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Fuzzy-PID Control Strategy for Grid Interface Ocean Wave Energy Conversion

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***Abstract* — Ocean wave technology is one of the most exciting areas due to vast but untapped energy potential worldwide. Technologies on ocean wave harvesting energy have been explored for centuries and are still undergoing with challenges. Optimally controlled Wave Energy Conversion System (WECS), designed to operate at full capacity a rather large reaction of their lifetime, may improve the economic prospects for wave power significantly. This paper presents a closed-loop vector control structure based on Fuzzy Proportional-Integral-Derivative (Fuzzy-PID) for a grid-connected WECS driven Self-Excited Induction Generator (SEIG). The paper proposes a Fuzzy-PID controller for Wave Energy Conversion System (WECS). the performance of the proposed controllers such as minimize the transient DC and AC voltage and current ripples, minimize the DC and AC voltage and current Total Harmonic Distortion (THD), deviations, minimize the RMS absolute voltage deviations at the DC and AC load collection buses. Simulation results show that the proposed design approaches are efficient to and Fuzzy-PID design of the controllers and therefore improves the transient performance of the hybrid Diesel-WECS over a wide range of operating conditions, sudden load change and phase-phase short circuit fault.**

***Keywords* — Wave Energy Conversion Systems (WECS), Self-Excited Induction Generator (SEIG), Proportional-Integral-Derivative (PID), Fuzzy-PID control, Membership Function Tuning**

I. INTRODUCTION

Although much less explored than other renewables, wave energy is gaining momentum as a possible significant contributor to the world energy portfolio. Recent studies showed that more than 2 TW of power [1] are potentially available on a 60-m bathymetry, corresponding to more than 10% of the world average power consumption as of 2010 [2]. This scenario strongly boosts research and investigation on wave energy conversion systems. Unlike the wind energy sector, a single leading technology has not emerged yet and many different WEC concepts are being studied and tested worldwide [3-5]. The wave energy industry is still in its relative infancy and, although exploiting some lessons learnt from the wind sector, wave energy applications have peculiarities that call for specific design approaches and tailored solutions. The wave resource is characterized by extreme variability [6], due to seasonal changes similar to corresponding wind patterns [7] (long-term variability) and the intrinsic oscillations of sea waves, with a period of 5–20 s (short-term variability). Moreover, unlike wind, wave energy short-term variation has a zero average value, so that the power extraction is zero twice per period. Such peculiarities pose major challenges to the design and operation of WECs, since they must withstand and operate efficiently in a variety of sea conditions, while ensuring a relatively constant power output to the onshore power system.

Research efforts need to be focused in this direction to extract electrical energy from sea waves in a commercially and technologically acceptable manner. Due to the introduction of new grid codes for renewable energy sources a number of issues have to be solved and need to be considered, such as the control applied by the generator and power conditioning system for increased production, low voltage harmonics and power fluctuations[8-10].

The control of the generator and power conditioning system is achieved traditionally by vector control technique based on proportional, integral and differential controllers (PID controllers). Suitable PID controller parameters are needed for a better system performance and stability. However, the coordinated tuning of these controllers is tedious and it might be difficult due to the nonlinearity and the high complexity of the system.

Therefore, it is interesting to use non-conventional control techniques, such as fuzzy logic, in order to achieve high performances and robustness [11]. Fuzzy PID controllers have self-tuning ability and on-line adaptation to nonlinear, time varying, and uncertain systems [12].

II. 2- STARTING MODEL

The starting model is very similar to the model described in [13]. It is composed of a cylindrical point absorber in heave with a hemispherical bottom (buoy), which is directly coupled to a rotating electrical machine via gearbox.

In the first part of the work, which is presented in the following paragraphs, in the model the electrical machine is not considered and all the parts associated at this (thus neglecting corresponding losses), because with these first simulations the goal is to understand better which values of the PTO torque (and corresponding PTO force) should be applied to obtain the maximum average mechanical power. Therefore these values will be applied as inputs into next models.

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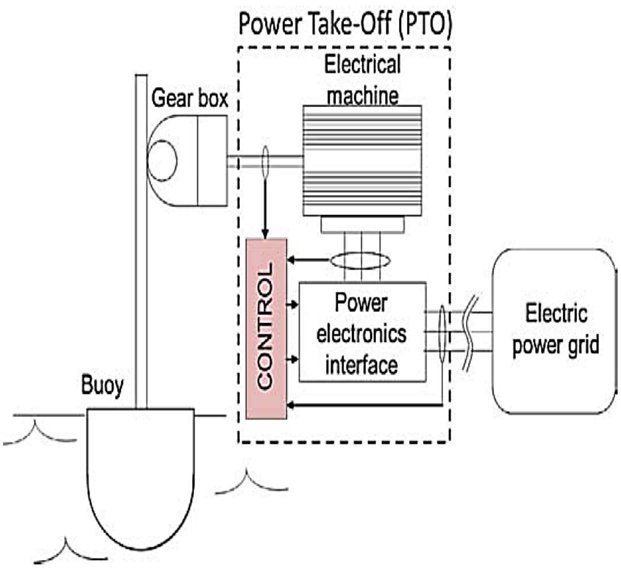


Figure 1 - Simplified model of the WEC (reproduces from [13])

2-1 Hydrodynamic model

In order to properly represent the interaction between the sea waves and the point absorber, which is a single degree of freedom device, the Cummins equation can be used (Cummins, 1962) [14]:

$$F_E(t) + F_L(t) = (M + a_\infty)\ddot{s}(t) + \int_{\infty}^{t} K_{rad}(t-\tau)\dot{s}(\tau)\,d\tau + Ks(t) \quad (1)$$

Where $\dot{s}$ is the speed of the buoy, $\ddot{s}$ its acceleration and s is its position. F_E is the excitation force applied by the waves to the point absorber and F_L is the force applied by the PTO. The radiation force that represents the effect of radiated waves produces by the buoy oscillation needs also be to taken into account. In equation (1) it is expressed by the convolution integral, K_{rad} being the radiation impulse response function. Moreover, M is the mass of the device including the contribution due to the PTO inertia, K is the hydrostatic stiffness and a_∞ represents the value of added mass at infinite frequency[15].

2-2 Point absorber (B)

A point absorber is a device that possesses small dimensions relative to the incident wavelength. They can be floating structure that heave up and down on the surface of the water or submerged below the surface relying on pressure differential. Because of their small size, wave direction is not important for these devices. There are numerous examples of point absorbers, one of which is Ocean Power Technology's Powerbuoy [16]. Figure 2 shows an artist's impression of a wave farmusing Power buoys.

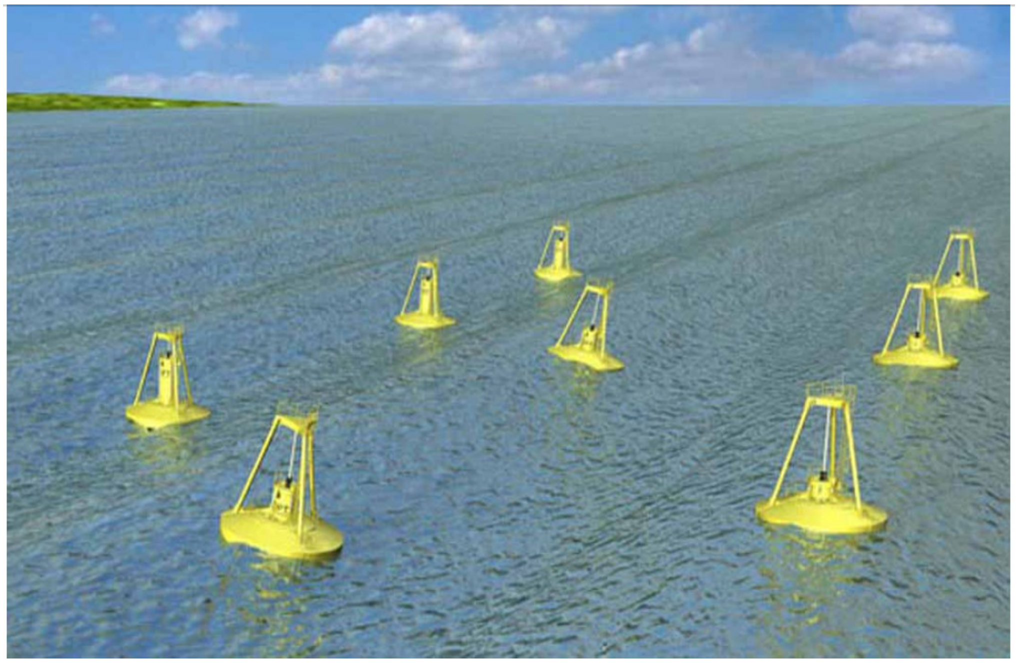


Figure 2. Point absorber device: OPT Powerbuoy [17]

III. Modeling of the Studied System

3-1 System Configuration

Figure 3 shows the system configuration of the proposed block diagram of the power circuit and control strategy for SEIG converting power from the wave to deliver power into the electric grid with constant frequency and RMS of the AC line voltage for a large range of wave variation [18]. The proposed AC/DC converter is designed to convert the variable-frequency variable-voltage power generated by the SEIG AC power to regulated DC power. The regulated DC power can charge a battery set and supply DC loads. Then DC power is delivered to the DC side of the three-phase inverter to be converted into a three-phase AC power for the AC loads and for the grid connection. To overcome the problem of the variation of the terminal dc voltage when the variation of the wave speed of the turbine or when changing the load, there is provided an effective method of control based on Fuzzy mode control system of the dc bus voltage. Direct vector control strategy with rotor flux orientation with high dynamic performance has been used in this paper for voltage and frequency control of grid-connected SEIG for both DC and AC power applications. The induction generator rotor flux is controlled by the d-axis stator current and the q-axis stator current controls the delivering active stator power. This method is used to control the electrical torque of the SEIG driven by a variable speed wave turbine, where different forms of wave speed variation effect taken into consideration. The simulation studies for different transient conditions such as phase to phase short circuit fault, sudden application and removal of both AC and DC loads have been carried out to demonstrate the effectiveness of the scheme.

3-2 Generator-Side Converter Control

The generator-side converter was implemented so that the field-oriented current control loop controls the rotor flux and the machine torque, as shown in Figure 4. The rotor flux can be controlled by controlling the *d*-axis rotor current. The machine torque can be independently controlled by controlling the *q*-axis rotor current. These controls are implemented by two fuzzy controllers in each control loop. The rotor flux λ_r and the machine torque T_e can be represented as functions of the individual current components. Therefore, the reference values of i_{dr} and i_{qr} can be determined directly from the λ_r and T_e commands. In the rotor flux control loop of the generator side converter, the actual signal of the rotor flux (λ_r) is compared with it's the command (λ_r^*) to form the rotor flux error signal. The rotor flux error is fed to the Fuzzy controller to generate the reference signal of the d-axis current component (i_{dr}^*) of the compensator reference AC current. In the torque control loop of the generator side converter, the actual torque is compared with the reference torque to generate the error signal which is passed through the Fuzzy controller to generate the reference signal for the *q*-axis current component (i_{qr}^*). The principal vector control parameters i_{dr}^* and i_{qr}^*, which are DC values in synchronously rotating frame, are converted to stationary frame with the help of unit vectors (cos θ_e and sin θ_e) generated from flux vector signals i_{ds}^* and i_{qs}^* . The instantaneous three-phase reference currents i_{abc}^* are generated by transforming the reference *d*-*q* components i_{ds}^* and i_{qs}^* in the stator-flux oriented reference frame. The actual three phase currents signals i_{abc} are then compared with their reference signals i_{abc}^* to generate the error signals, which are passed through the hysteresis current controller to form the switching signals. They are then used by the PWM module to generate the IGBT gate control signals to drive the IGBT converter. The main task of the hysteresis current controller in current regulated PWM inverters is to force the current vector in the three phase load according to a reference trajectory. The basic implementation of hysteresis current control is based on deriving the switching signals from the comparison of the current error with a fixed hysteresis band. This control is based on the comparison of the actual phase current with the hysteresis band around the reference current associated with that phase. Three hysteresis bands of the width ±*h* are defined around each reference value of the phase currents i_{abc}^* . The error of each phase current is controlled by a two level hysteresis comparator. The goal is to keep the actual value of the currents within their hysteresis bands all the time.

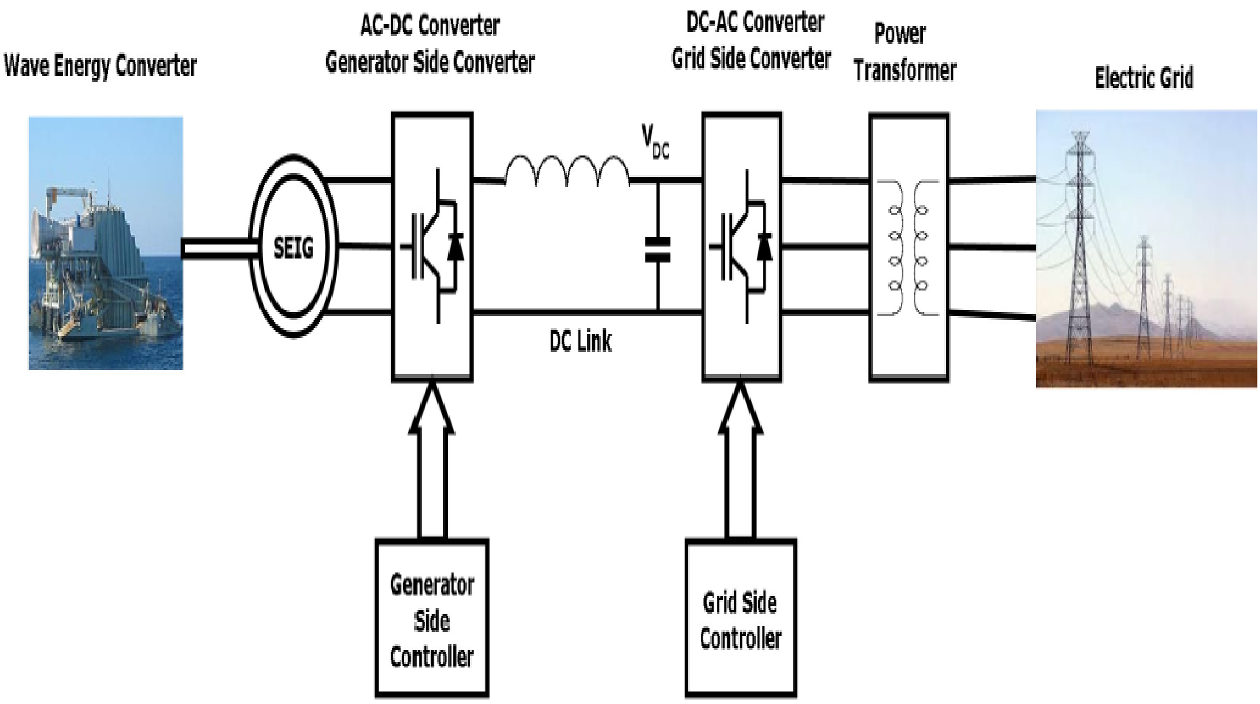


Figure 3. Schematic representation of wave energy converter with SEIG full-controlled induction generator.

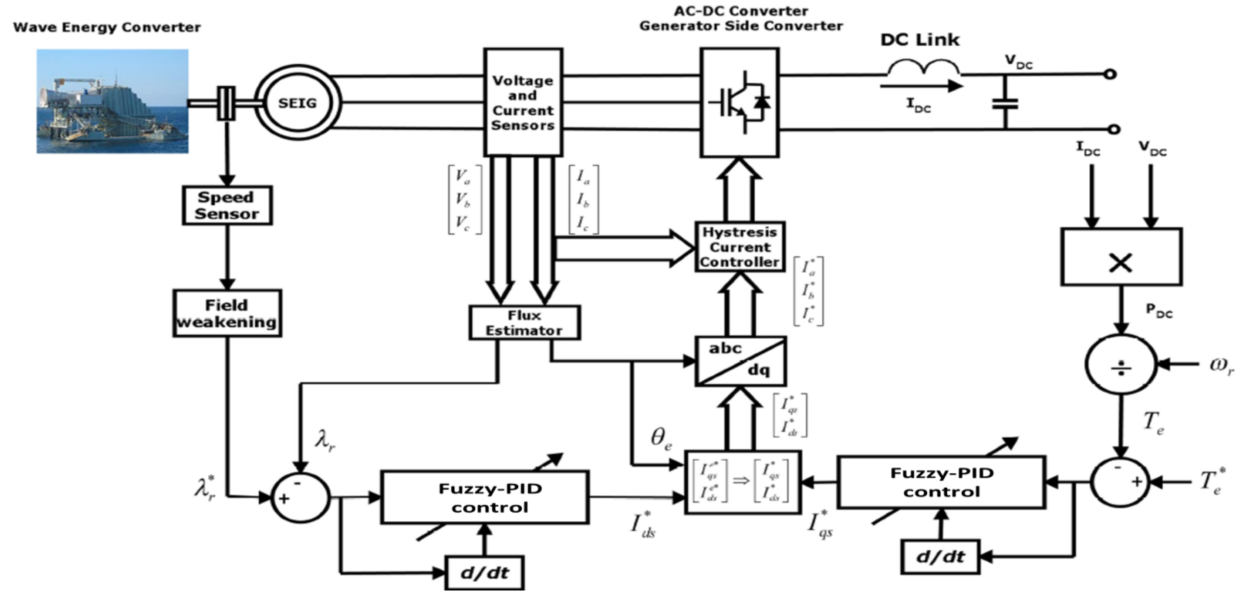


Figure 4. Generator-side converter control

3-3 Grid-Side Converter Control

The grid-side converter is also vector-controlled using direct vector control and synchronous current control in the inner loops. Figure 5 shows the overall control scheme of the grid-side converter. The main objective of the grid-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The control of the grid-side converter are organized in two loops; a DC-link current control loop, which controls the current through the grid filter, and DC-link voltage control loop that controls the dc-link voltage.

This implies that the dc-link voltage control loop has to act on the d component of the grid-filter current. An outer DC voltage control loop is used to keep the DC link voltage constant. The actual signal of the dc-link voltage (V_{dc}) is compared with its command (V_{dc}^*) to form the error signal, which is passed through the fuzzy controller to generate the reference signals for the *d*-axis current component i_{ds}^* . In the second loop, the actual signal of the line current (V_{ab}) is compared with the reference line current (V_{ab}^*) to form the line current error signal, which is passed through the fuzzy controller to generate the reference signals for the *q*-axis current component (i_{qs}^*) . The instantaneous three-phase reference stator currents i_{sabc}^* are generated by transforming the reference *d-q* components $i_{ds}^*$and i_{qs}^* in the stator-flux oriented reference frame. The actual three-phase stator currents signals i_{sabc} are then compared with their reference signals $i_{sabc}^*$to generate the error signals, which are passed through the hysteresis current controller to form the switching signals. They are then used by the PWM module to generate the IGBT gate control signals to drive the IGBT converter.

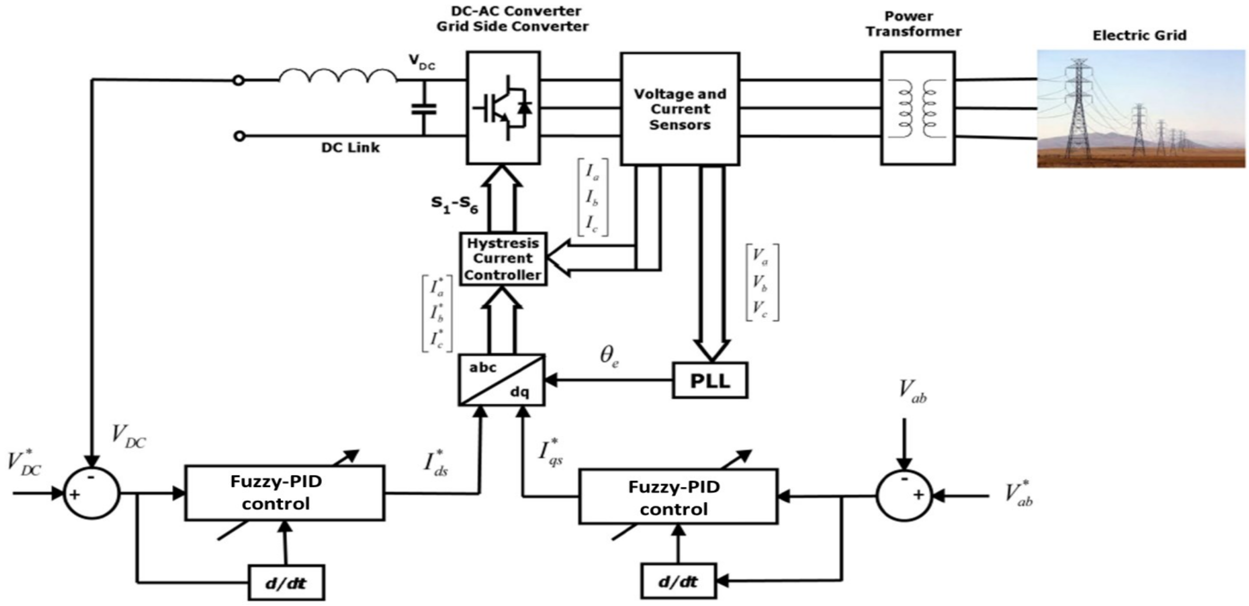


Figure 5. Grid-side converter control.

IV. Fuzzy Structure

Using fuzzy logic for solving the practical problems which cannot properly be resolved by classical control techniques is the main issue for fuzzy logic theory. Fuzzy controller does not need the accurate mathematical model of the controlled objects; it is based upon the control decision table to decide the size of the control amount [19]. In order to solve the problems that happened through load-mutation and nonlinear loads, the combination of conventional PID control and advanced control strategies is an effective solution for solving above problems. The aim of combining the conventional PID controller with fuzzy controller is to produce fuzzy self-tuning PID controller. Fuzzy controller relates its output to the input through the use of IF-THEN rules. IF part, determines the certain conditions. The THEN part, determines the values to the output variable to achieve optimum output for controller [19-20].

In this paper, the fuzzy PID is designed for either the inverter or for a boost DC/DC converter. Figure 6 illustrates the diagram of the fuzzy controller. The fuzzy controller has two inputs such as $e(t)$, $\dot{e}(t)$ and three outputs. PID coefficients are K_p, K_i and K_d.

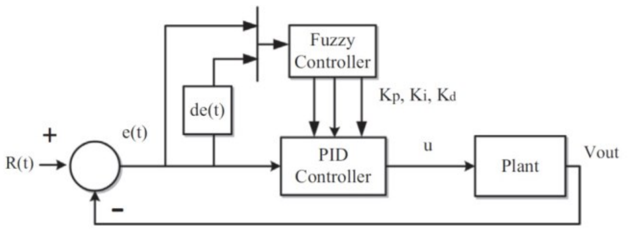


Figure. 6. Diagram of fuzzy PID control.

4.1- Design of Fuzzy-PID controllers for Generator-Side Converter Control

The conventional two input variables of Fuzzy-PID, namely the error $e(t)$ and, the change of $\dot{e}(t)$ and three outputs K_p, K_i and K_d. These inputs produce optimal control signal based on fuzzy rules to control the output of the AC/DC converter. Input fuzzy variables based on linguistic are expressed as follows:

NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big).

The input membership functions are shown in Figures 7 and 8. The output fuzzy variables are expressed as follows:

ZE (Zero), VS (Very Small), MS (Medium Small), ME (Medium), MB (Medium Big), VB (Very Big) and VL (Very Large). The output membership functions are shown in Figures. 9 and 10. Fuzzy rules for the form of ''If ... Then'' stated that has a total of 7 * 7 = 49 rule base, was available for each output. Rule base tables based on experience and trial-and-error test are obtained at Tables 1–3. For example: One of the rules in Table 3 is as follows:

$$If\ "E = NB\ and\ EC = PB\ \ Then\ K_p = ME" \quad (2)$$

This statement indicates that the error (*E*) is negative big, and change of error (*EC*) is positive big. In this instance, the error changes are big while the error decreases rapidly. Thus K_p, output is medium.

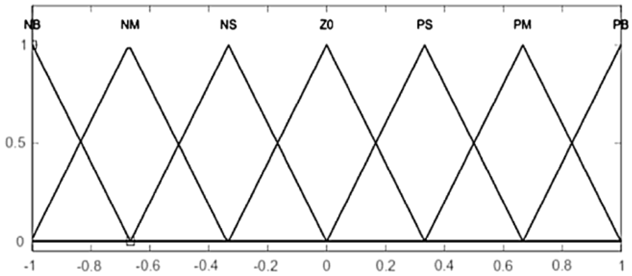


Figure 7. Fuzzy membership function of $e(t)$.

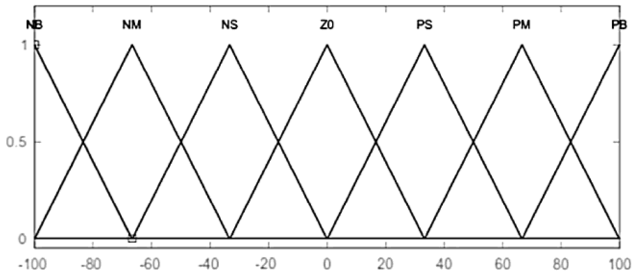


Figure 8. Fuzzy membership function of $\dot{e}(t)$.

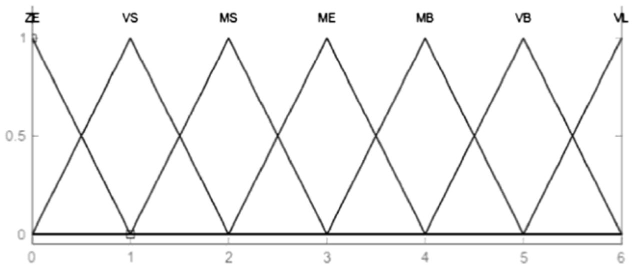
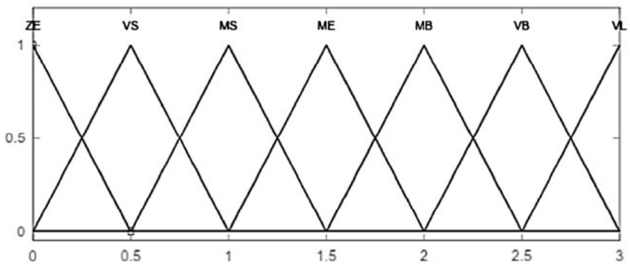


Figure 9. Fuzzy membership function of K_p.



Figures. 10. Fuzzy membership function of K_i and K_d.

Table 1 Fuzzy rule table for K_p .

E	CE						
	NB	NM	NS	ZO	PS	PM	PB
NB	VL	VL	VB	VB	MB	ME	ME
NM	VL	VL	VB	MB	MB	ME	MS
NS	VB	VB	VB	MB	ME	MS	MS
ZO	VB	VB	MB	ME	MS	VS	VS
PS	MB	MB	ME	MS	MS	VS	VS
PM	VS	MB	ME	MS	VS	VS	ZE
PB	ME	ME	VS	VS	VS	ZE	ZE

Table 2. Fuzzy rule table for K_i .

E	CE						
	NB	NM	NS	ZO	PS	PM	PB
NB	ZE	ZE	VS	VS	MS	ME	ME
NM	ZE	ZE	VS	MS	MS	ME	ME
NS	ZE	VS	MS	MS	ME	MB	MB
ZO	VS	VS	MS	ME	MB	VB	VB
PS	VS	MS	ME	MB	MB	VB	VL
PM	ME	ME	MB	MB	VB	VL	VL
PB	ME	ME	MB	VB	VB	VL	VL

Table 3. Fuzzy rule table for K_d

E	CE						
	NB	NM	NS	ZO	PS	PM	PB
NB	MB	MS	ZE	ZE	ZE	VS	MB
NM	MB	MS	ZE	VS	VS	MS	ME
NS	ME	MS	VS	VS	MS	MS	ME
ZO	ME	MS	MS	MS	MS	MS	ME
PS	ME	ME	ME	ME	ME	ME	ME
PM	VL	MS	MB	MB	MB	MB	VL
PB	VL	VB	VB	VB	MB	MB	VL

4-2 Design of Fuzzy-PID controller for DC/AC converter

Design of the Fuzzy-PID controller for the DC/AC converter is similar in terms of rule base and membership function. However, the inputs ranges are different together but the outputs ranges are similar to inverter which do not change such as:

$$e(t) = \{-100, 100\}, \dot{e}(t) = \{-100, 100\} \tag{3}$$

5- Digital simulation results

The proposed Fuzzy-PID strategy has been tested for validation using the Grid-Side and Generator-Side Converter Control. The wave model of Figure11 is adopted to generate a specific power reference and validate the good power tracking performances and therefore confirm the effectiveness of the proposed control strategy based on Fuzzy-PID.

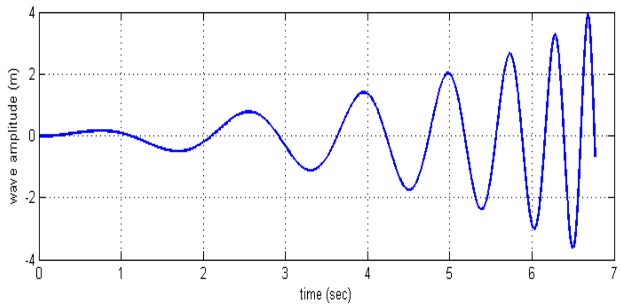
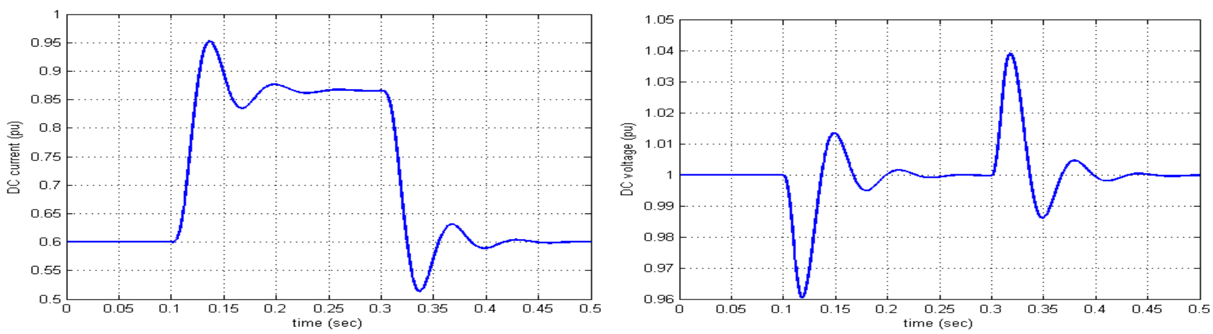


Figure 11: The wave model

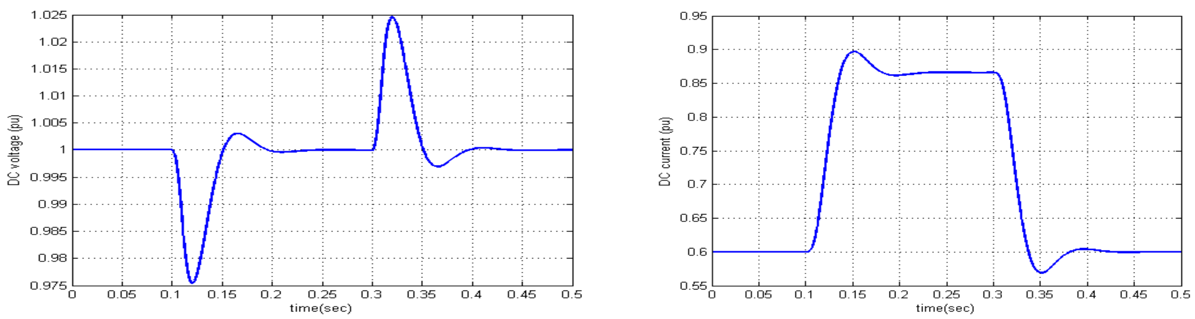
The dynamic simulations were carried out for two cases. In the first case, a step load change was carried out from 0.5 pu to 1 pu at time 0.1 s and lasting 0.3 s.

In the second simulation case, a phase to phase short circuit was carried out next to the generator bus at time t = 0.2s, lasting for 0.05 s. In Figure 12 and Figure 13, a significant reduction in the maximum overshoot and the oscillations of the DC voltage and current can easily be observed when Fuzzy-PID controller as compared with the conventional PID controllers.



(a) (b)

Figure 12: DC link Voltage and current responses-based conventional-PID controller when load is increased by 50/0



(a) **(b)**

Figure 13: DC link Voltage and current responses-based Fuzzy-PID Controller when load is increased by 50%.

Figures 14-15 show the AC-side voltage and current dynamic behaviors, when load is increased by 50% and Fuzzy-PID controllers as compared with the conventional PID controllers. A reduction in the over-current can easily be observed, when the gains are adjusted by the Fuzzy-PID as compared with those adjusted via conventional

Error!

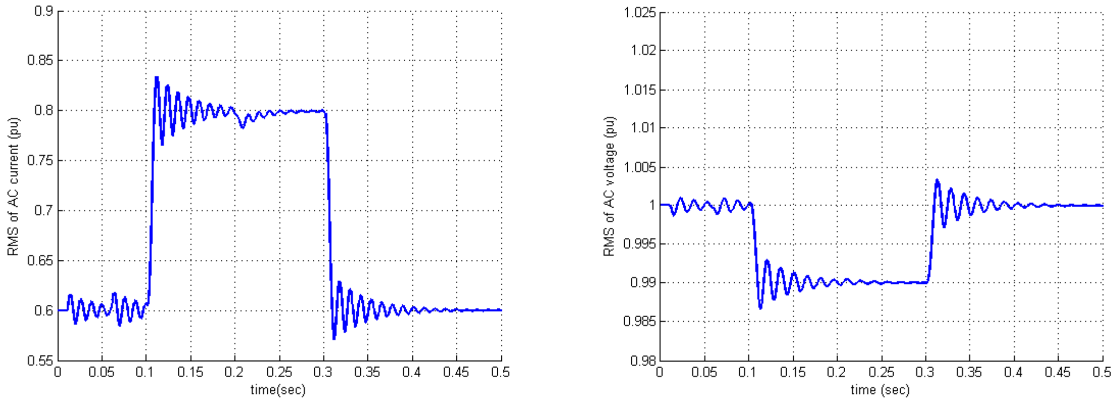


Figure 14: AC link Voltage and current responses-based conventional-PID controller when load is increased by 50%

PID, consequently contributes towards maintaining the converter in operation du ring the fault period. In addition, it is observed that with the use of gains obtained without Fuzzy-PID the terminal voltage presents deeper sag as compared with those controllers with gains adjusted by the proposed Fuzzy-PID procedure.

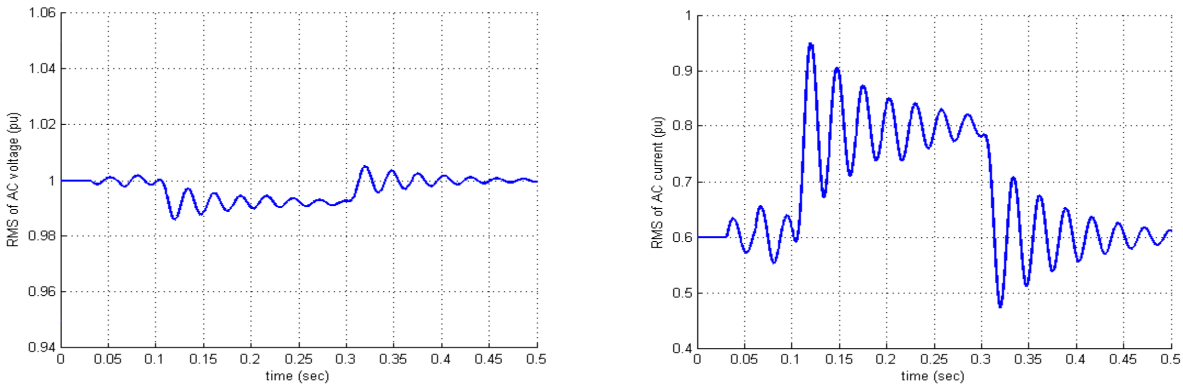
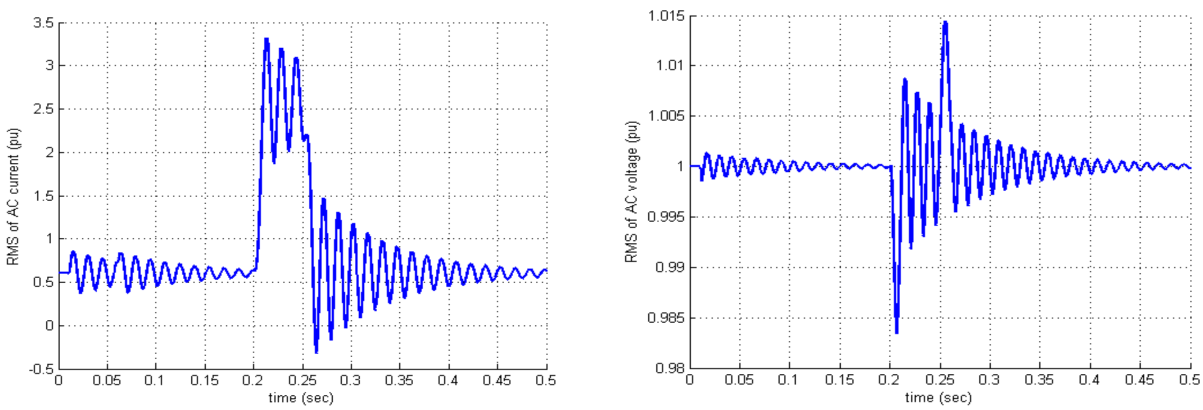


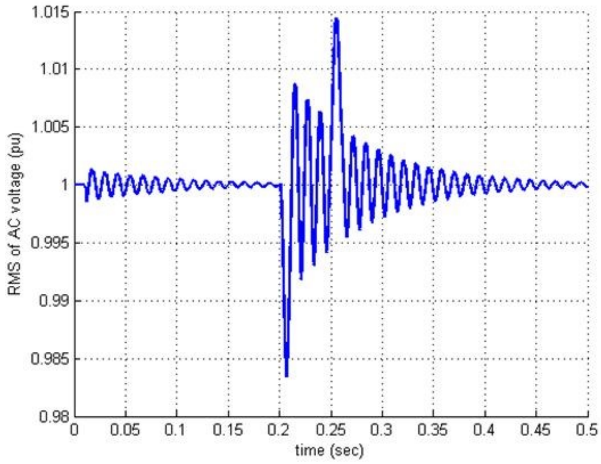
Figure 15: AC link Voltage and current responses-based conventional-PID controller when load is increased by 50%

Figure 16 and Figure 17 show the dynamic performance of the voltage and current of the AC bus based conventional-PID controllers and Fuzzy-PID controllers with phase to phase short circuit. It is observed that in the case when Fuzzy-PID controllers is used, the AC voltage and current present smaller settling time and oscillations as compared with the conventional PID controllers, consequently contributes towards maintaining the converter in operation during the fault period.

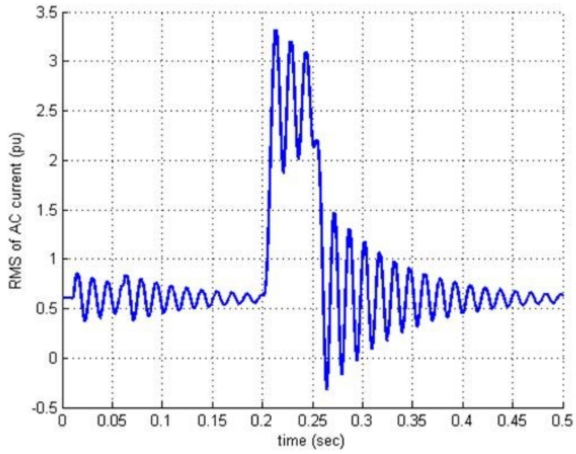


(a) (b)

Figure 16: AC link Voltage and current responses-based conventional PID controllers with phase to phase short circuit.



(a)



(b)

Figure 17: AC link Voltage and current responses-based Fuzzy-PID controllers with phase to phase short circuit.

IV. Conclusion

This paper has presented the modeling and simulation of wave energy driven self-excited induction generator which feeds power to the utility grid. The Fuzzy-PID controllers was applied to the sliding mode controller for adopting the controller parameters according to the tracking error to both the dc-link voltage and ac line voltage regulation. The indirect field-oriented mechanism was implemented for the control of the SEIG to regulate the dc-link voltage of the ac/dc power converter and the AC line voltage of the DC/AC power inverter with robust control performance. Simulation studies are carried out and compared the results obtained with the conventional PID controllers and Fuzzy-PID controllers The simulation results verified the effectiveness and robustness of the Fuzzy-PID controllers and it was comparatively superior than conventional PID controllers in the sense of the transient performance of the wave energy system over a wide range of operating conditions.

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