All-Electric Wave Energy Converter with Stand-alone 600VDC Power System and Ultracapacitor Bank.

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INTRODUCTION:

We are going to talk about Wave Energy Converter, in order to that we focus in the rectifiers, converters and ultracapacitor. We want to get energy from the wave movement. Then we need a generator to transform, later we use a rectifier to converter and we get dc voltage. Finally we use a inverter and there will be ac voltage. Between rectifier and inverter we can put an ultracapacitor (dc-dc converter), it is used to storage energy.

WAVE ENERGY:

To make use of the force we need a counter force. The heaving buoy reacts against a fixed anchor on the sea bed. This produces a force which is transmitted by mooring line to the winch. We can use that force to rotate the gearbox to produce energy in the generator.

The energy which is obtained from the waves is related to the force shown below:

\[ F = kX = \rho_w g A_b \]

We assume that this equation is for a cylinder and it supports the Archimede’s principle. The force of up-lift is the weight of the displaced water.

According to the mass balance, the mass is setting by:

\[ m = \rho_w A_b L \]

Being \( \rho_w \) the density of the water and \( A_b \) the area of the cylinder’s base.

Finally, it’s obtained the definition of the eigen frequency:

\[ \omega = \sqrt{\frac{\rho_w g A_b}{\rho_w A_b L}} = \sqrt{\frac{k}{m}} = \sqrt{\frac{g}{L}} \]
SYSTEM DESCRIPTION:

The electrical system is based on a common DC-bus that serves as the backbone for the internal power transfer. To make up for the missing grid converter a supply power is required with the bi-directional DC-Link. It is expected that the system produce a power surplus on average during a operation; although the stand-alone DC-system can only supply a very limited power.

It should be noted that the instantaneous power consumption can be high during pullback for short periods and is supplied by the capacitor bank.

The ultracapacitor bank should only be discharged to half of the nominal voltage during normal cycling. Moreover, the ultracapacitor bank can be directly connected to the DC-Link.
Rectifier:

Becoming more, it is frequent to use the inexpensive rectifiers with diodes to convert the input ac into dc in an uncontrolled manner.

A single-phase diode bridge rectifier is shown down. A large filter capacitor is connected on the dc side due to we want that the output voltage of a rectifier would be as ripple free as possible. The utility supply is modeled as a sinusoidal voltage source $V_s$ in series with its internal impedance, which in practice is primarily inductive.

In our project we use three-phase rectifiers, it is preferable to use three-phase rectifier circuits, compared to single-phase rectifiers. This is because the single-phase rectifiers contains significantly more distortion compared to a three-phase rectifier.

![Diagram of a single-phase diode bridge rectifier.](image1)

![Diagram of a three-phase full-bridge rectifier.](image2)

Figure 5-30 Three-phase, full-bridge rectifier.
Inverter:

The inverter is a converter dc-ac:

- **Pulse-width-modulated inverters**: The input dc voltage is essentially constant in magnitude. The inverter must control the magnitude and the frequency of the ac output voltages.

- **Square-wave inverters**: The input dc voltage is controlled in order to control the magnitude of the output ac voltage, and therefore the inverter has to control only the frequency of the output voltage.

- **Single-phase inverters with voltage cancellation**: It is possible to control the magnitude and the frequency of the inverter output voltage.

It is possible to assume that $V_o$ is sinusoidal. Since the inverter supplies an inductive load such as an ac motor, $i_o$ will lag $v_o$.

The output waveforms show that $i_o$ and $v_o$ change from positive to negative:
- If $P_o > 0$, the converter works in the inverter mode of operation.
- If $P_o < 0$, the converter works in the converter mode of operation.

One of the most important things is that the two switches are never off simultaneously.

![Diagram of inverter circuit](image)

**a) PULSE-WIDTH-MODULATED SWITCHING SCHEME:**

In order to generate the switching signals a control signal $v_{control}$ is compared with a repetitive switching-frequency triangular waveform. Controlling the switch duty ratios, the average dc voltage output to be controlled.

The frequency of the triangular waveform establishes the inverter switching frequency and is generally kept constant along with its amplitude $V_{tri}$. 
The amplitude modulation ratio is:

\[ m_a = \frac{\dot{V}_{control}}{\dot{V}_{tri}} \]

The frequency modulation ratio is:

\[ m_f = \frac{f_s}{f_1} \]

Small \( m_f (m_f < 21) \)

The triangular waveform signal and the control signal should be synchronized to each other. \( m_f \) should be an odd integer.

Large \( m_f (m_f > 21) \)

The amplitudes of subharmonics due to asynchronous PWM are small at large values of \( m_f \).

Overmodulation \((m_a > 1)\)

\( m_a \leq 1 \) sinusoidal PWM in the linear range. Overmodulation causes the output voltage to contain many more harmonics in the side bands as compared with the linear range.

**SINGLE-PHASE INVERTERS:**

**Half-bridge inverters**

Two equal capacitors are connected in series across the dc input and their junction is at a midpotential, with a voltage \( 1/2V_d \) across each capacitor. When \( T_+ \) is on, either \( T_+ \) or \( D_+ \) conducts depending on the direction of the output current, and \( i_o \) splits equally between the two capacitors. When the switch \( T_- \) is in its on state occurs the same.
Full-bridge inverters (single phase)

Full-bridge inverters consists of two one-leg inverters. With the same dc input voltage, the maximum output voltage of the full-bridge inverter is twice that of the half-bridge inverter. This implies that for the same power, the output current and the switch currents are on-half of those for a half-bridge inverter.

Push-pull inverters

It requires a transformer with a center tapped primary. We will initially assume that the output current $i_o$ flows continuously.

When $T_1$ is on, $T_2$ is off. $T_1$ would conduct for a positive value of $i_o$, $D_1$ would conduct for a negative value of $i_o$.

The main advantage of the push-pull circuit is that no more than one switch in series conducts at any instant of time.

THREE-PHASE INVERTERS

In applications such as uninterruptible ac power supplies and ac motor drives, three-phase inverters are commonly used to supply three-phase loads. It is possible to supply a three-phase load by means of three separate single-phase inverters, where each inverter produces an output displaced by $120^\circ$.

The most frequently used three-phase inverter circuit consists of three legs, one for each phase. The output of each leg depends only on $V_d$ and the switch
status; the output voltage is independent of the output load current since one of the two switches in a leg is always on at any instant.

**PWM in three-phase voltage source inverters**

The objective is to shape and control the three-phase output voltages in magnitude and frequency with an essentially constant input voltage $V_d$.

**Linear Modulation ($m_a \leq 1$)**

In the linear region, the fundamental-frequency component in the output voltage varies linearly with the amplitude modulation ratio $m_a$.

$$(\hat{V}_{AN})_1 = m_a \frac{V_d}{2}$$

**Overmodulation ($m_a < 1$)**

In PWM overmodulation, the peak of the control voltages is allowed to exceed the peak of the triangular waveform. The fundamental-frequency voltage magnitude does not increase proportionally with $m_a$. 
**Ultracapacitor:**

The performance of a battery-ultracapacitor hybrid power source under pulsed load conditions is analytically described using simplified models. We show that peak power can be greatly enhanced, internal losses can be considerably reduced, and that discharge life of the battery is extended. Greatest benefits are seen when the load pulse rate is higher than the system eigen-frequency and when the pulse duty is small. Actual benefits are substantial; adding a 23 F ultracapacitor bank (37 PC10 ultracapacitors) in parallel with a typical Li-ion battery of 7.2 V and 1.35 A hr capacity can boost the peak power capacity by 5 times and reduce the power loss by 74%, while minimally impacting system volume and weight, for pulsed loads of 5 A, 1 Hz repetition rate, and 10% duty.

ULTRACAPACITORS (or electrochemical double layer capacitors, supercapacitors) are increasingly interesting because of their high-energy density (compared to conventional capacitors) and high-power density (compared to batteries and fuel cells). Reports of ultracapacitor applications in power distribution systems, and in utility electronic apparatus have described improvements in power quality, uninterrupted power supply (UPS), and memory backup. Considerable efforts have been invested to exploit the high-power capability of ultracapacitor hybrids with batteries or fuel cells in pulsed operating modes, which are of particular interest to portable power systems, electric vehicles and digital telecommunication systems. Advanced battery technologies now allow extraordinary energy densities, but often insufficient power densities for applications where the load draws large power impulses. This deficiency can be overcome by paralleling more batteries if that is allowed by system volume, weight, and cost constraints. On the other hand, parallel hybrid power sources that combine advanced batteries with ultracapacitors can overcome the power deficiency at lower monetary, volumetric, or weight cost. Such systems have been experimentally demonstrated longer operating times compared to systems without ultracapacitors. However, the literature is deficient in theoretical analysis of such systems with respect to energy efficiency, power capabilities and cost effectiveness. It is of practical importance for engineers to have some reasonable theoretical basis to achieve optimized system designs.

For example, in the figure below is shown Circuit of an ultracapacitor in parallel with a battery, and its Thevenin equivalent in frequency domain:
Thevenin equivalent:
SIMULATION WITH PSpice
The page before shows the simulation with PSpice in which is measured the three ac input voltages and the dc output voltage.

In the next page, there are two graphics where are represented the three waveforms of the ac input voltages on the top (Va, Vb, Vc) and the dc output voltage waveform on the bottom. In this case the value of the capacitor is 1nf.

According to the values of the capacitor, the waveform obtained for the dc output voltage varies. This is shown with the second image of the simulation in which other two graphics appear. On the top, we can see again the same dc input voltages (Va, Vb, Vc) but the other one is the output waveform for a capacitor of 1mF. Comparing the waveforms of the capacitor for 1nf and 1mF, it is shown that with higher values of the capacitor, the wave is more continuous.
Mockup

To finalize, it has been made a mockup to demonstrate how to take energy from the waves.

This mockup consist of a generator and a tank with water inside.

The generator has been built up with:
1. A circular iron plate with six permanent magnets glued on it.
2. A circular plastic plate with coils glued on it.
3. A metal body for holding up the plates described above.
4. A shaft to supply the rotation of the generator.

The tank has been made with plastic and consists of a big amount of water inside and a circular cork which floats on the water. Moreover there is a cable connected to the cork to be able of measuring the strength of the waves.

What we want to obtain is the value of the output voltage in the generator and discuss according to the values measured if it is necessary to include a rectifier. We have done the first test with one coil (60 turns) and one permanent magnet.
The results show the following values for different distances:

- **d=2mm**

![Image of d=2mm graph]

- **d=10 mm**

![Image of d=10 mm graph]

With these images we can see that the peak-voltage is higher with lower distances between the coils and the permanent magnets.

In order to compute the voltage, it is possible to use these formulas:

\[
U = N \frac{d\phi}{dt} = N\phi \frac{d}{dt}\sin(\omega t)
\]

\[
U = N\phi\omega
\]

\[
U_{RMS} = \frac{U}{\sqrt{2}}
\]
It is known that if the area of the coils was high the voltage would be high too.

\[ \phi_{\text{coil}} = A_{\text{coil}} \times B_{\text{avg}} \]

This mockup represents this part of the electrical system: the generator followed by the rectifier.

At the same time, there are diodes to the output.

The performance of diodes is explained below:

From the six coils of the generator, three are connected in serie with the two antiparallel red diodes and the same occurs with the other three coils and the two green diodes. It is depending on the direction of the current a diode of every pair is switched on. It is possible to imagine the operation with the next figure:
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