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Implementation of a New Algorithm with Fuzzy Inference in FPGA for Synchronous Generators Wind Turbine Against Loss-of-Field Protection

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Abstract—The present study aims to present the contribution of a new algorithm for synchronous generators wind protection and the assessment of the effectiveness of the performance of the Loss of Field Protection Fuzzy (LOEPF), using Fuzzy inference implemented in reconfigurable computing with high level optimization of logical operations. A new model of sub and overexcitation by the wind generator capacity curve for the steady-state stability limit is introduced, serving as the basis for the development of this new algorithm and the evaluation of the effectiveness of the same. The LOEPF algorithm is implemented in FPGA with acquisition of voltage and current signals, for carrying out the tests of various conditions of simulated faults by means of a test box Doble F6150 compared with the results obtained with the use of a commercial relay. The results obtained in tests of the new algorithm showed superior performance compared to conventional protection, reducing lag time and time of trip. This feature allows for fast data throughput and processing allowing the relay handling samples high-frequency data and computational efficiency.

Keywords

Wind Power Generation; FPGA; Fuzzy Logic; Protection Against Loss-of-field; Synchronous Generator; Digital Protection.

1. Introduction

The excitation system of a wind generator unit is basically responsible for providing direct current to the field winding in order to establish and maintain the internal voltage of the Synchronous Wind Generators (SWG) in a proper range. The automatic regulation action adjusts the current supplied to the field circuit by comparing the output magnitudes of the generator to baseline values. Among the stand out functions of the excitation system there is the terminal voltage control, and the supply or monitoring of the reactive power to the electrical system and its contribution to the extension of the stability limits [1]-[2]. In normal operation, the excitation system of the generators must assure the voltage in their loading terminals of approximately ±0.5% of the adjusted value from the operation on empty to the fully-loaded operation, keeping frequency in the range of ±5% [3]. In terms of response times, the excitation control system has two categories: rotating and static. Fig. 1 represents the complete system of a Wind Generator Center (WGC), adopted as baseline for the development of this work, with a static exciter by IGBT - Insulated Gate Bipolar Transistor [4].

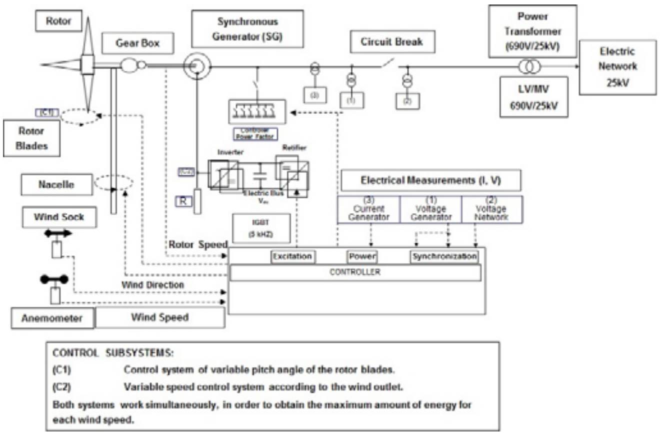

Fig. 1. WGC general scheme

There is a momentary over-speeding in the occurrence of excitation loss of a synchronous generator, and the generator starts functioning as an induction generator, at a speed inferior to the synchronous speed, absorbing reactive power of the system. In this condition, an undervoltage may occur, which causes instability in the wind turbine coupled to the wind generator, where it is extremely important that one of the protections of type un-dervoltage (function ANSI 27) or Impedance of type MHO (function ANSI 21) acts fast enough to prevent damage to the wind rotor.

This work aims to evaluate the performance of the methods of protection against loss of excitation in a synchronous generator commercial wind with use of Fuzzy Logic (FL). To this end, in the first part of the work are presented the characteristics of the field loss protection for wind generators. This implementation sets up a new methodology for evaluating the ability of generation and loss of field protection, in particular wind power generation units. The research also aims at obtaining a coordination with the Generator Capacity Curve (GCC) and the Steady State Stability Limit (SSSL) of a wind generator by the annual average values of the winds in a region-of-study in Northeast Brazil. The second part presents the FPGA implementation of the algorithm of Fuzzy inference for protection against loss of excitation in order to evaluate the response of the proposed algorithm. In the third part is performed the evaluation of algorithm in FPGA in comparison with data from tests on a commercial relay. In this sense, three distinct tests are presented. The last part addresses the conclusion of this work.

I. Protection and Generation Capacity for Brazilian Basic Network Acess

A. *Protection Against Loss-of-field or Excitation*

The protection against loss-of- excitation/field in a synchronous generator is a requirement for generators with power higher than 500kVA and voltage greater than 600V. This protection must act when there is an excitation loss by function (ANSI 40). This fault causes a sudden acceleration of the generator and it starts functioning as an induction generator operating as loaded, that is, consuming reactive power of the network instead of providing it. Even when this happens for a short time on the machine, a magnetic imbalance occurs, resulting in a dangerous overheating, especially if the rotor poles are flat and with no dampening winding, which is only tolerable for 2-3min [3]. Some systems do not tolerate the continued operation of the generator without or with low excitation and there could be instability, especially if there is no prompt automatic voltage regulator, due to a sudden voltage fall and consequent of the inversion of the reactive flow [5]. Within this context, the rapid and automatic protection performance with digital estimation techniques of the inversion of the reactive flow is imperative. Two positive sequence elements (offset-mho) must detect the excitation loss conditions. Adjustable timers must be able to reject power oscillations on the impedance feature of the machine. One of the mho elements can be set by using a directional supervising algorithm, to coordinate with the minimum excitation limiter of the generator and with its stability limit in use [6]. The eddy currents induced in the rotor overheat this part of the machine. As the machine behaves as a short-circuit with small reactance (X'_d), the high currents in the stator windings can cause severe heating damages into the insulation of the windings. For the electric power system, the loss of reactive power support may generate power oscillations in the system, which causes tripping of the transmission lines. Fig. 2 considers real data of the wind SWG modeled in this work, used as reference for the representation of the capacity curve of wind generators. Such SWG defines the protection element against Loss-of-Field (LOF) by under or overexcitation and the capacity curve of the wind generator for the stability limit of stationary state. It is worthwhile to mention that this model for a synchronous generator connected to a wind rotor with a multiplier gearbox has not been presented in the literature.

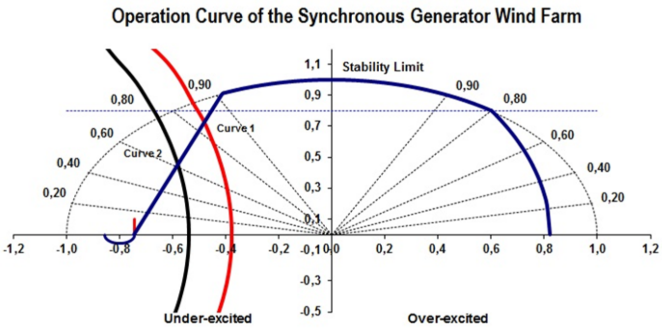

Fig. 2. P-Q plan representation of the capacity curve in stability limit of stationary state for a wind generator and highlights of regions for (LOEPF).

Fig. 3 represents the setting with offset mho LOF element that does not consider the capacity curve of the generator, the stability characteristic limit in stationary state and the underexcitation limit of the wind generator. The response diagram to the loss-of-field shows how an offset mho element can detect a loss-of-field situation. When the machine loses the field current, the line of the apparent impedance, initially located at the point marked as "0 second", moves to the fourth quadrant. The apparent impedance stops at a point located next to the point corresponding to the negative value of the transient reactance of the X'_d machine. This occurs in approximately 2 seconds.

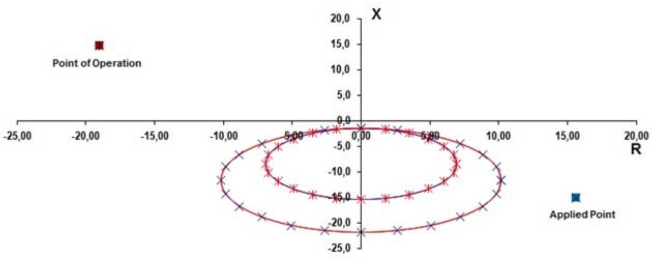

Fig. 3. Diagram of two LOF protection zones using the offset mho LOF element.

Fig. 2 and 3 indicate that the characteristics and performance of the protection system and the excitation loss must suit the automatic performance of functions perfectly, required by the starting and stopping automatic control sequences of the wind turbine-generator group, where at least the following characteristics must be met [7].

- Field voltage response time ≤ 0.1s;
- The conduction capacity in CC should not be less than 110% of the excitation current required to keep the generator operating at maximum power and 105% of nominal voltage;
- The voltage of positive peak must be lower than 2.5 times the field nominal voltage (in nominal conditions of active power, voltage and power factor);
- The voltage of negative peak should not be lower than 80% of the positive peak;
- The maximum value of the response curve of the terminal voltage (overshoot) must be ≤ 10%; and
- The stabilization time of the nominal voltage must be ≤ 1s.

An important requirement for generation units connected to the transmission system is the elimination of all types of faults by the unit protection, including an opening time of all circuit- breakers of the generator unit that does not exceed 100ms for the generator units accessing the basic network in voltage level equal to or higher than 230kV [7]. The backup protection should be gradual for faults between phases and between phase and ground, providing suitable WCG protection, and maintaining a coordination with the protection of adjacent equipment in cases of sustained external faults. In the following sections, those requirements are evaluated with respect to the effectiveness of the proposed protection.

B. LOEPF Algorithm in FPGA

É It is difficult to quantify the exact time of excitation loss in a generator, when a moment of overspeed results in a rapid transition to a lower speed condition, followed by overvoltage [8]. The definition of such frontier, as the threshold of normal operation for the fault state, is a uncertain research area. Thus, the use of an intelligent mechanism as the Fuzzy Logic (FL) is reasonable.

The basic principle of the FL consists in define variables and linguistic mode rules that apply properly the case studied, for from these rules set up associations and get a result [8]. Following this reasoning will be defined in this section, the input variables to support the use of the provisions of the FL applied to the assessment of the effectiveness of LOEPF protection of SWG with implementation on FPGA with VHDL (Very Hardware Description Language).

The output variable for this study will be precisely the level of output voltage of the generator for evaluation of the effectiveness of the protection, as well as the apparent impedance plan R-X (impedance plan), which will be submitted the rated generator with parameters (real) for performance of LOEPF protection in order to raise the generator circuit breaker. In this case, the input variables are some indicators of possible conditions that generate the failure of loss of excitation by accidental opening of the field circuit, a short-circuit in the field circuit, voltage regulator failure or bad contact brushes of Exciter and power supply failure of excitation system, increasing your level of stress and Consequently, reducing its useful life [9].

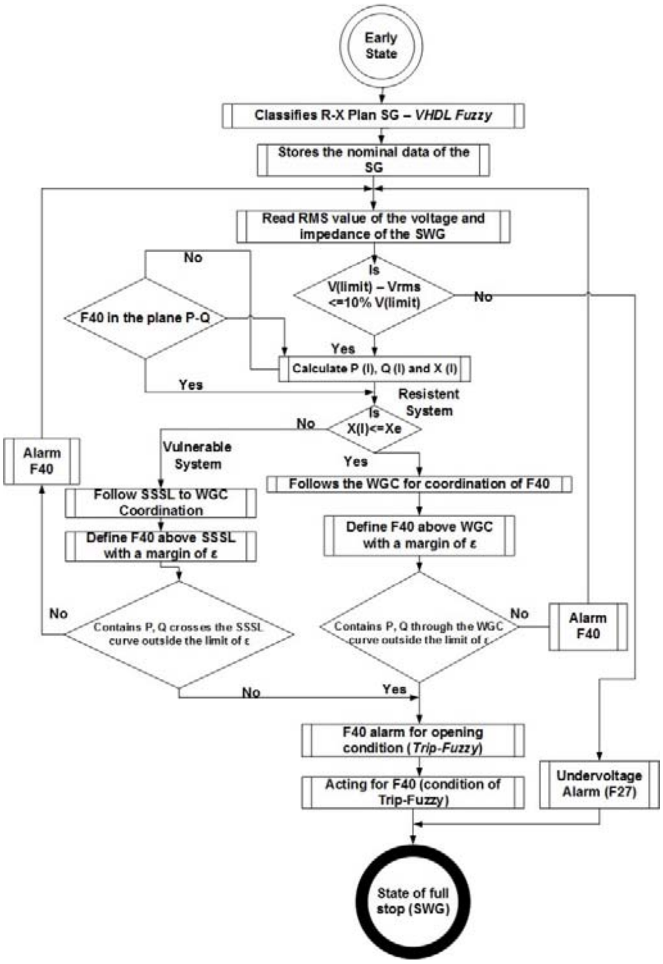

Fig. 4. Flowchart of FPGA LOEPF algorithm in VHDL

The flowchart of Fig. 4 shows a feed system that provides a preprocessor to the voltage and current, which are converted to RMS values for the algorithm. Those signals provide the apparent impedance for the generator and for the voltage terminal, in p.u. in the machine basis [10]-[11]. Eq. (1) and (2) are used for the protection performance. The apparent impedance and voltage on the generator terminal provide data to the Fuzzy inference algorithm, which, in turn, sends, as output, the signal to be analyzed by the rules, and, then, decides between trip, activate the alarm or no actuation [12].

At the beginning of state, the algorithm checks whether there was excitation loss or if conditions (1) [11] were not met.

$$LOEPF = P_{(i)}{}^{2} + Q_{(i)}{}^{2} \leq \left(R_{(i)_{LOE}}\right)^{2}$$

Where $R_{(i)_{LOE}}$ is represented by

$$\frac{V_{rms}.x_d}{(2x_d^2 + x_{d'} + 2x_d.x_{d'}}\sqrt{2\left\{V^2 + \frac{1}{(x_d + x_{d'})^2}\right\}} \quad (1)$$

If this criterion is met, P-Q trajectory is characterized as out- of SSSL shooting and the instantaneous trip is initialized. € accounts for the small margin representing 3% of the generator MVA [11].

In order to test if P (I) and Q (I) points are located inside or SSSL curve, the following inequality is verified by the algorithm (2).

$$\left[{P_{(i)}}^2 + (Q_{(i)} - C_{(i)_{SSSL}})^2\right] - \left(R_{(i)_{SSSL}}\right)^2 \geq € \qquad (2)$$

Where $R_{(i)_{Stator\ heating}} = K2.\frac{V_t(i)^2}{x_d}$ and $C_{(i)_{Stator\ heating}} = K1.\frac{V_t(i)^2}{x_d}.492.$

2. Reconfigurable Hardware implementation – FPGA Xilinx Zynq

Loss-of-Field Protection Fuzzy (LOEPF) protection implemented in FPGA Zynq-XC7Z010 combines Digital Signal Processing (DSP) in ARM Cortex-A9 architecture, a FPGA chip with 12 transceivers channels of 10.3 Gbps and a PCI Ex-press Gen 2 block for high-speed "off- chip" connectivity and two Analog-to-Digital converter blocks (A/D) of 12bits with 1Msps (Mega-Samples Per Second). FPGA provides low latency and high resolution for the imple-mentation of digital protection functions, based on the instantaneous measurement of basis signals to be in-quired and sampled by FPGA SoC A/D module (System-on-Chip) and on the processing of voltage and current phasors. Due to the high performance of FPGA, about 0.6% of the reconfigurable core logic cells are used for implementing Fuzzy-LOF algorithm, which allows data processing within a few microseconds.

In the FPGA are implemented the non-linear trigonometric functions required by Fuzzy module, generated from the module COordinate Rotation DIgital Computer (CORDIC) iterative [13]. The CORDIC algorithm is a method aimed at systems that do not have dedicated hardware arithmetic operations.

The setting of the algorithm is made by adjusting the limits of each set. The defuzzification process runs through five Fuzzy sets using type inference Mamdani and the center of areas for the calculation of the output variable Z. All sets used are triangular, and limits are set on the block Fuzzy Rules. The rules are implemented using mechanisms for analysis of standard set by calculating the maximum degree of relevance to the operations of type "OR" and the minimum degree of pertinence to operations of type "AND".

LOEPF rule is implemented as follows:

"IF V_{RMS} is **Very Small (**μ_1) ***AND*** Z_T is **Very Small** (μ_1) ***OR*** V_{GRMS} voltage is **Medium (**μ_3) **AND** Z_T is **Medium** ***THEN*** *trip* is **Very Large (**μ_5)**".**

Linguistically, this means:

$$\mu_{ik}(X_i) \in \{\mu_1, \mu_2, \mu_3, \mu_4, \mu_5\} \qquad (3)$$

Tab. I presents the input parameters of Membership Functions (MF), having as first input the total impedance Z_T and the effective voltage V_{GRMS} internal to SWG, for which LOF protection is given by (1). The relevance degree μ_{MP} identifies very small values of total impedance of SWG for values lower than $0.4x_d/2$. The relevance degree μ_M detects values between 50% of Z_T and 50% below the circumference radius of $x_d/2$. The relevance degree μ_G identifies the normal operation and initial condition for triggering the alarm for LOF protection, and degree μ_5 indicates a trip condition.

Table I. - Input parameters of Membership Functions

Fuzzy Variables	μ_1	μ_2	μ_3	μ_4	μ_5
Z_T	0	$0.4x_d/2$	$x_d/2$	$0.69x_d/2$	0.96
V_{GRMS}	0	0.3	0.4	0.92	0.98

Tab. II shows the output parameters and MF for Z_T and V_{GRMS}, respectively. They are used to implement the Fuzzy rules based on the behavior of variables Z_T and V_{GRMS} during SSSL events, LOF condition and normal.

Table II. - Input parameters of Membership Functions

Fuzzy Output	μ_1	μ_2	μ_3	μ_4	μ_5
Z	0	0.3	0.4	0.7	0.9

A. Practical Scheme

On the practical scheme, as 1° step by extracting the files of COMTRADE standard (Common format for Transient Data Exchange for power systems), taken from the prototype of the protection relay, whose faults are generated from the voltage and current signals of testing box Doble F6150. The test box is useful for validating and lift the operation characteristic curves of the prototype developed, primarily for validation of the effectiveness of protection LOEPF. Step 2 is already characterized by evaluating the behavior of the operation of the prototype to fault situations. Conceptual illustration of architecture developed for testing is presented in Fig. 5, whose proposal is to increase the efficiency in detecting faults for loss of excitation and sags in synchronous wind turbines, allowing through design in VHDL Vivado 2015.1 version software from Xilinx [14], the reduction of processing time and also the simplification of hardware. In this way, develops a prototype of computationally efficient and robust relay, since it is able to perform Fuzzy inference correctly for different types of excitation loss.

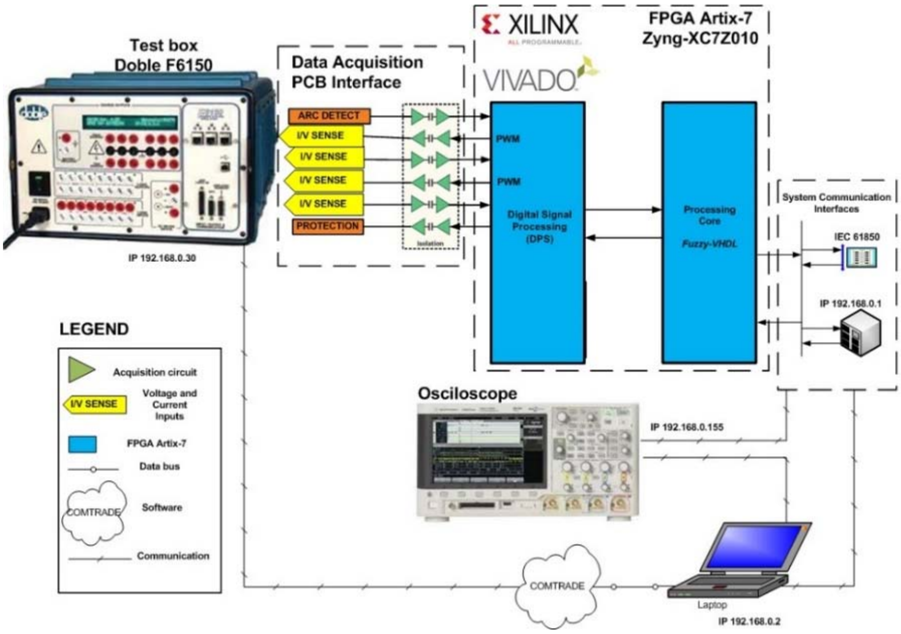

Fig. 5. Diagram of LOEPF system and the testing methodology

3. Results

For both LOEPF methods in prototype in FPGAS and relay GE G30 tests were carried out on the basis of actual data of a commercial GS (2.1 MW-0.4 p.u.), as well as study data were used for Micrositing (study of wind potential) of a new Park in the Northeast Brazil. The Fuzzy algorithm proposed obtained an excellent performance against the operation time, compared to a model with oscillography of lack to a scheme of excitation loss protection, obtaining an answer around 115% faster.

Due to the high capacity FPGA, a small percentage, around 10% of the core logic, reconfigurable cells are used for implementation of the LOE-Fuzzy and can process all the data around 280ns (nanoseconds).

The Tab. III presents the results for a lag time of 41.78 µs to protect Conventional and 280ns-LOE-latency required for protection and-Fuzzy in FPGA, respectively. The clock frequency is 500 MHz project.

In Fig. 6 and 7, are presented oscillografy regarding the condition of fault for loss of excitation of synchronous wind generator for testing the condition No 2, of Table III.

Table III. - Comparison of the Trip time for loss of excitation (commercial relay and prototype)

Test	**Type of Fault**	**Processing time *(41.78µs)* Relay GE G30 Conventional (ms)**	**Processing time *(280ns)* *FPGA LOE Fuzzy* (ms)**	**Reduction (ms)**
1	Circuit-bracker opening in field a-b-c-g (ANSI 40)	81.28	13.68	67.6
2	Exciter Loss (ANSI 40)	64.80	11.50	53.30
3	Loss of Power Directionality (ANSI 32)	74.11	15.04	59.07

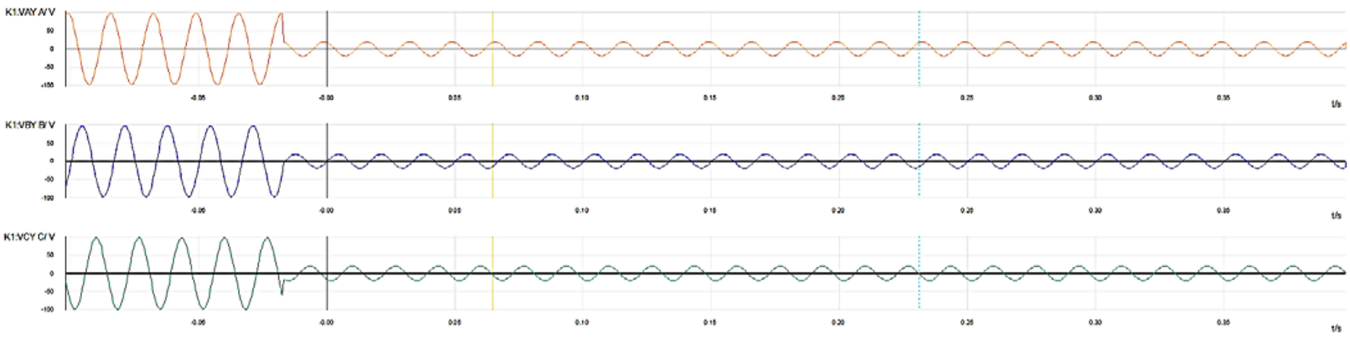

Fig. 6. Conventional detection of loss of excitation of generator in 64.80 ms

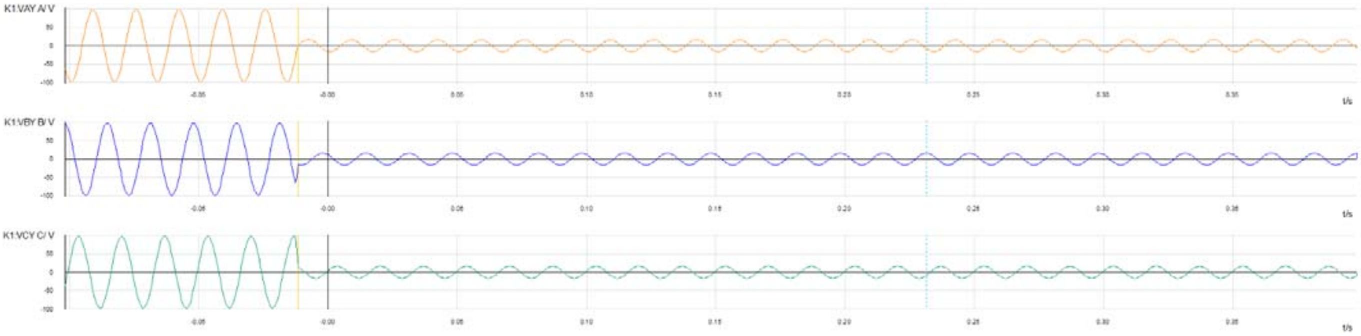

Fig. 7. Detection algorithm of Fuzzy excitation loss protection on generator in 11.50ms

4. Conclusion

This article presented a new contribution of an algorithm for protection against loss of excitation using Fuzzy inference in FPGA Zynq for wind generators, evaluating different excitation loss situations compared to a commercial relay. The tests made it possible to detect faults by circuit breaker opening in the field, the loss of the exciter and the loss of control of the wind rotor, in addition to the tests by using a practical scheme implementing the algorithm LOE-Fuzzy in FPGA, getting a shorter time in comparison with a conventional algorithm. Moreover, the lag time of the FPGA with the Fuzzy algorithm has been improved significantly, reducing the processing rate.

All the Fuzzy logic on the FPGA applied to digital protection was developed in VHDL language which can be easily transported to the development of different protection functions using Fuzzy inference. The logical proposal is oriented to optimize the pipeline to achieve high operational efficiency and speed in the protection. The case studies show the operational effectiveness of the logical proposal with a very low hardware latency. With the abundance of available hardware resources in this prototype, this approach can also be upgraded to a multifunction relay for protection of wind generators in specific, with smart metering capabilities, location of missing internal stator, with more functional elements to be added in the future.

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