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Control of Offshore Marine Substation for Grid-Connection of a Wave Power Farm

Rickard Ekström¹ and Mats Leijon^{1,2}

¹ *Division of Electricity,
Department of Engineering Sciences,
Swedish Centre for Renewable Electric Energy Conversion
Uppsala University,
Box 534, SE-751 21 Uppsala, Sweden
E-mail: Rickard.Ekstrom@angstrom.uu.se*
² *University of Southampton
Engineering and the Environment, Highfield Campus
Southampton SO17 1BJ UK*

Abstract

To grid-connect an offshore wave power farm, an intermediate marine substation is suggested. As a part of the Uppsala University wave power project, a marine substation has been designed, assembled and deployed at sea. The substation is capable of connecting up to seven wave energy converters (WECs), and to transfer the power to the onshore 1kV-grid. In this article, the control procedure for grid connection of the WECs is described step-by-step, and the practical implementations are presented. The system is designed with autonomous control and will connect or disconnect the WECs, depending on the sea state. Fault handling is taken into account, and grid power quality such as harmonic distortion and flicker are considered in the design. Experimental results are presented to verify the system functionalities.

Keywords: Marine substation, Wave Energy Converter (WEC), Grid-Connection, Wave Power Farm, Voltage-source Inverter (VSI)

1. Introduction

The global energy demand is continuously increasing, whereas the resources are limited and the environmental effects are a critical issue. The use

Figure 1: (a) Point-absorbing wave energy converter. (b) Cluster of WECs connected to the marine substation.

of renewable energy sources, such as wind, solar and ocean energy, could provide the solution to this. While the extraction of wind and solar energy has increased exponentially for the last decade, ocean energy has not reached the commercial stage yet. The energy available in the oceans around the world is immense, and several wave energy converter (WEC) prototypes have been developed during the last decades [1]. At the Centre for Renewable Electric Energy Conversion, Uppsala University, a WEC concept has been developed and experimentally verified [2, 3]. The point-absorber type WEC, shown in Fig.1a, consists of a linear generator placed on the seabed, connected with a line to a buoy on the surface. The generator is of the direct-driven permanent magnet type, and only electrical damping is applied. The mechanical design is simple and robust to withstand violent sea states and increase the lifetime of the device. As the main characteristic of the point absorber is to have a buoy diameter much smaller than the wavelength of the waves, its capture width will be limited. To increase the total power absorbed from the sea, large clusters of WEC units have to be deployed, as illustrated in Fig.1b.

To reduce the number of sea cables from the offshore farm to the coastline, and to improve the transmission efficiency, an offshore marine substation is put on the seabed within the farm. The benefits of a seabed installation compared to a platform installation includes e.g. cost savings, easier and more reliable cable layout (no flexible cables required) and avoidance of extreme wave forces on the substation hull. The drawbacks include the difficult

Figure 2: (a) Assembly of the marine substation in the Ångström lab at Uppsala University. (b) Sea deployment of the marine substation. The research site is located outside Lysekil on the Swedish West coast.

maintenance, pressurization and more expensive cable connections. These are discussed in more detail in [4].

The marine substation collects the cables from the WECs, and transfers the WEC powers to the electric grid onshore via a single sea cable. As a part of the Uppsala University project, a marine substation has been designed and assembled, as shown in Fig.2a. The substation was deployed during the summer of 2013 (Fig.2b), for grid connection of seven WECs to the local onshore grid at a distance of 2.5km. The substation has a power rating of 160kW, and transfers the power using a three-phase 1kV AC-link. A summary of both the mechanical and electrical layout is found in [4], and the onshore experimental verifications in [5].

The selection of transmission technology to shore depends on the electrical characteristics of the farm (power and voltage output) as well as the distance to a sufficiently strong grid point. In the end, the choice of power transfer type will be a compromise between capital expenditures (CapEx), operational expenditures (OpEx) and transmission efficiency. Experience from offshore wind farms shows that the CapEx may be in the range of 20-25% of the total farm investments [6]. Various cost factors for grid connection of wave power are discussed in [7]. To make these installations viable, the OpEx must be sufficiently low. For better utilization of the installed cable capacity, it has been suggested to combine offshore wind farms with wave farms [8]. Overviews of grid connection topologies in offshore installations are discussed in [9, 10, 11]. Alternative topologies, such as the cascaded H-bridge multilevel

inverter (CHB-MLI), which is suitable for a farm with many isolated units, has been proposed in [12].

As the distance of the sea cable increases, the required charging currents become excessive, resulting in both increased transmission losses and limitations in the cable power transfer capability. At these distances, the selection of high-voltage direct current (HVDC) transmission [13] may not only be more viable than HVAC, but also the only technical solution. In [14], it is concluded that HVAC is viable for cable distances up to 50km, while HVDC becomes more interesting at distances above this.

In this paper, the marine substation control procedure for grid connection of the WECs is described in detail. The step-by-step software implementation is shown, and the proposed strategies are demonstrated experimentally. The control system is autonomous and is designed to cope with any internal faults in the substation, as well as grid voltage unbalances and grid black-outs. No islanding detection has been implemented. Grid power quality is discussed, and methods to reduce grid harmonics and flicker are presented.

2. Control system overview

The main objective of the control system is to reliably transfer the power from the WEC farm to the local electric grid. The damping of the WECs should be applied to maximise the delivered power. Also, the grid-connection must comply with the local grid codes, and the substation must be able to handle any internal faults. The control tasks can be divided into two major areas, the input and the output of the marine substation:

1. WEC-side (input) controller
 - WEC damping control
 - WEC protection
2. Grid-side (output) controller
 - Active power control
 - Reactive power control
 - DC-link voltage control
 - Injected power quality
 - Grid synchronization
 - Voltage harmonic compensation

- Fault handling

The primary aim of the WEC damping control is to optimize the power output from the WECs, as well as minimizing the system losses. This is further discussed in Sec.3. Assuming the translator is centred in the generator, it will hit the end stop if the wave height is larger than the stroke length of the translator. The force by which this will occur depends on the excitation force from the wave and the buoy dynamics, but also on the damping force applied by the PTO. The sea state at the Lysekil research site, presented in [15], shows wave heights up to 4m, whereas the stroke length of the generators are only 2m. The current generation of WECs have damping springs mounted in the top, to reduce the peak forces on the structure. Another option could be to predict these peak forces, and then apply a stronger PTO damping force to counteract them. However, this method has not yet been evaluated, to the best of the authors' knowledge.

There are various ways of implementing the grid synchronization method, as discussed in [16, 17, 18, 19]. Here, the synchronous reference frame (dq) control is selected due to its simplicity and robustness in steady state. PI-controllers are used throughout. In Fig.3, the one-line diagram of the electrical circuit is displayed along with the basic blocks of the grid power control system. Each WEC is passively rectified, and the DC-bus is common for all inputs. A two-level voltage-source inverter (2L-VSI) is used to synthesize the sinusoidal voltage output. A step-up tap transformer is used in series with an LCL-filter. The offshore point of common coupling is defined as the substation end of the sea cable. To compensate for sea cable charging and to get unity power factor onshore, an offset in reactive power is injected from the substation. The voltage at the offshore PCC is detected, and the reactive power produced by the sea cable is calculated by:

$$Q = 3\omega CV_{LN}^2 \quad (1)$$

where ω is the grid frequency, C the cable capacitance and V_{LN} the grid phase voltage. This reactive compensation will work irrespective of the active power transmission.

The grid voltage phase is tracked by means of a phase-locked loop (PLL). The grid currents are transformed into the stationary dq-reference frame, and used to control active and reactive power independently. The DC-voltage is used as a reference for active power balance, while the reactive power is set

Figure 3: Overview of the electrical circuit and the grid control system. The WECs are connected to the marine substation by their individual contactors B_{WEC} . The marine substation is connected to the subsea power cable with the contactor B_{PCC} , and the connection of the sea cable to the onshore grid is done with the contactors B_{damp} and B_{bypass} . The purpose of these is further described in Sec. 5b.

to the offset given by Eq.1. To get a more dynamic control response, cross-coupling terms must be included between the active and reactive parts, as discussed in [20]. This would be needed for grid fault ride-through, which is not the case at these power levels.

3. WEC damping control

To optimize the absorbed wave power, both mechanical and electrical damping control strategies have been proposed. In [21], the optimal resistive load was evaluated as a function of sea state. To boost the power absorption further, an external passive resonance circuit was suggested in [22]. For better generator efficiency, the power factor of the generator current has to be improved. This can be done by means of a boost PWM converter [23, 24]. Another damping control method of point-absorbers is reactive control, also referred to as optimum control or complex-conjugate control. This can be performed electrically by means of a bidirectional active rectifier, as suggested in e.g. [25, 26, 27]. Despite the improved WEC performance, many of these topologies suffer from: increased control complexity, need for precise wave prediction, larger investment costs, semiconductor device losses, and an overall reduced reliability. For WECs with a more modest power output, a simpler strategy may be advantageous. In [28, 15], passive rectification onto a constant DC-bus is evaluated, where the optimal DC-

voltage is a function of the sea state. Since the DC-bus is common for all the WECs, the WEC control strategy becomes very simple, and is allocated to the grid-side control of the marine substation. Assuming the WECs in the farm have the same characteristics, and the shadowing effects between buoys are negligible, the same value of V_{DC} can be used without penalty in the power output. If this is not the case, different DC-buses with different V_{DC} can instead be adopted for the different WECs. In the current set-up, there is also a possibility to connect a DC/DC boost converter, and compare the two damping strategies.

4. Automatic grid connection procedure

The control system is implemented in a real-time controller and a field-programmable gate array (FPGA), using the Labview compactRIO module. This is capable of autonomous control, and will send status updates for possible monitoring to a remote PC. In Fig.4, the automatic grid connection process is described step-by-step. These will be described in the subsections below.

4.1. Sea cable connection

Prior to the start-up of the substation, the sea cable is connected to the grid. Due to the capacitive nature of the sea cable, an instant connection will result in large charging inrush currents. This may be followed by resonance between the cable and the onshore transformer, and possibly saturation of the transformer. The cable capacitance is $145\mu F$ and the onshore transformer leakage inductance is $2.7mH$, resulting in a resonance frequency at 254Hz. Fig.5a shows the 1kV/11kV transformer installed onshore. A picture from the deployment of the subsea power cable is presented in Fig.5b. The only current-limiting parameter is the resistance in the transformer windings and sea cable. A commonly used strategy is to bypass the transformer overcurrent protection, so that it will not trigger at the inrush current. This option is, however, not available at the Lysekil site. The issue of high inrush currents may be solved by soft charging, using a thyristor circuit where the firing angle is gradually decreased. Once the cable is charged and stable, the thyristors may be bypassed. An even simpler strategy is used here. External damping resistors are connected in series with the sea cable by the contactor B_{damp} , as shown in Fig.3. Once the system has stabilized, B_{bypass} is turned on to

Figure 4: Procedure for the automatic grid connection.

bypass the resistors. The damping resistor value is set to 9Ω per phase, which will limit the inrush current to less than 100A.

4.2. Grid phase tracking

The grid phase is tracked for two reasons. Primarily, it is used for the grid current reference frame, to control active and reactive power. Secondly, it works as a check-point that all phases are connected, and to determine the sequence of connection. The sequence of the grid voltages is detected and accounted for in the current-control feedback loop. This is to match the sign of the PI feedback errors with the sign of the PI control coefficients. Otherwise, there is a risk the feedback control will not work. There are various known methods to track the grid phase based on the grid voltages, such as the zero-crossing detection (ZCD), the phase-locked loop (PLL) and the Kalman filter. A more detailed comparison of these can be found in [29]. In this set-up, the PLL-loop is selected. The phase order does not affect the dynamics of the PLL-loop. In a balanced and non-distorted grid, the dq-terms of the

Figure 5: To avoid inrush current, the sea cable is connected to the onshore transformer via damping resistors. (a) shows the 1kV/11kV 200kVA power transformer installed onshore. In (b) the deployment of the offshore power cable is conducted.

voltage are constants. V_{dq} is calculated by the Park/Clarke transformation as [30]:

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (2)$$

The PI-controller of the PLL works as a low-pass filter, making it insensitive to measurement noise, switching ripple and grid notches. A sequence filter may be added if there is a problem with unbalance in the grid voltage, but this has to match the sequence connection.

If one or two grid phases are lost, this is directly reflected in V_{dq} , which in turn may be used to detect the phase loss. In Fig.6, the PLL output is shown when one and two phases are lost respectively.

To confirm all phases are connected and the PLL has synchronized, the V_{dq} -values are monitored. If they stay within their pre-calculated values ($\pm 5\%$) for at least 50 fundamental cycles (1 s), the next step is initiated in Fig.4.

4.3. WEC connection

The WECs are connected to the marine substation via their respective contactor B_{WEC} . In case of a grid-fault, the DC-voltage of the capacitor

(a) PLL output with one grid phase lost.

(b) PLL output with two grid phases lost.

Figure 6: Experimental measurements of the grid voltage in dq-frame, with one or two phases lost.

bank may get overcharged by the WECs. The DC-voltage is monitored, and if it exceeds the safe operating range of the DC-capacitors, the WECs will be disconnected. Once they have been connected, the WECs will not be disconnected unless there is a permanent (as opposed to transient) grid fault. This is implemented to protect the DC-bank from getting overcharged. Some WECs have an associated resistive damping load that is connected to keep them damped when they are disconnected from the substation. Other WECs are designed to withstand undamped conditions. If a WEC gets connected to the substation during high translator speed, and the DC-level is low, there may be large inrush currents from the WEC. To reduce the stress on both the WEC and the input contactor B_{WEC} , the contactors are programmed to

only turn on when the translator is close to an endstop (or near stand-still). The translator velocity $\dot{x}$ is coupled to the induced stator voltage V_{abc} by:

$$|\dot{x}| = A(x)k[\max(V_{abc}) - \min(V_{abc})] \quad (3)$$

where $A(x)$ is the relative active magnetic area in the generator, which is a function of the translator position x . The parameter k represents the coupled inductance between the stator and the translator, and is typically in the range of $10^{-3}[\frac{m}{V_s}]$. By monitoring the voltage envelope, $\dot{x}$ can be approximated, assuming maximum active area ($A(x) = 1$) in Eq. 3. B_{WEC} can be turned on when $\dot{x}$ is sufficiently low. In Fig.7, this is demonstrated. When $\dot{x}$ is below the set threshold limit $\dot{x}_{th}$, it is safe to turn on the contactor.

Figure 7: Experimental measurements of one WEC. The translator speed is calculated from the voltage envelope according to Eq.3, and is used to detect when the translator is near stand-still. By connecting the WEC during this time, the current stresses on the WEC and the contactor B_{WEC} are reduced.

4.4. DC-level charging

There are two options in how to charge the DC-bus, either by the WECs or by the grid itself. In the second, the VSI operates in rectification mode. However, if the grid is directly connected to a discharged DC-bus, the inrush currents will be very high, and there may be resonance between the sea cable and the substation transformer. If the VSI is up and running, the DC-bus can be charged smoothly. To avoid this extra control sequence, the DC-bus is

instead charged directly by the WECs. This will also give a good indication on the current sea state. If the DC-level is not charged fast enough, the sea state is not considered good enough for grid connection, as the internal losses of the system are anticipated to be higher than the input power from the WECs.

The required V_{DC} is calculated in Sec.4.6, but will have to be higher to compensate for the sea cable reactive power. Depending on sea state, the tap transformer turns ratio may be selected to match the WEC voltage output.

4.5. Transformer magnetization and voltage synchronization

As discussed in Sec. 4.1, large inrush currents may flow when the transformer is connected to the sea cable. In the substation, the transformer is pre-magnetized softly using the VSI. The transformer output voltage is synchronized with the grid voltage at the offshore PCC. The error is fed into an integral controller loop with very long time constant. This is used to ramp up the transformer voltage and reduce the effects of any remanent flux. In Fig.8, the transformer voltage is synchronized to the 1kV grid over a period of 3 s. When the voltages on both sides of the contactor B_{grid} are synchronized, B_{grid} is closed. At this moment, the VSI control is switched to the current control loop described below.

4.6. PQ-control

The basic power equations are derived assuming a stiff, lossless grid with grid impedance X . The active power P and reactive power Q for a grid-connected VSI are governed by:

$$P = \frac{|V_g||V_i|}{X} \sin(\delta) \quad Q = \frac{|V_g||V_i|}{X} \cos(\delta) - \frac{|V_g|^2}{X} \quad (4)$$

where V_g is the grid voltage and $V_i \angle \delta$ is the inverter voltage.

Here, the sinusoidal pulse-width modulation (SPWM) control has been used [31], where a control signal V_c is compared with a carrier wave signal to generate the inverter output pulses. V_c is generated by:

$$V_c = V_{cd}^* \cdot \sin(\omega t) + V_{cq}^* \cdot \cos(\omega t) \quad (5)$$

$$= m_a \sin(\omega t + \delta) \quad (6)$$

where V_{cd}^* and V_{cq}^* are current-control feed-back variables used to control the active and reactive power flows. The amplitude modulation index is

(a)

(b)

Figure 8: Experimental results with smooth magnetization of the transformer and synchronization to the grid voltage at 1kV. In (a) the transformer is slowly magnetized to its rated voltage. In (b) the initial voltage curve is shown. It will be slightly distorted due to the remanent flux in the transformer, but will soon stabilize.

$m_a = \sqrt{(V_{cd}^*)^2 + (V_{cq}^*)^2}$ and the load angle is $\delta = \tan^{-1}(\frac{V_{cq}^*}{V_{cd}^*})$. If $m_a < 1$, the inverter fundamental output phase voltage V_{i1} is derived as:

$$V_{i1} = m_a \frac{V_{DC}}{2\sqrt{2}} \quad (7)$$

4.7. Low sea state

The power in the waves fluctuates with different time constants. First of all, the wave-to-wave power fluctuation occurs in the range of seconds. Also,

the average sea state can vary widely in timescales ranging from 20min up to tens of hours. There are also seasonal variations. In deep water, the average power of the waves can be derived using linear potential wave theory [32] as:

$$J = \frac{\rho g^2}{62\pi} T_E H_s^2 [W/m] \quad (8)$$

where $\rho = 1025 kg/m^3$ is the sea water density, $g = 9.81 m/s^2$, T_E is the average energy period of the waves and H_s is the significant wave height. From this, the WEC absorption has been measured up to 25% for passive rectification [33].

When the average power from the wave farm into the substation is lower than the internal losses of the system (primarily transformer magnetization losses), which will occur at very low sea states, the substation is disconnected from the grid and put in stand-by mode. The sea state is monitored by an external wave rider buoy. The total active power output from the substation will also be a good indication of the current sea state. In stand-by mode, the WECs are still connected to the substation, and the DC-level is monitored. When V_{DC} increases again, the transformer is re-magnetized. If the system is able to keep the magnetization without a drop in V_{DC} , the sea state is considered sufficiently energetic to reconnect with the grid.

5. Grid harmonic distortion

It is important to keep the total harmonic distortion (THD) of the grid current low to comply with the grid code requirements (IEEE 519-1992). This is especially important for weak grids where the grid voltage may easily become distorted. It is anticipated that future wave energy farms will be connected to the distribution network [34], which are often characterized by higher grid impedance, and thus a weaker PCC. In these cases, the WEC farms will play an important role in maintaining a good power quality. There are various ways of improving the power quality: active, passive and hybrid solutions [35]. In the current set-up, harmonic compensation is possible for either the grid current or the grid voltage. For the second one, a FFT of the grid voltage is calculated. Harmonic currents are injected to counter-induce the voltage harmonics. Fig.9a shows one example of how the 5th and 7th grid voltage harmonics are reduced, injecting the currents in Fig.9b. In this example, the harmonic compensation is performed in parallel with the injection of 10 kW at unity power factor. For larger installations, a separate

Figure 9: The grid-connected VSI is also utilized to improve the grid voltage quality. (a) shows experimental results for active voltage harmonic reduction of the 5th and 7th grid voltage harmonics. (b) shows the harmonic current required for this, while supplying 10kW at unity power factor.

power conditioner should be used instead. It is, however, important to keep track of resonances in the system, especially between the harmonic LCL-filter, the sea cable and the transformers.

6. Fault handling

A fault detected at the offshore PCC may be due to an internal fault in the substation, or an external fault in the grid. The common grid faults include:

- One or two grid phases lost connection
- Balanced or unbalanced voltage dips
- Overcurrents/Short-circuit currents

If two of the grid phases are lost, the third will not conduct as no neutral is connected. This is equivalent to a complete loss of the grid, and will result in overcharging of the DC-bus by the WECs. The WECs have to be disconnected immediately. As additional hardware protection, there are also varistors connected across the DC-buses, that will short-circuit in case of the DC-bus getting charged above its rating.

If one phase is lost onshore, this will probably result in severe ferro-resonance between the sea cable and the substation transformer. As no fault-currents will be detected, no overcurrent protection or fuse will trip. If unfortunate, this results in an overvoltage at the substation transformer terminals, resulting in a winding voltage overshoot. To avoid this, the entire system is disconnected if one phase is continuously lost. Also, only three-phase breakers are used to always disconnect all phases simultaneously.

To compensate for voltage dips and unbalances, grid codes may require reactive power compensation to maintain the grid voltage. However, this is mostly applicable to units above 5 MW. If $P < 5MW$, as is the case for the wave power farm in this paper, unity power factor is usually accepted. Thus, no such control has been implemented in this set-up. According to the IEEE 1547 *Standard on Interconnecting Distributed Generation*, distributed generation on this power level should not try to alter the grid voltage in case of a grid fault. Instead, they should disconnect from the grid within time range of 2s.

Most faults in the grid voltage will be reflected in the grid current. Thus, these are continuously monitored, and if they exceed an overcurrent limit, the contactor B_{grid} is turned off. Overcurrents and short-circuits across the inverter are more time-critical than the contactor response time, and have to be monitored by a desaturation protection across each semiconductor device. The collector-emitter voltage V_{CE} across an IGBT is a function of the current I_d . If this is detected high despite the device has been turned on, a short-circuit is concluded and the device is turned off again. A capacitor of a passive RC-network is charged in case of a fault, and when the capacitor voltage exceeds a threshold voltage, the protection is triggered. The RC-

values set the delay time of the protection according to:

$$\tau_d = \frac{k_{desat}}{V_{CE}} \quad (9)$$

where $k_{desat} = 920 \cdot 10^{-6} [Vs]$. The delay time before turning the device off is a function of V_{CE} , which equals V_{DC} during a short-circuit. The relation between τ_d and V_{CE} is shown in Fig.10a. To keep the fault time below $10\mu s$, V_{DC} is always kept above 100V. To make the delay time independent of V_{DC} , a digital desaturation protection must be implemented.

When an overcurrent is detected, the VSI is abruptly turned off for the next 20 ms. If the reason for the fault was temporary, the VSI will continue its operation. However, if the phenomena reappear more than five times in a row, the substation is disconnected completely from the grid, and tries to resynchronize. In Fig.10b, the grid currents are displayed when the desaturation protection is triggered repeatedly. Observe how the grid currents change into charging currents of the filter capacitor when the VSI is turned off.

7. Energy buffer

If there is a stiff link between the WEC input power and the power fed to the grid, i.e. no intermediate storage, the fluctuating power absorption of the WECs is directly reflected in the grid active power. If the fluctuations are sufficiently large, or if the grid point is weak, this will result in local voltage fluctuations. The resultant lighting intensity oscillations are referred to as flicker. As the number of WECs in the farm increases, the relative power fluctuations are expected to reduce. This is shown experimentally for a wave power farm of three WECs in [36], and in [37] the power fluctuations are evaluated as a function of the farm layout, using 32 WECs. However, active flicker suppression may still be required, especially if the PCC is weak. This is done by either active or reactive power compensation. Reactive power compensation is limited by the grid impedance as well as the equipment ratings, whereas active power compensation requires an external energy storage.

To mitigate power fluctuations from the substation, a large capacitor bank of $0.25F$ has been installed as a short-time energy storage. The necessary capacitor size C depends on the allowed DC-voltage range $[V_{DC,low} V_{DC,up}]$ and must full-fill:

$$\frac{1}{2}C(V_{DC,up}^2 - V_{DC,low}^2) = \int_{t_1}^{t_2} \left(\left(\sum_{n=1}^N P_{WEC}(t) \right) - \bar{P} \right) dt. \quad (10)$$

(a) Desaturation protection delay time as a function of V_{CE} . The experimental results are compared with the theoretically derived based upon Eq. 9

(b) The overcurrent protection is allowed to trip and reset 5 times, before a manual reset is required. The plot shows grid currents where a fault has been simulated in the control system.

Figure 10:

where $P_{WEC}(t)$ is the WEC power input and $\bar{P}$ is the average active grid power. If the substation transformer is operating on a higher tap, it may be stepped down to utilize more of the DC-bank, in case of a required discharge.

There is a contradiction between the constant DC-link damping strategy and using a large capacitor bank as energy buffer. It is clear from Eq.10

that variations in V_{DC} must be allowed. Thus, a compromise between WEC power optimization and flicker levels has to be accepted. An active rectifier, on the other hand, would allow for a much wider operating range of V_{DC} .

8. Conclusion

The control system for grid connection of a wave power farm has been developed and implemented in a full-scale prototype marine substation. The substation is able to safely and autonomously connect the WECs and transfer the WEC power to the grid. Each step of the grid integration has been described and experimentally validated. Different types of faults have been taken into account, and the WEC farm is set to stand-by during low sea states. Compensation for grid harmonics and flicker have also been discussed and implemented.

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