FACTS-based Grid Interface with Embedded Energy Storage for Ocean Wave Power

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Abstract—**This article presents the state-of-the-art application of a Unified Power Flow Controller (UPFC) to directly interface ocean wave energy converters (WEC) with the utility grid. It is shown that the transformer flux saturation problem at variable low-frequency operation poses no technical issue for the ocean power applications because a direct-proportionality relationship exists between frequency and amplitude of the WEC output voltages. We have proposed a direct interface of WEC with the utility grid using a series compensation transformer of the UPFC controller. The shunt input rectification segment of the UPFC acts not only as the DC bus for the UFPC operation but also as an embedded energy storage stage for the WEC. The mathematical formulation and simulation results are presented as a proof-of-concept for FACTS-based WEC-grid integration with the integrated energy storage capability.**

Keywords—wave energy capacitor, energy storage, ultra-capacitor, FACTS, UPFC

I. INTRODUCTION

The variable output of renewables presents integration challenges, especially at high levels of penetration [1]. Grid integration aspects of renewable sources have become increasingly important, and FACTS devices such as Unified Power Flow Controller (UPFC) are proving to be a viable solution [2]. Counter to the wind or the solar generation, the Wave Energy Converters (WEC) inherit very large variation in the output power at very low frequencies because a typical period of ocean waves is approximately 10 sec. The Super-capacitor Energy Storage System (SESS) has proved to be a good solution to tackle the variability issues, especially in the WECs, due to the demand for continuous cyclic charging and discharging of the storage media [3]. Other than the requirement of energy storage capability, we also need a power electronics converter system to couple the WEC with the power grid [4].

The application of UPFC in power systems has been gaining popularity with the availability of cheap and reliable power electronics [5], however, the use of UPFC for ocean power applications is very limited. UFPC operation generally involves two three-phase transformers, the shunt input transformer, and the series output transformer. Since a WEC has an output voltage that vary in amplitude as well as frequency, so little has been explored in the literature to use a UPFC as a direct interface between the WEC and the utility grid. The very low operating frequencies of WEC also pose a challenge due to transformer core flux saturation issues. In this paper, we have proposed a strategy to use the UPFC as a direct interface between an ocean

WEC and the utility grid. The input shunt part of UPFC supplies the DC power to the series output part of the UPFC, and in the process, the DC part also acts as energy storage media to smooth the WEC output power fluctuations. The control algorithm ensures not only to provide a series compensation voltage that corrects for the amplitude and frequency of the WEC output voltages but also to control the flow of power between the WEC and the utility grid.

II. FLUX ANALYSIS FOR WEC-OUTPUT FED TRANSFORMER

Let us consider the open-circuit voltage of a synchronous machine with constant magnetizing flux and variable speed,

$$e(t) = k\omega(t)\cos(\theta(t) + \theta_o) \tag{1}$$
$$\theta(t) = \int \omega(t)dt \tag{2}$$

Under the regular oscillatory motion condition due to ocean waves, the variation in the frequency of a WEC power takeoff generator can be described by,

$$\omega(t) = \widehat{\omega}sin(\omega_{osc}t) \tag{3}$$

Where $\widehat{\omega}$ is the peak machine speed (with a typical range of a couple hundred rad/s), and ω_{osc} is the frequency of oscillation (which for WEC applications would be $2\pi/T$, where T is the wave period, with a typical range of around 10 seconds). Now, putting (2) and (3) in (1), and assuming a zero initial angle θ_o and we get,

$$e(t) = k\widehat{\omega}sin(\omega_{osc}t)\cos\left(-\frac{\widehat{\omega}}{\omega_{osc}}cos(\omega_{osc}t)\right) \tag{4}$$

The instantaneous core flux of a coil is given by,

$$\varphi(t) = \frac{1}{N}\int e(t)dt \tag{5}$$

Putting (4) in (5) gives us,

$$\varphi(t) = -\frac{k}{N}\cos\left(-\frac{\widehat{\omega}}{\omega_{osc}}cos(\omega_{osc}t)\right) \tag{6}$$

Now, it is clear for (6) that for any given frequency, the amplitude of the core flux remains constant, which depends on the WEC design parameter k and winding design parameter N. This fact justifies that an appropriately selected transformer can be directly coupled to the output of WEC, and it will not result in the core flux saturation issues due to the low-frequency operation of a WEC.

The theoretical result in (6) is verified for a practice transformer coupled to a WEC in the Matlab/Simulink. The amplitude of the transformer core flux remains constant despite the variable amplitude and variable frequency output voltage profile of a WEC.
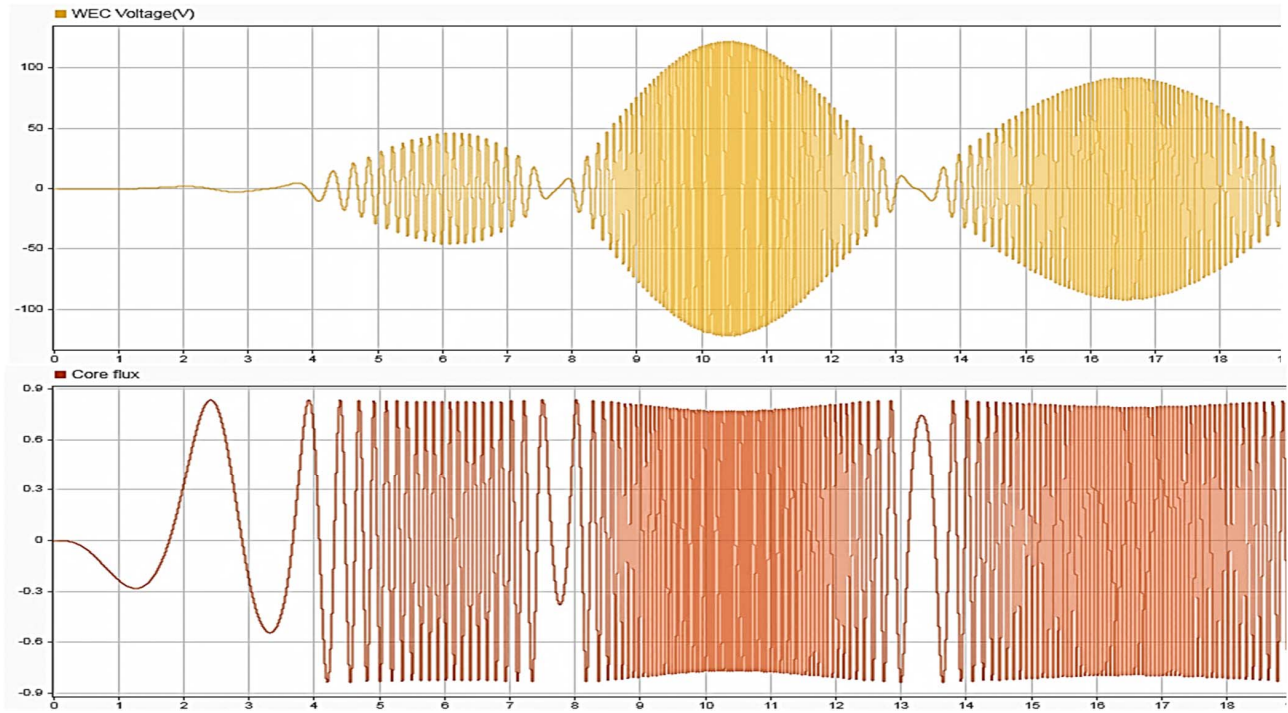
Fig. 1 A typical output voltage profile of WEC (top), and the corresponding transformer core flux profile (bottom).

III. WEC-Grid Interface with UPFC

The results of (6) and Fig. 1 open the possibility of using the series transformer of a UPFC as a direct interface between a WEC and the load or utility grid. We can use the series compensation of the UPFC to correct for the variations in the frequency and amplitude of the WEC output voltage. The UPFC corrective action would yield an output voltage of the desired amplitude, frequency and phase. Moreover, UPFC can also be used to perform its fundamental power flow control action. Note that we are neglecting the typical UPFC shunt transformer, however a AC/DC rectifier in the same position serves the same purpose.

The UPFC corrective action can be explain using the simplified single-line diagram of the WEC-grid interface through the UPFC series transformer in Fig. 2. The load/grid side voltage is given by,

$$v_L(t) = v_{wec}(t) + v_c(t) \qquad (6)$$

Where,

v_L Load (grid) side voltage

v_{wec} WEC output voltage

v_c UPFC output voltage

Because we have the full control on the UPFC output voltage v_c, we can control v_c to correct for the amplitude and frequency variation of v_{wec}, while also controlling the power flow between the WEC and the grid, following the standard phasor-circle diagram of a UPFC, as shown in Fig. 3.

The proposed UPFC-based WEC-Grid interface design is shown in Fig. 4. The three-phase output of WEC is directly fed to the utility grid through the series transformer of the UPFC.

The series transformer adds voltage signal to WEC output. One part of this voltage corrects for the variation the amplitude and frequency of the WEC output and the other part can be used to control the power flow between WEC and grid.
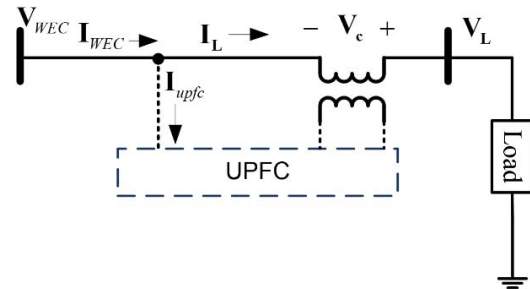

Fig. 2.   The single-line diagram of WEC-Grid interface using a UPFC.

IV. Simulation

The proposed scheme in Fig. 4 was simulated using Matlab/Simulink Simscape tool, as shown in Fig. 5. The simulation results are shown in Fig. 6. The UPFC stores energy in the DC-bus ultra-capacitors using its shunt rectification stage. The output of the shunt stage can also include a boost converter for the DC-bus voltage control. The UPFC utilizes the DC-bus energy to perform the series compensation stage and corrects for the amplitude and frequency variations in the WEC output voltage. The third plot in Fig. 6 shows the UPFC correction voltage. A part of this signal cancels the undesirable variations in the WEC output voltage, and another component of the correction voltage accounts for the desired voltage generation at the output.
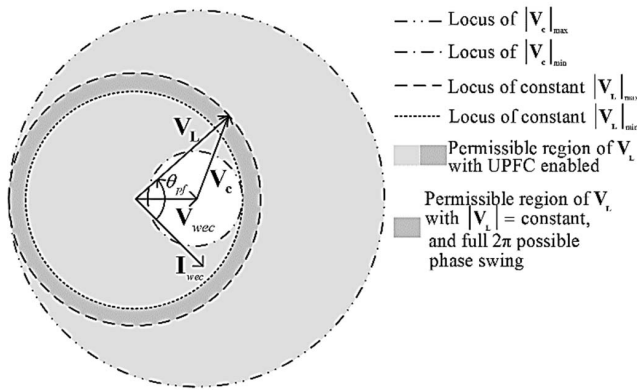
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Fig. 3. The phasor-circle diagram for a UPFC.

The fourth plot in Fig. 6 shows the load side output voltage, which has the desired amplitude and frequency. Hence, the simulation results prove the success and viability of the proposed WEC-Grid interface using a UPFC.

V. CONTROL SCHEME

The control strategy for the proposed design is shown in Fig. 7. The current and voltage measurements are made for the WEC generator, power grid, and the UPFC DC-bus. These measurements are conditioned (filtering and range adjustments) and passed to the real-time controller, which is broken down into two parts, namely, the high-level control and the low-level control. The low-level control is responsible for directly controlling the power electronic components through the PWM signals. Three separate low-level control segments are required to control the active rectifier, DC-bus, and the inverter. The high-level control is responsible for interacting with the user through the GUI interface and to control the overall function of the system. The high-level control is also responsible for other functions, such as, incorporating Phase-Locked-Loop (PLL) for grid synchronization, monitoring system parameter thresholds to shut down the operation under abnormal conditions, and maintaining resilience.

VI. CONCLUSIONS AND FUTURE WORK

A novel WEC-grid interface idea has been presented, which involves the utilization of power regulation and control capability of FACTS-based technology to directly interface a WEC with the utility grid. A UPFC based design is presented, that embeds the energy storage in its DC bus capacitors, and corrects for the WEC voltage variations using built-in series voltage compensation capabilities of UPFC. The simulation results prove that the unique output voltage amplitude and frequency profile of a WEC converter lends itself to be fed directly to a UPFC-series transformer, without transformer core flux saturation issues. The simulation results also prove that the proposed design is feasible. The proposed scheme is will be implemented and tested on the hardware setup.

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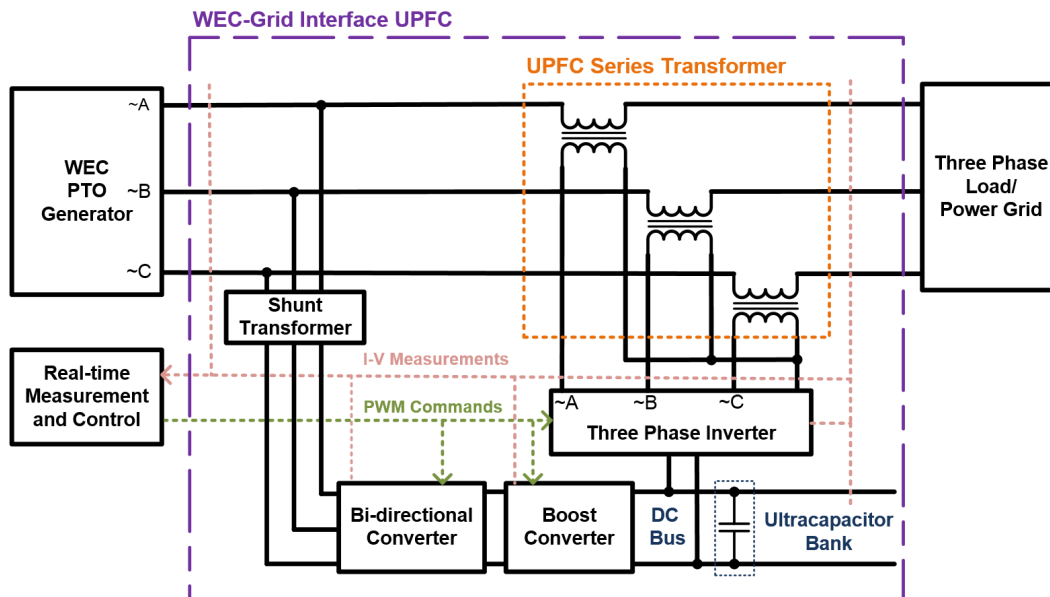
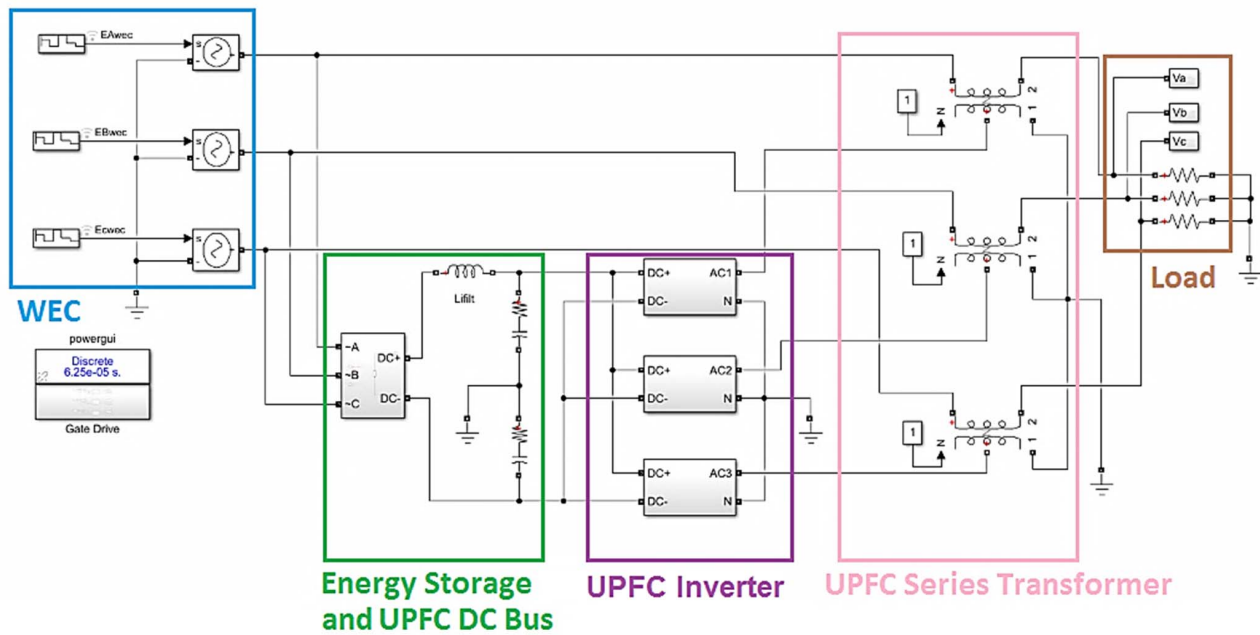Fig. 4 The proposed WEC-Grid interface design using a UPFC.

3081

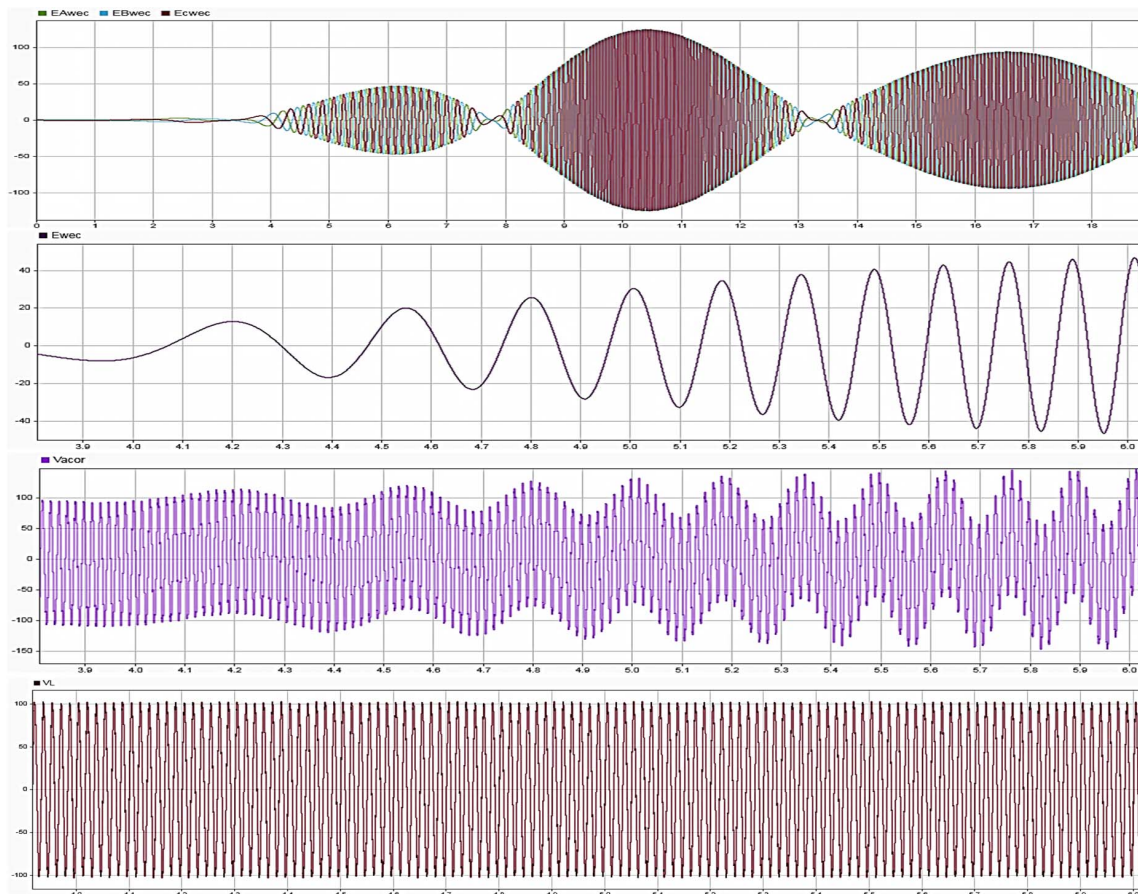Fig. 5   A UPFC-based WEC-Grid Interface Simulink Design

Fig. 6   (top down) The output voltages of a 3-phase WEC; the phase-A voltage zoomed-in from 4 to 6 seconds; The correction voltage from the UPFC series transformer for WEC phase A; The grid side voltage output voltage at a desired amplitude and frequency.
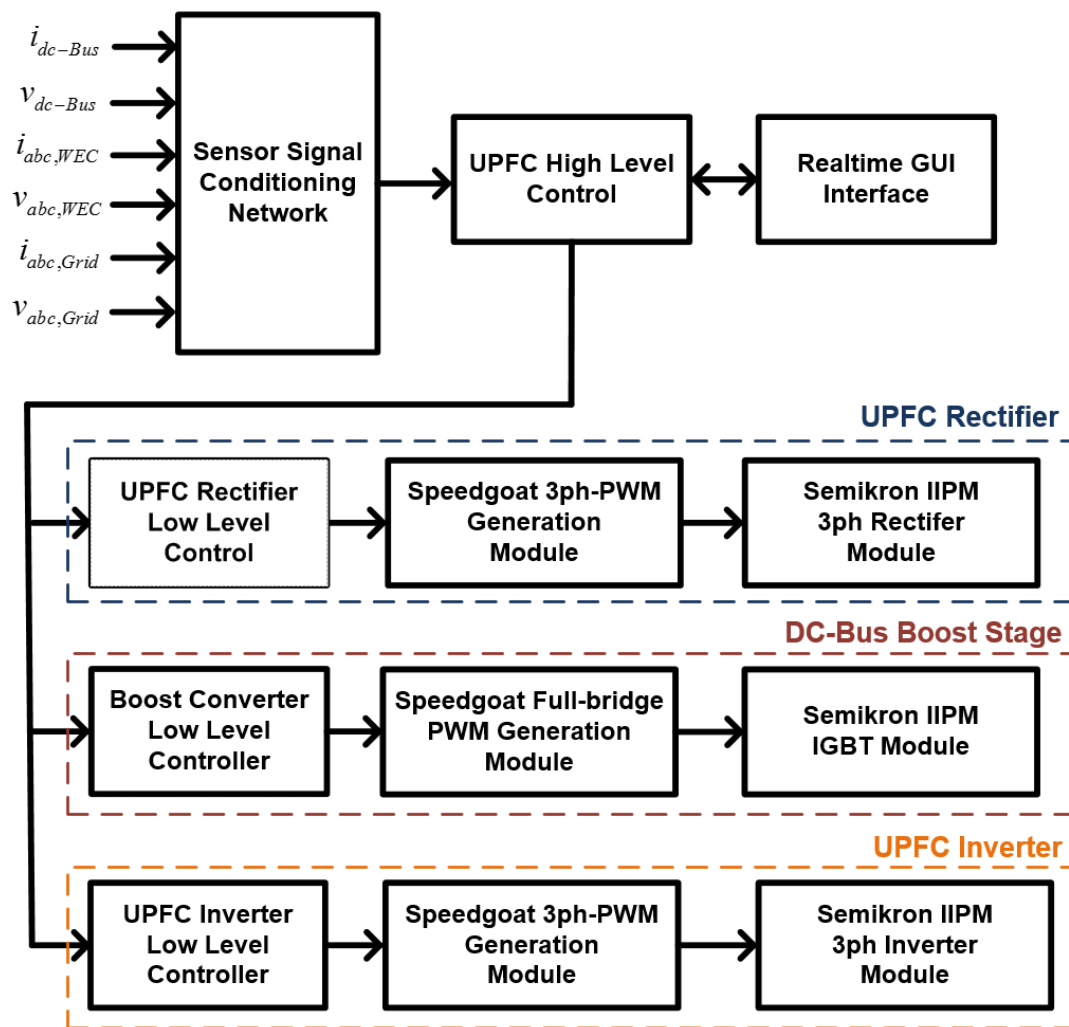
Fig. 7   Control scheme for the proposed design.