CURRENT SOURCE INVERTER
FOR A 400 kW OCEAN WAVES INDUCTION GENERATOR

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Abstract

Electrical energy generated from the ocean waves is a renewable energy being developed. One form of retrieving this energy is using the Oscillating Water Column (OWC) principle.
In order to optimise this energetic resource, the electric generator must work at variable speed depending on the input power. For the energy to be delivered to mains, the voltage magnitude and frequency must be constant.
This paper describes a system that uses a generator based on a wound induction machine with slip energy recovery, which allows operation with variable speed and direct connection to the mains.
The Slip Energy Recovery System (SERS) is based on a wound induction machine being controlled through the amount of rotor energy delivered to the mains by means of a static converter.
The AC variable rotor voltage is converted to DC voltage with a rectifier groupment and then converted again to AC in order to be injected into mains.
The use of an IGBT Current Source Inverter (CSI) as DC-AC converter minimises current harmonics and allows smooth interaction between the random and variable input power and the mains.
The main advantage of this system is the ability to generate 400 kW using a 200 kW machine and a 200 kW CSI.
The prototype appears as an important development due to work with a large renewable energy source at a significant power level. The good performance carried out by the equipment based on an induction generator is reached through a well-controlled IGBT based current inverter that is presented within this paper.

Introduction

Among the various methods to capture the energy of the sea waves, the Oscillating Water Column (OWC) is a promising one.

Using the OWC, the power plant installed in island of Azores in Portugal presents a Wells turbine coupled with a generator group of 400KW for an estimated annual energy production of 1 GWh.

The OWC consists on a chamber with an opening to the sea below the surface line (Fig 1).

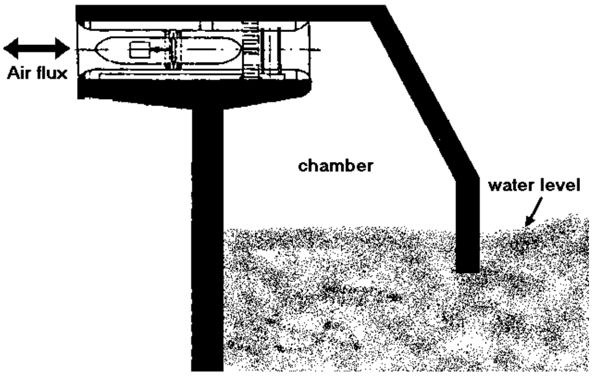

Fig.1: Schematic of the Oscillating Water Column principle

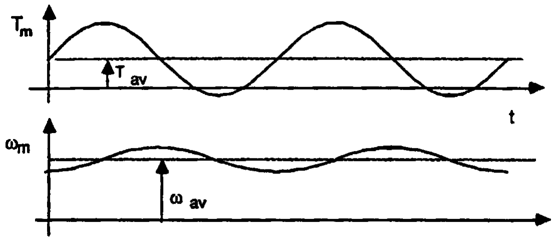

Fig.2: Shape of the torque produced by the turbine and speed of the turbine-generator group

When the waves move towards the plant, the water level outside and inside the chamber rises. The water rise inside the chamber leads to an increase of the air pressure, moving the air to the outside. When the waves move away from the plant, the opposite phenomena occur making the air flow from the outside to the inside of the chamber.

The alternating flow of air is used to move a Wells turbine. This kind of turbine operates as auto-rectifier, producing torque and rotating always to the same direction, for both flux air directions. The simplified shape of the torque produced by the turbine is illustrated in Fig 2.

The oscillating torque is filtered by the inertia of the turbine-generator group causing a generator rotation of a smaller oscillation at an average velocity (Wav). The generator is controlled to produce a nearly constant power (P), through varying its speed, accumulating and consuming energy from the inertia accordingly to available turbine torque.

The available power (P) depends on the sea conditions, and it is constant for constant waves amplitudes. In order to maximise the turbine efficiency, the average speed (Wav) must adapt to optimum power curves (P).

This means that the generator must work at variable speed, adjusting instantaneous speed to the turbine torque and average speed to optimum operation point for available power.

The need for a generator that works at variable speed producing power to be delivered to mains and the operating characteristics of an induction machine controlled by slip energy recovery, points out the adopted structure for the system. The machine ability to work as a generator above synchronous speed is useful for this application since that significant power is extracted from the turbine only above half the maximum speed. The structure is shown in Fig 3.

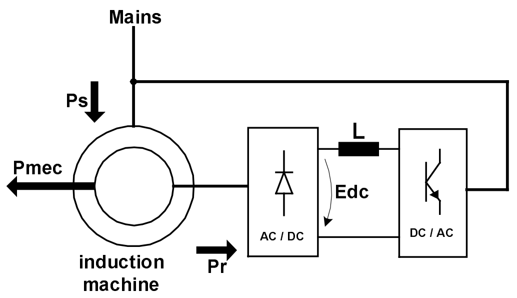

Fig.3: Principle of the Slip energy Recovery System (SERS)

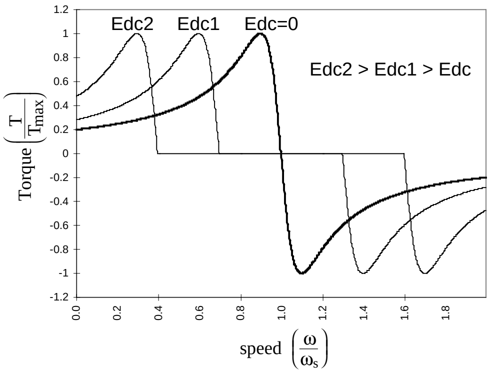

Fig.4: Torque curves for the SERS

By acting on the DC-AC converter the Edc voltage is controlled leading to the torque curves show in Fig 4. These show that in the stability zone the torque is almost only dependent on the voltage imposed by the converter. This characteristic becomes the machine behaviour to the equivalent to one of separately excited DC machine, making the system simple to be controlled.

The basic equations regulating the steady-state operation are:

$$s = (\omega_s - \omega) / \omega_s \qquad \text{(eq 1)}$$

$$Pmec = Ps - Pr \qquad \text{(eq 2)}$$

$$Pr = s.Ps \qquad \text{(eq 3)}$$

$$Pmec = (1 - s).Ps \qquad \text{(eq 4)}$$

being 'ωs' the synchronous speed, 'ω' the instantaneous speed, 's' the slip, 'Pmec' the mechanical power, 'Ps' the stator power and 'Pr' the rotor power.

When the generator is rotating at twice the synchronous speed (s = -1) and the current in the windings is the nominal (Ps = Pnominal), the power produced is twice the nominal one (Pmec=2.Pnominal) as it can be seen in eq 4. This means that to produce 400 kW at 1500rpm the system only needs a 200kW / 750rpm machine. This happens because the output power is delivered to the mains divided by the stator and the rotor.

As the maximum power that the converters must handle, is the maximum power of the rotor, the converters must be designed for only 200 kW

In an asynchronous machine with slip energy recovery the stator voltage and frequency are imposed by the grid, while the open circuit rotor voltage and frequency vary with the speed, being proportional to the slip. At the synchronous speed they equal zero (s = 0), being the same ones as the blocked rotor voltage and frequency at twice synchronous speed (|s| = 1).

The rotor voltage, variable in magnitude and frequency, is first converted to DC current.

The rotor current harmonics generated by the rectification disturb the stator current. To reduce these harmonics a 12-pulse diode rectifier (two three-phase rectifiers) is used and the rotor has 2 windings displaced of 30º elect. Each winding feeds a three-phase rectifier.

To avoid the existence of 6 rings in the machine, the diodes are mounted in the rings, and the rotor power is collected as DC.

Fig 5 shows the overall diagram of the system. The stator voltage is 400 V, and the rotor voltage was chosen to have that same value at |s| = 1. The maximum DC bus voltage is 540 V. With no load the rectified voltage can be expressed by:

$$Edc = K.|s| \quad (K = \text{constant}) \qquad \text{(eq 5)}$$

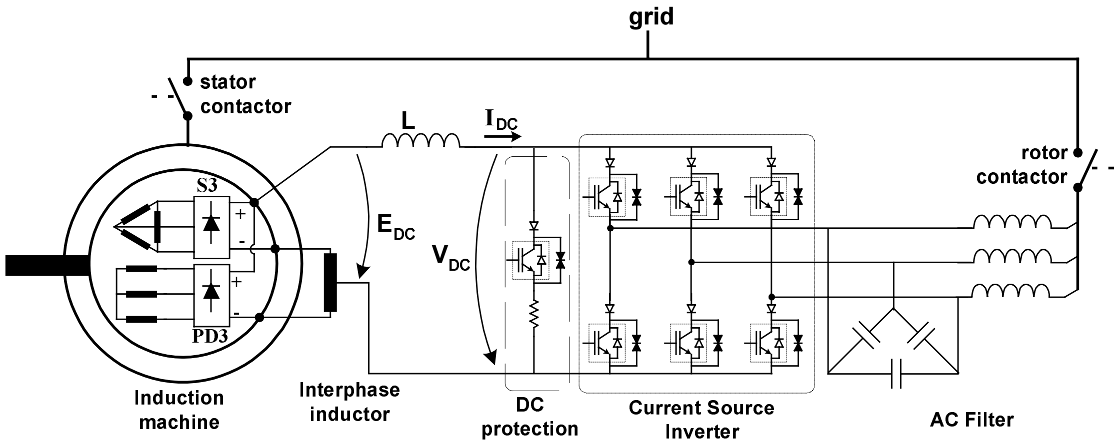

Fig 5: Overall diagram of the system.

This communication discuss the application of a current source inverter to interconnect the rotor rectified voltage source to the grid, and the adopted method to control the power flow, and consequently the optimisation of the generated electrical power.

Current Source Inverter

The power electronic converter adopted for this system is a Current Source Inverter (CSI) due to improve the quality of the interconnection of the equipment with the main. The CSI schematic can be seen in Fig 5.

General description

The CSI uses IGBTs with PWM control to deliver a very low harmonic content current to the grid and to control the value of the voltage generate in the DC side (Vdc).

Each arm of the CSI uses a 1000A/1200 V IGBT and a diode connected in series. The diode is needed because the voltage across each arm of the CSI is negative for some periods of the PWM pattern.

Each IGBT has an 800 V over voltage protection device at its terminals, to act as a clamp for the commutation transients. Special care was taken in the physical lay out of the CSI to reduce the parasitic inductances responsible for the commutation energy to be dissipated. The commutation clamped voltage is illustrated in Fig 6.

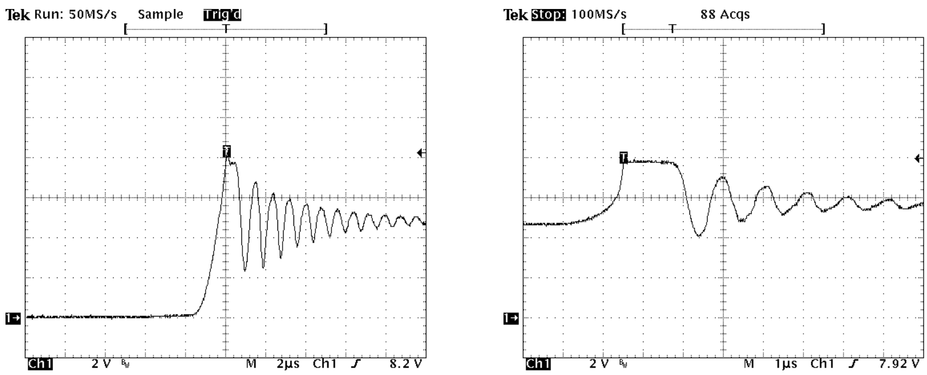

Fig 6: Voltage clamping on the IGBT collector-emitter terminals by the protection device.

A slower IGBT OFF commutation compared to the ON, and a sufficient overlapping time, assure that the DC current is transferred from one arm to the next one without generating high over voltage transients.

A protective IGBT with a resistor is added in the DC bus, which is used to give an alternative path to the current when the CSI must stop as a consequence of any failure or emergency.

When a fault in the CSI is detected, this IGBT is turned ON, the CSI IGBTs are turned OFF, and the contactors are opened. This circuit only dissipates power in the resistor for the time necessary for the stator contactor to open, and the rotor current reach zero.

A filter reactor is used in the DC bus to supply the CSI with smoothed DC current and to limit the CSI switching frequency currents that the rotor windings absorb.

AC capacitors are necessary for the CSI commutation, and operating together with an inductor plus the grid impedance form a low pass filter for the CSI output current. This filter is relatively small by the use of a switching frequency of 2.25 kHz, which is an appropriated switching frequency for this type of IGBTs.

The PWM pattern adopted by the system controller, in conjunction with the switching frequency and the filters, reduces the current harmonics injected into the grid to about 2% THD. Fig 7 shows the current injected in the grid by the CSI.

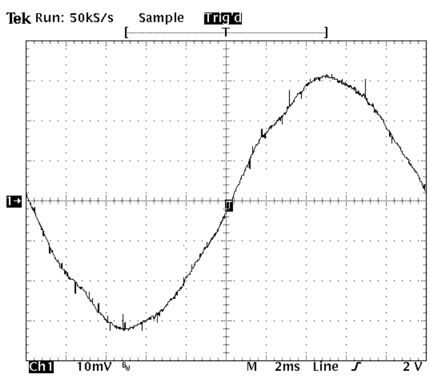

Fig 7: Injected current in the grid by the CSI (Irms=100A)

CSI control

Among different PWM patterns it was chosen the PWM that improves the elimination of the lower harmonics and increases the rectified voltage generated in the CSI input [6].

Fig 8 shows the voltage at the input of the CSI, presenting a waveform like a chopped 3 phase full wave rectified.

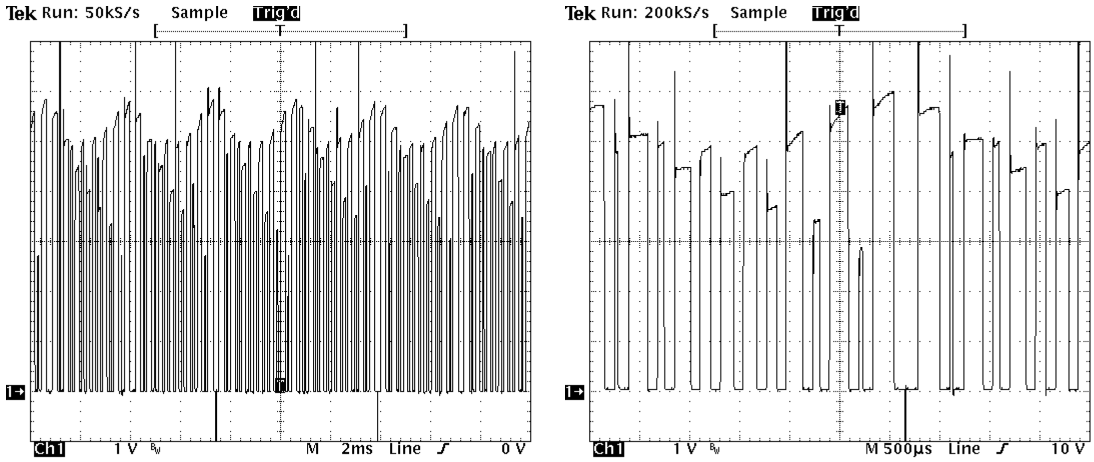

Fig 8: Voltage at the input of the CSI.

The software module responsible for the CSI control receives the parameter 'im' from the other software modules, generating the control signals for the six Igbts. 'im' is the modulation index and relates the magnitudes of the output AC currents and the DC input current. The principle of the CSI software module is shown in Fig 9.

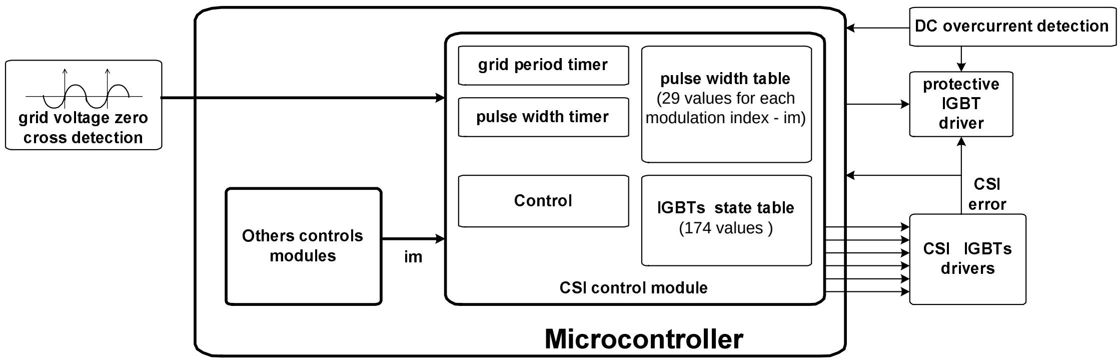

Fig 9: Overall diagram for control the CSI.

The DC over-current detection and the error signal generated by the CSI IGBTs drivers actuate directly in the protective IGBT so minimise the actuation time reducing the risks of over-voltage due to turn-off of the CSI.

'IGBTs state table' stores a one period sequence of all possible states for the 6 IGBTs. This sequence is independent of im. The duration (width) of each state is stored in 'pulse with table'. Since the duration of each state is dependent of im there is one table for each im. The states width are repeated 6 times for each period, so the size of 'pulse with table' is 6 times smaller than the size of 'IGBTs state table'

When the time of each state ends, the width for the next state is loaded in 'pulse with timer' and the CSI IGBTs are driven form the next position of the table 'IGBTs state value'

In order to synchronise the CSI output currents with the grid voltages, the microprocessor receives an interrupt signal when the grid voltage phase R crosses zero. This signal is used to measure the actual grid frequency in timer 'grid period timer'. The CSI output currents frequency is adjusted to the grid frequency by adding / subtracting a value to the width of each state. The synchronisation between the CSI output currents and the grid voltages is made by slightly changing the CSI output currents frequency until the state 1 of the PWM pattern coincides with the voltage zero crossing in a kind of software PLL (phase lock loop).

DC Current control

Fig 10 shows the schematic model of the CSI and the filter connected to the grid and the rotor rectifiers.

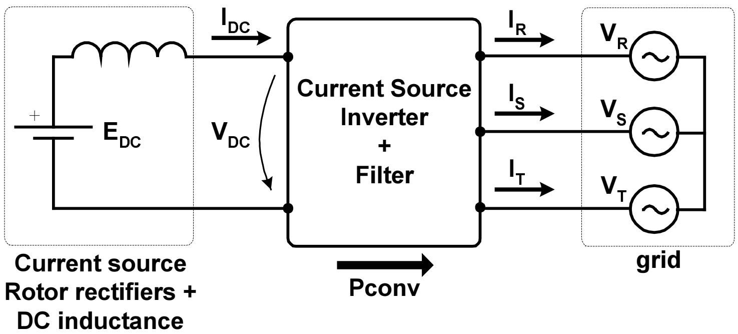

Fig 10: Modelling the Current Source Inverter plus the Filter connected to the rotor rectifiers.

Considering the high harmonics negligible, the group CSI-Filter can be modelled by the following equations (Fig 10):

$$V_{DC} = \sqrt{\tfrac{3}{2}}.\text{im}.V_C \qquad \text{(eq 6)}$$

$$P_{CONV} = V_{DC}.I_{DC} \qquad \text{(eq 7)}$$

Pconv is the power that the CSI injects into the grid.

By controlling Vdc, the DC current is regulated according to:

$$\text{Idc} = \frac{1}{L}\int\left(\text{Edc(t)} - \text{Vdc(t)}\right)\text{dt} + \frac{1}{R}\left(\text{E(t)} - \text{Vdc(t)}\right) \qquad \text{(eq 8)}$$

Where L and R are equivalent parameters for the circuit and Edc is the rotor no load DC voltage (proportional to the slip – eq 5).

By controlling the DC current, the CSI controls the rotor current, so the torque and consequently the power converted to the grid.

The DC current control is a strong requirement for this kind of system. In fact, the electrical power flow controller needs to increase the action of the mechanical speed filter inherent to the inertia momentum.

Power control

The power quality to the mains requires an injected power as constant as possible. This task is performed allowing some variation on instantaneous rotational speed, referencing the DC bus current to the power flow level and storing/providing the remaining energy in kinetic energy form..

A simplified expression for the power taken from the turbine can be derived from the power handled by the CSI (Pconv), and the eq. 3, 4 and 5:

$$Pmec = K.I_{DC}.(1-s).sign(s) \qquad \text{(eq 9)}$$

While the sea conditions remain unchanged the turbine rotates at a mean speed (Wav) and the generator must delivery to the grid a nearly constant power (Pav). The relation between Wav and Pav is obtained through a table stored in non-volatile memory. The microcontroller obtains Wav by integrating the instantaneous speed for some period. This period is referenced to same conditions of sea waves input power.

After obtaining PavRef the power controller determines the DC current by estimating the eq 9 and by using closed loop controller for accuracy.

The estimation from eq 9 gives the upper and lower limits for the Idref. The actually value is determined comparing PavRef with the measure power increasing or decreasing the Idcref.

Conclusions

This paper discusses issues related to electrical energy generation from the ocean waves and the solution developed by the authors to handle with performant interconnection to the grid.

As primary source is constituted by a Wells turbine, the operation point is controlled in such way that the rotational speed is just the one optimising the system efficiency.

In other hand, the system control using an induction generator with recovery of slip energy through an IGBT Current Source Inverter is a low cost solution even satisfying the requirements for keeping quasi constant the generated power. Furthermore, one of the major features of the system is the ability to generate nominal power (400 KW) sharing it by the generator stator (200 kW) and the static converter (200 kW).

The system is shown to be a good solution achieving a very good figure of 2% THD for the grid current, with a light low pass output filter due to high frequency operation of the inverter for this level of power and type of inverter.

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