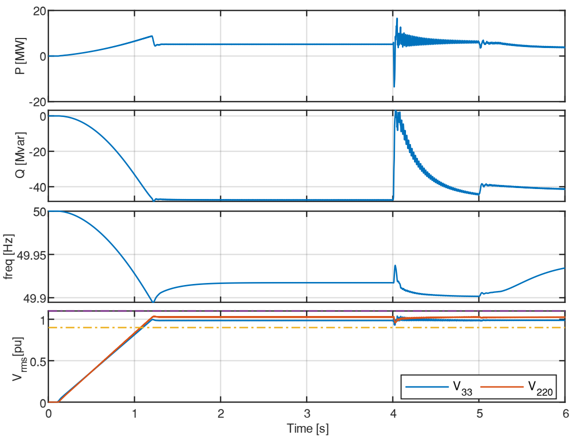

Fig. 5. IBESS output active and reactive power, frequency and IBESS transformer voltages during soft-charging and subsequent synchronization of WT units at 4 s.

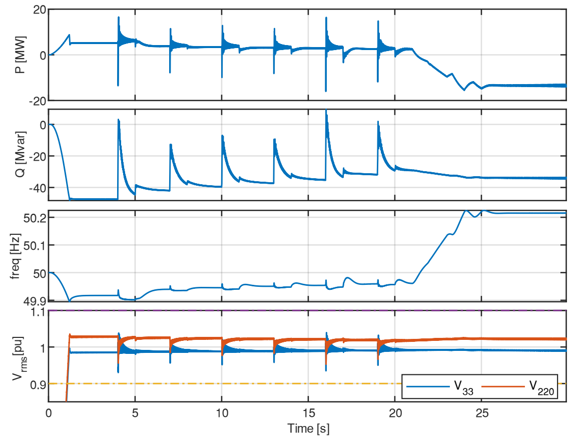

Fig. 6. IBESS output active and reactive power, frequency and IBESS transformer voltages during synchronization of WT units.

0.984 pu and 1.027 pu at the 33 kV and 220 kV terminals of the IBESS transformer, respectively. Since, the IBESS is controlled to regulate the HV terminals, the IBESS is absorbing 47.5 Mvar reactive power to decrease the voltage. Thus, for energizing the offshore grid, the active power requirement is very small, but it needs to absorb a large amount of reactive power.

C. WT Synchronization and Power Ramp up

The first WT group (WTB1), which is an aggregate of 9 WT units, is synchronized at 4 s. Consequently, the voltage at T2 drops instantly to 0.96 pu, and the IBESS output power drops to −13.5 MW as shown in Fig. 5. There is a momentary rise in the IBESS frequency by 20 mHz. The reactive power shows a larger transient as it changes from −47.5 Mvar to 3.2 Mvar within 30 ms. As the grid voltage recovers, the reactive power absorbed by the converter changes back to 43.7 Mvar in a period of 1 s.

After a delay of 1 s, i.e. at 5 s instant, the converter of WTB1 is deblocked and its controllers are simultaneously activated. It starts absorbing reactive power as the terminal voltage is 1.07 pu. Likewise, its phase locked loop (PLL) estimates the frequency as 49.94 Hz, and hence it provides a droop frequency response of 0.024 pu. This incremental power is available at the output.

At 5 s, when the 2nd WT group (WTB2) is synchronized, the voltage at WTB1 terminal drops by 6% from 1.07 pu to 1.01 pu. The voltage at the HV terminals of the IBESS drops by 3.5% from 1.024 pu to 0.989 pu. Thereafter, the remaining 5 aggregated WT units are synchronized one by one with a gap of 3 s as shown in Table III and Fig. 5. A transient disturbance appears whenever a WT group is connected to the grid, and another small disturbance is visible when the WT converter is deblocked.

Large transient disturbances are observed in the simulation study when the WT groups are connected as each group comprise of an aggregation of multiple WT units. Thus, the resultant transient at 4 s is the consequence of the simultaneous connection of 9 WT units through an 81 MVA transformer, and an aggregated LC filter. In a real application, where WTs are connected one after another, the transient disturbances would be smaller than in a simulation using aggregated WT groups.

Even though the power reference to the WT groups is zero for the first 21 s in the simulation, the WT responds to the frequency deviations and helps reduce the frequency deviation as they get synchronized. Furthermore, when the WT group is connected it creates a momentary drop in the grid voltage which affects the whole grid, including the IBESS HV terminals. Consequently, the transients are observed in the reactive power output of the IBESS.

D. WT Synchronization and Power Ramp up

At 21 s, the power reference to WTB1 is ramped up from 0 to 0.15 pu in 1 s. Similar ramps in the active power reference is applied to all other WT groups at the instants of 22 s, 23 s or 24 s as shown in Table III. There is no need for reactive power reference as the WTs are in voltage regulation mode. The changes in the active and reactive power of the IBESS along with its frequency and the voltages at its transformer terminals are shown in Fig. 6.

In response to the change in the reference, the output active power from the WT groups rise. Since the grid is in an islanded mode of operation, all the generated power has to be absorbed by the battery. Hence the IBESS frequency is raised and when the WT responds to the frequency rise, the actual output of WTB1 is reduced as shown in Fig. 7 and Fig. 8. The WT frequency response acts on the frequency estimated by its PLL which tends to be oscillatory during the different switching events in the offshore grid as shown in Fig. 8(c). Hence, the frequency droop regulation has a first order filter of 0.5 s time constant, which slows the frequency response as shown in Fig. 8(b). Hence, the actual WT output power is only 0.064 pu in steady state. For the 37 WT units aggregated into 6 groups, 0.15 pu translates into 44.4 MW active power generation. Due to the 5% droop frequency regulation, the OWPP is generating 21 MW, and the IBESS is absorbing 13.8 MW at 27 s.

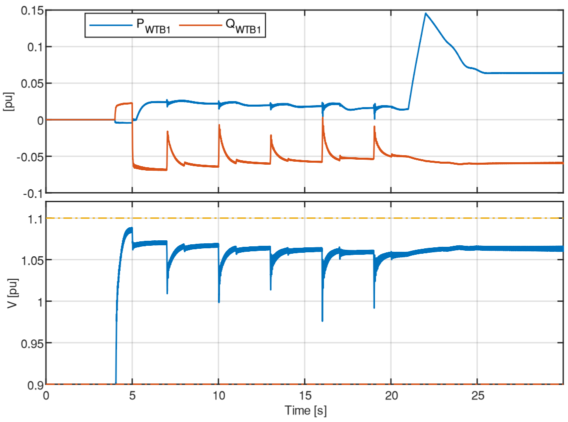

Fig. 7. WT group WTB1. (a) Output active and reactive power of WTB1; (b) rms voltage at its terminal.

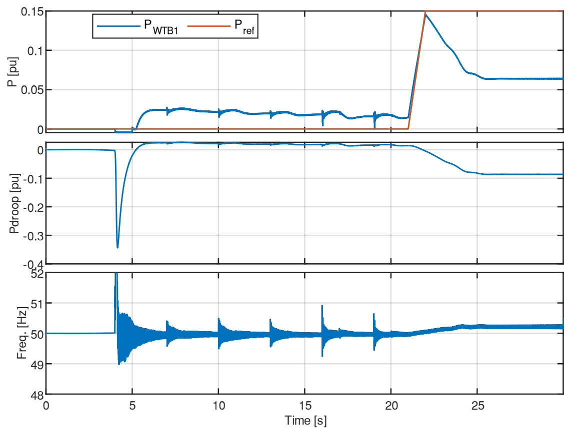

Fig. 8. WT group WTB1. (a) Output active power against the reference power, (b) frequency droop response and (c) frequency estimated by the PLL.

E. Overall Results

During the whole simulation, the IBESS was found to be well within the current limits, so the current limiting control does not get activated at all. The voltages at different buses in the OWPP remain well within the tolerance range of ±10% around the nominal voltage as shown in Fig. 9. Actually, if the transient spikes are ignored, the rms voltages are between 1.01 – 1.09 pu. In all the cases the IBESS frequency remains in the range of 49.88 Hz to 50.24 Hz. Thus, the success criteria are fulfilled in all the simulated events in this study.

V. Conclusions

This paper demonstrates the use of IBESS in the islanded operation of an OWPP. Even though hard-switching cannot be supported by the IBESS due to large transient current of over 2.0 pu, soft-switching can be used to energize the whole OWPP. As the IBESS tends to regulate the rms voltage at the high voltage terminals of its transformer, it absorbs all the excess reactive power generated by the export cables in the OWPP. Whenever a new WT unit is switched in, it creates a momentary dip in the voltage which affects the voltage throughout the OWPP. The IBESS is fast enough to respond to the voltage dips. All the while the IBESS supplies the losses. When the WT units start generating power, the IBESS automatically absorbs the excess power. In response to the IBESS power variation, the IBESS frequency changes according to the PSC. In turn, the WT units responds to frequency deviations as that is enabled. Thus, the grid forming control of the IBESS is demonstrated to start and operate the islanded OWPP successfully.

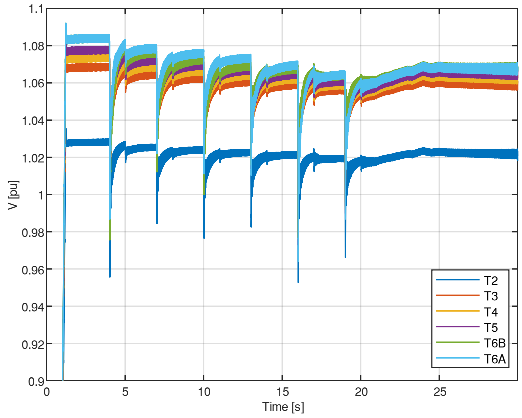

Fig. 9. RMS voltages at different terminals in the OWPP.

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