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Direct AC–AC grid interface converter for ocean wave energy system

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ABSTRACT

Ocean wave energy is very promising. However, existing systems are using rectifying circuits to convert variable voltage and variable frequency output of electric generator into DC voltage and then use grid-tied inverter to connect to the power grid. Such arrangement will not only reduce the overall efficient but also increase the cost of the system. A direct AC–AC converter is a desirable solution. In this paper, a six-switch AC–AC converter has been proposed as a single phase grid-connected interface. New switching scheme has been derived for the converter such that the virtual input AC–DC conversion and the output DC–AC conversion can be decoupled. State-space averaging model and pulse width modulation scheme have been derived for the converter. As the input and the output operations can be decoupled, two independent controllers have been designed to handle the input AC–DC regulation and the output DC–AC regulation. The proposed scheme demands for two separate duty ratios and novel switching scheme has been derived to realize the combined duty ratios in one switching cycle. Power regulation, harmonics elimination and power factor correction control algorithms have also been derived for the converter when it is connected to the supply grid. Experimental results of a small scale model are included to demonstrate the effectiveness of the proposed switching and control schemes.

1. Introduction

Fossil fuel reserves are running out and the environmental impact of the emissions from their combustion is undesirable [1]. Interest in renewable energy is increasing due to concerns about global warming, air quality and sustainability [2]. The use of more renewable energy is a good way to reduce carbon emissions and environmental pollutions. Photovoltaic systems are gaining increased interests from governments, industry and academia because it is green and sustainable [3]. However, another very important source has not been fully developed is ocean energy. As ocean covers approximately 70% of the earth's surface, large amount of energy can be extracted from its motion. For the various methods to extract energy from the ocean, the largest potential is the wave motion. Wave energy is a renewable energy source with high power density and low impact on environment compared to other renewable sources [4]. According to International Energy Agency (IEA), the global resource is somewhere between 8000 and 80,000 TW h. In terms of power, ocean wave in the world is estimated as around 1000–10,000 GW [5]. Moreover, Esteban and Leary [5] also estimated that the renewable energy production from various ocean-based devices could be capable of covering about 7% of the world's electricity production by 2050. As with other forms of renewable energy, wave energy can be highly variable and of limited predictability. However, wave power flux can be well probabilistically forecasted 48 h in advance [6]. The planning and operation of wave energy converters require reliable estimates of the available power and their seasonal variations and [7] provide a thorough resource assessment for the Black Sea based on monthly, seasonal, and annual distributions of wave height and wave power.

Wave energy could be extracted by a range of wave energy converter (WEC) technologies. There are several different methods for extracting energy from the waves [8]. The mechanism for most common concepts can be categorized into one of six different methods, Oscillating Water Column (OWC), Attenuator, Point Absorber, Submerged Pressure Differential, Oscillating Surge Converter or Overtopping Devices. Among various wave energy converters, OWC type converters are the most studied and best developed. An OWC is an air chamber with an opening below the water level and has an air outlet through a turbine at the top. The incoming waves cause the water level inside the chamber rises and falls and the oscillating air pressure inside the chamber can drive a turbine at the top for electricity production [9]. Apart from using turbine, a linear generator was also proposed to convert wave kinetic energy directly into electricity [10]. However, it is necessary to install a controlled voltage source inverter (VSI) between generator

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and distribution networks [11]. Apart from using electromagnetic generator that is driven by the waves via a mechanical or hydraulic transmission, electroactive polymer (dielectric elastomer) which is based on the change in capacitive energy of a deformable dielectric was also proposed [12].

Since mechanical wave energy conversion mechanism will oscillate back and forth, the coupled electric generator produces an output voltage that varies in time in both amplitude and frequency. It is common practice to use rectifying circuit to convert the generator output into DC voltage and then using a grid-connected inverter [13] to deliver the wave energy onto the power grid. However, the power efficient of such approach is not good because of the energy loss in the AC–DC conversion due to the rectifying circuit. To improve the electricity production from WEC, direct AC–AC conversion is desirable. AC–AC power conversion finds wide applications in motor drives. The most traditional AC–AC conversion is a pulse width modulated voltage source inverter with a front-end diode rectifier and a DC link capacitor. The matrix converter has several advantages over traditional rectifier–inverter type power converters. It provides sinusoidal input and output waveforms, with minimal higher order harmonics and no subharmonics. Moreover, it has inherent bi-directional energy flow capability and the input power factor can be fully controlled. Last but not least, it has minimal energy storage requirements, which allows to get rid of bulky and lifetime-limited energy-storing capacitors. But the matrix converter has some disadvantages. First of all it has a maximum input output voltage transfer ratio limited to around 87% for sinusoidal input and output waveforms. It requires more semiconductor devices than a conventional AC–AC indirect power converter and the switching loss is higher than conventional AC–AC power converter. Finally, it is particularly sensitive to the disturbances of the input voltage system. Instead of the conventional eight-switch AC–AC converter, a six-switch AC–AC converter is proposed in this paper. The proposed converter has the advantages of reduced number of switching elements, voltage boosting capability and independency of input and output operation frequency. Experimental results of a small scale model are included to demonstrate the effectiveness of the proposed switching and control schemes.

2. State-space averaging model for six-switch AC–AC converter

A recent converter structure [14] reduces the number of switching elements by sharing switches. Fig. 1 shows a schematic diagram for a single phase six-switch AC–AC converter based on [14]. Fig. 2a–d shows the 4 operation modes of the converter.

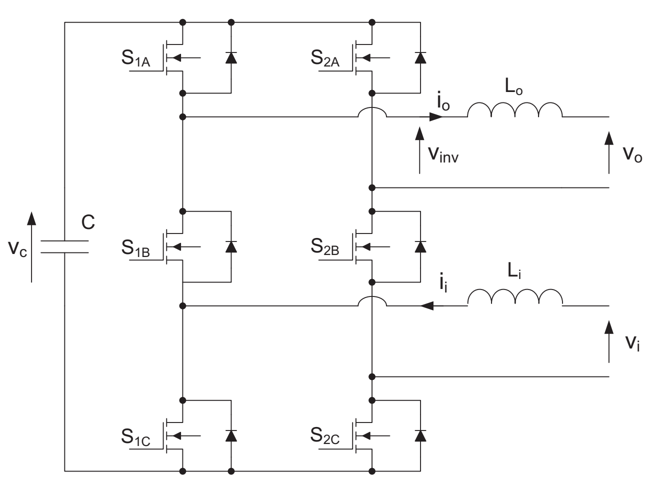

Fig. 1. Six-switch single phase AC–AC converter.

Assume the magnitude of the capacitor voltage $v_c(t)$ is higher than the magnitude of the input voltage $v_i(t)$ and the magnitude of the output voltage $v_o(t)$. The dynamic equations describing the state θ are given by

$$|v_i(t)| = |L_i\dot{i}_i(t)| \tag{1}$$

$$0 = L_o\dot{i}_o(t) + v_o(t) \tag{2}$$

where L_i is the input inductor, L_o is the output smoothing inductor, $i_i(t)$ is the input current, $v_i(t)$ is the input voltage and $v_o(t)$ is the output voltage, respectively. For output state 0, the dynamics can be described as

$$|v_i(t)| = |L_i\dot{i}_i(t)| + v_c(t) \tag{3}$$

$$C\dot{v}_c(t) = |i_i(t)| \tag{4}$$

$$0 = L_o\dot{i}_o(t) + v_o(t) \tag{5}$$

where $v_c(t)$ is the capacitor voltage and C is the capacitance. For output state 1,

$$|v_i(t)| = |L_i\dot{i}_i(t)| \tag{6}$$

$$v_C(t) = L_o\dot{i}_o(t) + v_o(t) \tag{7}$$

$$C\dot{v}_C(t) = -i_o(t) \tag{8}$$

and finally for output state −1,

$$|v_i(t)| = |L_i\dot{i}_i(t)| \tag{9}$$

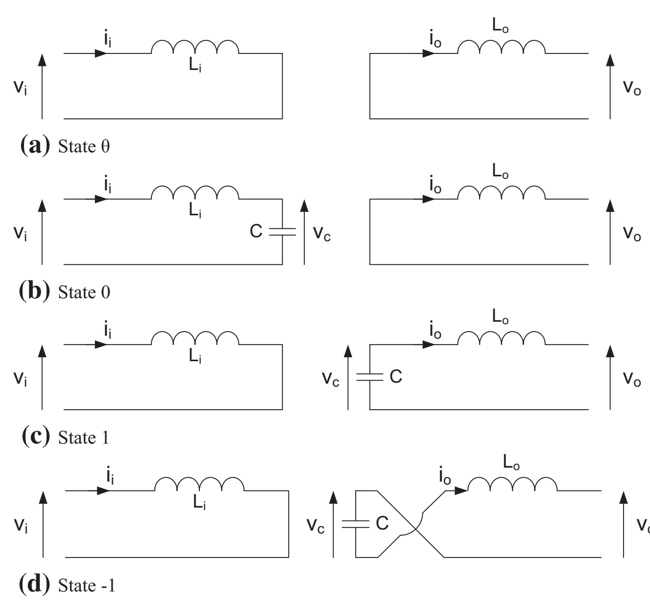

Fig. 2. Operation modes of the proposed AC–AC converter.

Table 1
Switching table for six-switch AC–AC converter.

State	Switch position					
	S_{1A}	S_{2A}	S_{1B}	S_{2B}	S_{1C}	S_{2C}
θ	On	On	Off	Off	On	On
0	On	On	Off	Off	Off	Off
1	On	Off	Off	On	On	On
−1	Off	On	On	Off	On	On