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Forced commutation controlled series capacitor (FCSC) circuit applied to stand-alone wave energy conversion buoys

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Stand-alone buoys are used as navigation aids and for scientific marine research, including the measurement of seismographic movements of the seabed as part of a tsunami warning system. Solar power is commonly used to power up the electronic devices of these buoys. However, due to limitations in delivering constant power from solar panels, linear electric generators have been employed as an alternative/additional power source to convert the energy of oceanic waves into electricity. The variable AC amplitude and frequency of the generated voltage waveform is usually converted to DC using a simple, low cost diode bridge rectifier resulting in a low operating power factor (PF) and low power transfer capacity because of the high inductive reactance of linear electric generators. A Forced Commutation Controlled Series Capacitor (FCSC) technique is employed in this paper to improve the PF of these variable amplitude and very low and variable frequency devices. FCSC circuits have been employed in the past in power transmission networks where the voltage and frequency are fixed, but never in a wave power application where the amplitude and frequency of the AC voltage are variable. This paper provides an analytical description of the proposed FCSC converter. The method is experimentally demonstrated and evaluated using a 2.25kVA test circuit. A comparison of the performance of the FSCS circuit with a standard uncontrolled single-phase diode bridge rectifier circuit is included.
A buoy’s electronic equipments generally include a central processing unit, batteries, lights and, depending of the buoy’s function, a transmitter. In order to power up the electronic equipment, solar panels are usually employed for generating power which is then stored in the device batteries. The use of solar panels, however, has limited applications. For example in areas with frequent cloud cover, solar energy might not be a viable source. As an alternative to solar energy, stand-alone buoys can utilise the energy from ocean waves using a linear electric generator connected to a power rectifier to convert the AC variable amplitude and frequency of the generated voltage waveform to the required DC voltage.

Stand-alone Wave Energy Conversion (WEC) buoys come in different shapes and sizes and can operate to a maximum power level of 3kW. As the movements of the waves are slow, so is the electric frequency generated by the machine. Commonly used single-phase machines operate between 0 and 3Hz, but machines generating frequencies up to 21Hz have also been reported. The slow oscillation produced by WECs. These machines convert the slow motion produced by WECs. These machines convert the slow motion of the translator into a high rate of change of flux, which is required for large emf generation.

Variable reluctance permanent magnet machines, such as transverse-flux and vernier hybrid machines, have been specifically developed for the slow motion of the translator into a high rate of change of flux, which is required for large emf generation.

Variable reluctance permanent magnet machines have a major drawback however, namely a high machine inductance resulting in a low operating power factor. Many studies have therefore been published focusing on novel machine designs to reduce the generator inductance, but with limited success. Other techniques include the use of a DC/DC boost rectifier or a PWM rectifier with PF correction to improve the operating PF of the machine and hence obtain higher power transfer efficiencies. However, circuits making use of a DC/DC boost rectifier operate at high switching frequencies leading to high switching losses while PWM rectifier circuits require four switching components increasing system cost and control complexity.

A third method using capacitive series compensation to improve the PF in a WEC device has also been suggested. In this technique, a fixed capacitor is added in series with the machine inductance to reduce the effective inductance of the circuit and hence improve the performance of the system. This, however, improves the operating PF for one electric frequency only and is of limited value in WEC applications where the generated electric frequency is variable. To overcome this limitation, the use of a variable series compensation capacitor for WEC devices is proposed. Fig 1 shows a schematic diagram of such a variable capacitor series compensation circuit where \( L_m \) and \( R_m \) are the machine inductance and resistance, respectively, and \( V_m \) is the back EMF of the generator. The variable capacitor \( C_{var} \) is connected in series with the generator, as shown.

Frequency controlled variable capacitors are not commercially available and thus the use of a capacitor in combination with a power electronic circuit that changes the effective value of the series capacitance is proposed. These electronically controlled capacitor circuits can be readily found in high voltage power transmission circuits where they are commonly referred to as Controlled Series Capacitors (CSC). To-date CSCs have never been applied in low power variable-frequency, variable-voltage applications such as WEC buoys. Based on simple simulation models, an overview of possible CSC circuits for buoys applications showed that the forced-commutated CSC circuit (FCSC) offers the biggest potential benefits in terms of improved power factor, higher power capture ability and lower costs.

The design, construction and test of a FCSC circuit applied to a WEC device is presented in this paper. The operation of the circuit is experimentally verified using a 2.25kVA prototype test circuit showing very good agreement between measurement and predicted results. Test results are also shown to compare the performance of the proposed FCSC scheme with that of a standard single-phase diode bridge circuit device.

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**FORCED COMMUTATION CONTROLLED SERIES CAPACITOR (FCSC)**

The FCSC scheme consists of a capacitor and a pair of forced-commutation switches such as IGBTs connected in anti-parallel, as shown in Fig 2.

The effective capacitive reactance \( X_c \) of the supply can vary from its minimum value of \( X_c = 0 \) when the IGBT switches \( S_1 \) and \( S_2 \) are permanently closed, to a maximum of \( X_c = 1/(\omega C_{cyc}) \) when \( S_1 \) and \( S_2 \) are open. The effective capacitive reactance \( X_c \) of the circuit, for a given machine current \( I_m \), can therefore be varied by controlling the duty cycle of the IGBT switches, ie, by closing and opening \( S_1 \) and \( S_2 \) once in each half-cycle, in synchronism with the AC system’s frequency, to vary the AC voltage \( V_c \) across the capacitor:

\[
X_c = \frac{V_c}{I_m}
\]

(1)
Depending on the polarity of $I_m$, the appropriate IGBT switch is turned on when the current crosses zero. The switch is then turned off with a delay angle $\gamma$ ($0 \leq \gamma \leq \pi$) corresponding to the angle between the peak of the machine’s current and the zero crossing of the back EMF voltage as demonstrated in Fig 3. The switch is on from $\omega t = 0$ to $\omega t = (\pi/2 + \gamma)$ and off from $\omega t = (\pi/2 + \gamma)$ to $\omega t = \pi$.

The fundamental component of the capacitor voltage as a function of the delay angle $\gamma$ is given by the following equation:

$$V_c(\gamma) = \frac{I_m}{\omega C_{FCSC}} \left(1 - \frac{2}{\pi} \gamma - \frac{1}{\pi} \sin 2\gamma\right)$$ (2)

Consequently, the overall capacitive reactance $X_c$ is also a function of $\gamma$ and the FCSC circuit behaves like a variable capacitive impedance:

$$X_c(\gamma) = \frac{V_c(\gamma)}{I_m} = \frac{1}{\omega C_{FCSC}} \left(1 - \frac{2}{\pi} \gamma - \frac{1}{\pi} \sin 2\gamma\right)$$ (3)

In order to minimise the total reactance of the circuit ($X_c = X_i$), the correct delay angle $\gamma$ must be applied. However, $\gamma$ cannot be calculated in real time as operating conditions change. This is because equation (3) is a transcendental equation resulting in a very high processing requirement. For given capacitance and machine inductance values, the delay angle $\gamma$ must therefore be stored in a look up table as a function of frequency.

Using a commercially available capacitor value of 420µF, Fig 4 shows the variation of reactance $X_c$ with frequency for different values of delay angle $\gamma$ (generator parameters are given in the appendix). Fig 4 also shows the variation of the inductive reactance $X_i$ of the generator with the frequency of the supply. The interception points between the $X_c$ and $X_i$ lines represent the minimum reactance operating points at the given frequencies.

Table 1 shows the delay angles calculated for minimum reactance at different frequencies.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Delay angle $\gamma$ (° degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>45.86</td>
</tr>
<tr>
<td>11</td>
<td>42.99</td>
</tr>
<tr>
<td>12</td>
<td>40.13</td>
</tr>
<tr>
<td>13</td>
<td>37.26</td>
</tr>
<tr>
<td>14</td>
<td>34.39</td>
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<tr>
<td>15</td>
<td>31.53</td>
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<tr>
<td>16</td>
<td>28.66</td>
</tr>
<tr>
<td>17</td>
<td>25.80</td>
</tr>
<tr>
<td>18</td>
<td>22.93</td>
</tr>
<tr>
<td>19</td>
<td>20.06</td>
</tr>
<tr>
<td>20</td>
<td>17.20</td>
</tr>
</tbody>
</table>

Table 1: FCSC delay angles for minimum reactance
OPERATION WITH AN UNCONTROLLED SINGLE-PHASE DIODE BRIDGE RECTIFIER

In stand-alone systems, cost is important and the use of a simple and low-cost converter is preferred. The standard single-phase diode bridge rectifier circuit is the simplest possible rectifier circuit and thus the most common in such applications. The rectifier does not have any voltage feedback control and the output voltage is determined exclusively by the amplitude of the input voltage. A schematic diagram of the standard single-phase diode bridge rectifier circuit is shown in Fig 5.

This type of rectifier provides a DC voltage at the output, for any AC voltage input. During the positive half cycle of the back EMF voltage waveform diodes D1 and D2 conduct; during the negative half cycle diodes D3 and D4 conduct. Because of the presence of the generator inductance, however, current cannot transfer instantly from diodes D1 and D2 to diodes D3 and D4 and there will be a period of overlap when current in D1 and D2 is falling and current in D3 and D4 is rising, causing a phase shift between the back EMF voltage \( V_m \) and the first harmonic of the generator AC current \( I_{m1} \), as shown in Fig 6.

On the DC side of the standard single-phase diode bridge rectifier, this ac phase shift between the generator voltage and the fundamental current waveforms is seen as a reduction in the mean value of the rectifier dc output voltage. This results in a loss of available power that could be transferred from the generator to the load. The duration of overlap, and hence the reduction in output power, is greater for greater values of generator inductance, load current and supply frequency. Significant improvements in power transfer can be made if the effective reactance of the generator could be minimised through the application of FCSC.

Assuming a purely sinusoidal back emf voltage, the generator power output \( P \) is given by the equation:

\[
P = V_m I_{m1} \cos \alpha\]

(4)

where \( \alpha \) is the phase angle between \( V_m \) and \( I_{m1} \). Minimising \( \alpha \) will clearly increase the power delivered to the load. This is the function performed by the proposed FCSC circuit.

\[
\begin{align*}
\text{Fig 4: Reactance } X_L(\gamma) \text{ (solid lines) and reactance } X_C \text{ (dashed line) as a function of electric frequency.}
\end{align*}
\]

\[
\begin{align*}
\text{Fig 5: Standard single-phase rectifier circuit for stand alone applications.}
\end{align*}
\]

\[
\begin{align*}
\text{Fig 6: Generator back EMF } V_m \text{ and the fundamental current waveform } (I_{m1}) \text{ showing the effects of overlap.}
\end{align*}
\]
EXPERIMENTAL COMPARISON BETWEEN THE STANDARD SINGLE-PHASE DIODE BRIDGE RECTIFIER AND THE FCSC CIRCUIT

The experimental set-up used in this investigation for both the standard single-phase diode bridge rectifier circuit and the FCSC circuit is described in this section. The aim was to construct and successfully operate the FCSC circuit under typical WEC low and variable-frequency, variable-voltage conditions to verify the above analysis and compare the results to those obtained with a standard single-phase diode bridge rectifier circuit.

A variable-voltage, variable-frequency AC power supply (EAC-3P-2000 AC power supply from ET Power Systems Ltd) capable of producing up to 270V and 2kW over a frequency range from 1Hz to 1kHz was used in conjunction with a function generator and a control board to synthesise the variable frequencies and variable voltages representing the back EMF waveform of the WEC generator, as shown in Fig 7. All laboratory tests were carried out for a frequency range from 10Hz to 21Hz, a frequency range that is becoming increasingly more popular in recent WEC designs. Most stand-alone WECs operate at low voltages (typically below 60V) but the laboratory power supply used in this investigation was unable to provide a stable AC waveform at these voltage levels. Therefore, the emulated back EMFs was set higher than those normally used in stand-alone buouys, Table 2 shows the emulated back EMFs and corresponding frequencies used in this investigation.

Based on OrCAD/PSpice simulations, the required value of the AC capacitor for the FCSC rectifier was found to be 420μF with a minimum voltage rating of 250V. A capacitor bank combining six General Electric 97F5251S capacitors each rated at C=70μF at 440V AC were connected in parallel to achieve the required values.

Table 2: Back EMF in relation to electric frequency

<table>
<thead>
<tr>
<th>Back EMF (V rms)</th>
<th>Electric frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>77</td>
<td>11</td>
</tr>
<tr>
<td>84</td>
<td>12</td>
</tr>
<tr>
<td>91</td>
<td>13</td>
</tr>
<tr>
<td>98</td>
<td>14</td>
</tr>
<tr>
<td>105</td>
<td>15</td>
</tr>
<tr>
<td>112</td>
<td>16</td>
</tr>
<tr>
<td>119</td>
<td>17</td>
</tr>
<tr>
<td>126</td>
<td>18</td>
</tr>
<tr>
<td>133</td>
<td>19</td>
</tr>
<tr>
<td>140</td>
<td>20</td>
</tr>
<tr>
<td>147</td>
<td>21</td>
</tr>
</tbody>
</table>

The two IGBTs were placed very close to the AC capacitor bank, in order to minimise any EMI effects. The two IXYS IXDR30N120D1 IGBTs were driven by two ACPL-J313-000E gate drivers from Avago Technologies. Two IXYS DSEP29-12A fast power diodes were added in series with each IGBT to extend the reverse bias region. The two IGBTs were controlled by two PIC16F819 microcontrollers (one PIC controls one IGBT) and a zero voltage crossing circuit based on a TL072CN voltage comparator.

The converter circuits were tested for discrete frequencies between 10Hz and 21Hz (in steps of 1Hz) and voltage and current waveforms were recorded. A constant R-C load (R=5Ω, C=23mF) was used in the experimental investigations. The appropriate input voltage Vm for each frequency was defined by the value provided in Table 2. The two circuits were compared in terms of output power and PF. Fig 8 shows the average output power that both circuits can deliver. Clearly, the FCSC circuit is able to transfer more power to the load compared with the standard single-phase
diode bridge rectifier circuit, especially at higher frequencies where the FCSC output power is about three times the output power of the standard single-phase diode bridge rectifier circuit.

The reduced output power of the standard single-phase diode bridge rectifier at higher frequencies is caused by the larger phase shift between the back EMF and the fundamental machine current. Figs 9 & 10 show the input and output voltages and current waveforms for the diode bridge rectifier circuit when operating at 11Hz and 21Hz, respectively. As expected, output voltage and output current increase when supplied at a higher input frequency. The phase shift between the input AC voltage and current waveforms is clearly reduced by the inclusion of the FCSC circuit for both frequencies (Figs 11 & 12), increasing the mean power delivered to the load.

The average output voltage for the standard single-phase diode bridge rectifier circuit at 11 Hz is about 38V compared to 45V with the FCSC circuit. At 21Hz, the output voltage of the standard single-phase diode bridge rectifier circuit is 58V compared to 90V with the FCSC circuit. These results reflect the reduction in the effective rectifier AC supply impedance and the corresponding PF improvement. The peak value of the FCSC circuit AC current is also higher than the corresponding peak current of the standard diode bridge rectifier circuit because of the lower effective circuit impedance. This increase in current amplitude can be observed in all four figures. Operating at 11Hz, the fundamental frequency of the
current peak of the FCSC circuit is about 7.4A, 0.5A higher than the corresponding component for the standard diode bridge circuit. Operating at 21Hz the current peak of the FCSC circuit is about 15A compared with 10.2A for the diode bridge circuit.

Fig 13 shows the operating PF for both circuit topologies. The FCSC circuit operates at nearly unity PF for the whole operating period, while the PF of the standard single-phase diode bridge rectifier is 0.758 lagging at 11Hz, dropping to just about 0.625 lagging at 21Hz. The power factor of the standard single-phase diode bridge rectifier is on average 25% smaller compared to the PF of the FCSC over the measured frequency range.

The FCSC circuit achieves nearly unity PF by adding two switches to the diode bridge rectifier circuit. The switching losses generated by the two additional switches are low compared to PWM rectifier circuits and DC/DC boost rectifier circuits which operate at a switching frequency between 5kHz to 100kHz, depending on the power level. The two switches in the FCSC circuit, however, switch at the generator electric frequency (11Hz to 21Hz) substantially reducing the switching losses.

PERFORMANCE COMPARISON UNDER VARIABLE VOLTAGE CONDITIONS

Fig 14 shows a simplified arrangement of a linear generator. The translator’s movement of a linear generator is bidirectional resulting in a variation of translator’s speed between zero and maximum, depending on the translator position in relation to the stator.

At position A, the translator is at its highest point and it is about to start moving downwards. The velocity at this point is zero, which therefore makes the output voltage zero. At point B, the translator has just started moving, so the output voltage has a low frequency and a low amplitude. At point C, the translator has maximum speed, so it can deliver maximum voltage at

![Fig 13: PF for the FCSC and the standard single-phase diode bridge rectifier circuit at various frequencies](image-url)
maximum frequency. After that, the translator slows down and the output signal is the same as that at point B. Finally, at point E, the translator reaches its lowest point and it is ready to change direction. The velocity is therefore zero, and consequently the output voltage is zero too. The final graph F shows the output voltage when the translator travels from position A to position E. During this period, the amplitude and the frequency of the generated voltage are not constant.

In this section, the performance of the FCSC circuit is compared with that of the standard single-phase diode bridge rectifier circuit when operating with a variable voltage supply, using the test rig described earlier to produce a more realistic WEC back EMF waveform. Real life wave energy devices operate at variable amplitude and velocity of course in a random manor depending on sea conditions, resulting in a variable magnitude, variable frequency electrical output from the reciprocating linear generator. In this paper, however, only ideal monochromatic waves are considered because of the limitations of the experimental setup used in the investigation.

Fig 15 shows the measured waveforms of the back EMF ($V_m$) and the machine current ($I_m$) for both circuits. The periods when the emulated back EMF drops below 70V and the current is zero represent Points A and E along the movement of the linear translator. Fig 15 shows clearly that voltage and current are nearly in phase when operating the FCSC. The PF for each shown cycle varies between 0.989 and 0.980, whereas the PF for the standard single-phase diode bridge rectifier varies from 0.739 to 0.682 lagging. The measured output power over 1s is 496W for the FCSC and 310W for the standard single-phase diode bridge rectifier, an improvement of 60%.

**CONCLUSION**

Stand-alone buoys usually employ a linear electric generator connected to a diode bridge rectifier which is directly driven from the linear movement of ocean waves in order to power up their electronic devices. The downside of such a power take off system is the low power factor, which limits the power transfer capability due to the high inductive reactance of the generator.

In this paper, controlled series compensation is proposed to compensate the inductive reactance of the generator. The technique is used in AC power transmission networks to ease line congestion and change network voltage profiles but has never been suggested for a variable-frequency, variable-voltage application such as an ocean wave energy conversion device.

A forced commutated, controlled series compensator FCSC circuit capable of correcting the operating power factor of the converter over the whole of the operating frequency range and thus maximising the energy conversion from the WEC device has been proposed in this paper.

The proposed FCSC device was tested in the laboratory and its performance compared to that of a standard diode bridge circuit using a 2.25kVA test circuit and its performance characteristics compared with those of a standard single-phase diode bridge rectifier circuit, using a variable-frequency, variable-voltage AC power supply to emulate the operation of the WEC linear electric generator. The power factor achieved in the lab with the proposed FCSC circuit was near unity over the entire operating range, maximising the energy transfer from the machine to the load.

**APPENDIX**

Linear generator parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum output volt-amperes</td>
<td>2.25kVA</td>
</tr>
<tr>
<td>Maximum back EMF</td>
<td>150V</td>
</tr>
</tbody>
</table>

**Fig 14:** Different translator’s positions and the output voltage

**Fig 15:** Variable-voltage back EMF and phase current test waveforms: top figure shows waveforms for the FCSC and bottom figure shows waveforms for the diode bridge rectifier.
Forced commutation controlled series capacitor (FCSC) circuit

- Maximum current: 15A
- Winding inductance: 105mH
- Winding resistance: 5Ω

The above parameters were based on those of the machine described in 11 for a larger PM linear generator.

REFERENCES

22. Kalpaktsoglou D and Pickert V. 2008. Controlled series capacitor converters applied to wave energy conversion buoys - A simulation study. IET International Conference on Power Electronics, Machines and Drives, April 4–6, York, UK.