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FUZZY CONTROL APPLIED TO AN ELECTRICAL POWER GENERATION SYSTEM MOUNTED ON TRACTORS FOR DRIVING OF AGRICULTURAL IMPLEMENTS

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ABSTRACT: The demand of the agricultural sector for more operationally efficient machines and implements motivated the development of alternatives for driving of this equipment. Aiming an electrical supply to apply in agricultural implements, this study proposes a system that uses the tractor power take off to activate a synchronous generator, using a fuzzy logic controller designed to regulate the generated voltage level. Different control architectures were tested and evaluated by simulations. In the initial stage were evaluated fuzzy PI, fuzzy PD and fuzzy PID controllers of multiple inputs and single output (MISO) and the error of the generated voltage as state variable. Subsequently, it was evaluated a fuzzy PI controller of single input and multiple outputs (SIMO) with a modified rule base for the system. In the final stage, the angular drive speed was included as state variable of the controller. The behavior of each architecture was analyzed by means of performance indexes. The results show that among the tested controllers, the modified fuzzy PI SIMO presented the best performance values while maintaining the operating variables within the established limits.

KEYWORDS: synchronous generator, power take off, electrical implements.

INTRODUCTION

The demand of the agricultural sector for greater efficiency and controllability of operations carried out by tractors and implements boost the development of these machines to replace mechanical and hydraulic systems widely spread in the market. Functions such as variable-rate application (VRA), as assessed by MACHADO et al. (2015), geo referenced applications, monitoring and operation control by means of on-board devices such as productivity sensors, and complex drives are examples of applications that feed this demand and are correlated with the advancement of precision agriculture (PA). One of the alternative drives already explored by manufacturers is the electric drive (KARNER et al. 2012).

Conventional tractor has as power source to implement the mechanical power take off (MPTO) and hydraulic power take off. With the proposed use of electric drives, the need arises to develop a new source of power (PRANKL et al. 2011), the electric power take off (EPTO). Unlike the MPTO the EPTO can eliminate the dependency relationship between the activation of the implement and the angular speed of the diesel engine traditionally used in agricultural tractors, also enabling the use of electronic control systems, as in UMEZU & CAPPELLI (2006) and GARCIA (2014).

There are generators that use the tractor as a mechanical power source for electric power generation, aimed for the activation of agricultural machinery and implements, as well as to power of small rural electric grids in emergency situations. However, conventional systems are stationary, requiring that the tractor remains stopped and maintaining a constant angular speed of the diesel engine so that the generator can work at constant voltage and frequency generation. Otherwise, the generated power could be out of voltage and frequency tolerances required for operating the equipment, preventing its use. These limitations preclude the use of operations in which conventional systems, powered by tractors, during agricultural operations in which the angular speed of the MPTO axis is not constant.

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Studies of on-board electricity generation on agricultural machines basically explore two architectures for the conversion of mechanical power into electric in agricultural tractors. The first, and most common, is based on the concept of hybridization of vehicles (KARNER et al., 2012), where the generator is integrated into the vehicle power train. The second architecture is on board generation module, powered by the axis of the MPTO and fixed to the structure of the three points of the tractor ((PRANKL et al., 2011 and RUSSO, 2013). This last configuration, different from hybridization, allows the adaptation of generation systems on conventional tractors, offering a flexible alternative, as an intermediate stage towards the establishment of ETPOs on tractors and agricultural implements.

This study presents an on-board power generation system powered by the tractor MPTO. The objective of this study is to validate the operational viability of the fuzzy controller, designed to regulate the voltage generated in the proposed system. To operate the system, it must be able to operate on simultaneous variations of the demanded load power and the angular speed drive, keeping the energy generated within the established limits.

MATERIAL AND METHODS

The proposed system and its main components are shown in Figure 1, where: MPTO, tractor's mechanical power take off; SG, synchronous generator; w, angular speed of the SG rotor; Frequency Inverter (where PWM is pulse-width modulation); V_{fd}, voltage on the SG field circuit; V_{dc}, voltage on the DC busbar of the frequency inverter circuit; P_o, load power.

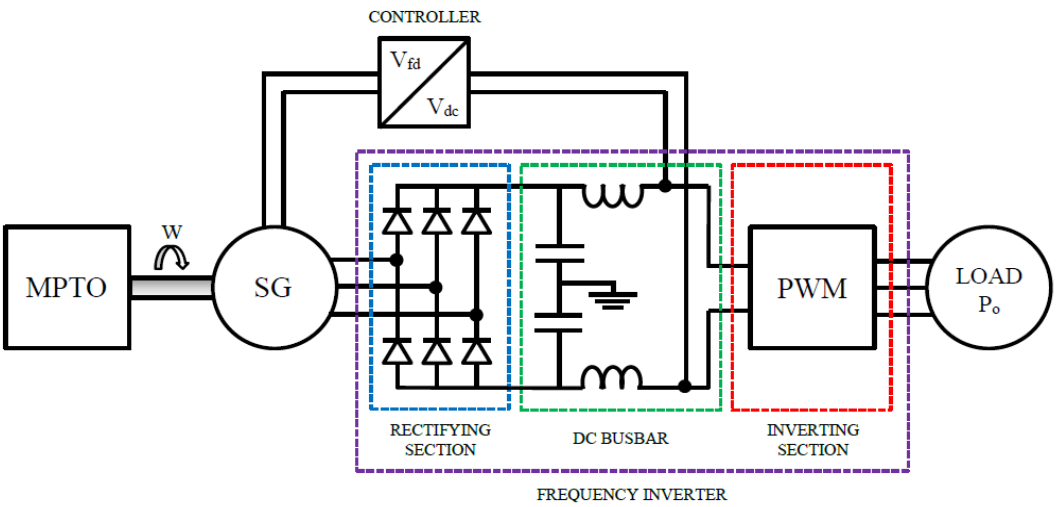

FIGURE 1. Block diagram of the electric power generation system architecture.

It can be seen that the SG is driven by the axis of the mechanical power take off from the tractor, while the three phases are connected to a frequency inverter circuit which supplies power to the load, could be an electric implement, or another compatible load. The parameters of the SG, necessary for the mathematical modeling of the system were based on a model of three-phase synchronous generator with salient poles, with the nominal voltage value of 380 Vac, frequency of 60 Hz, power of 20 kW and angular speed of 188. 5 rad s^{-1} (1800 rpm), from the manufacturer WEG, GTA161AI22 model.

The construction and configuration of the proposed system, as well as the design and tests of the fuzzy controller were conducted through computer simulations using MATLAB / Simulink, program as well as GARCIA et al. (2014). A simplified version of the block diagram of the mathematical model of the system designed in the Simulink program is illustrated in Figure 2.

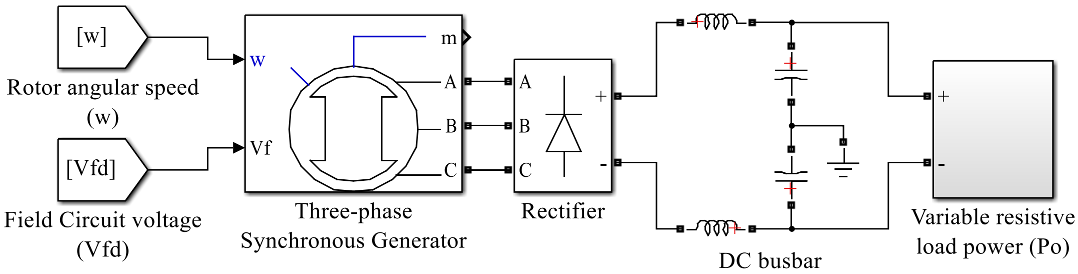

FIGURE 2. Simplified block diagram of the mathematical model of the system.

The SG is represented by a 6th order model in the time domain which takes into account the dynamics of the field circuits (rotor) and phase (stator). The mechanical system SG is dismissed with the direct application of the angular speed of the rotor axis. The rectifier consists of a three phase rectifier bridge of six diodes (naturally commutated). The DC busbar adds a set of inductive and capacitive filter for attenuation of voltage variation caused by the switching of the diodes bridge. The variable resistive load in DC enters the system performing the role set of the inverting section and the three-phase load, as used by JADRIĆ et al. (2000).

With the tractor operating outside the steady state (moving) will be changes in the drive axis speed as a result of power demand and gear shifting, in models of mechanical transmissions, equipping most tractors with up to 111,8 kW (RIBAS et al. 2010). As the generator is powered by the MPTO, the change of the axis angled speed causes variations in the voltage and frequency generated. In the adjustment of voltage and frequency of the supplied power, the proposed system uses two main features in power electronics and control. To control the frequency generated the solution adopted is the indirect power supply of the load by frequency inverter circuit, similar to PRANKL et al. (2011). This solution allows the SG operate with variations in the angular speed drive, since the frequency supplied to the load is controlled solely by the inverter, just as the voltage on the DC bus bar (V_{dc}) is maintained at the nominal operating level, around 515 V. To maintain the DC bus bar voltage, the solution adopted is the generated voltage control by actuation in the field voltage circuit (V_{fd}), a task performed by the fuzzy controller.

Figure 3 illustrates the surfaces of the voltage values on the DC busbar (V_{dc}) during steady state of the system in open loop and constant angular speed drive, for three scenarios of angular speed, being: w_1 of 150.8 rad s^{-1}; w_2 of 188.5 rad s^{-1}; and w_3 of 226.2 rad s^{-1}.

In Figure 3 it is possible to see the behavior of the voltage on the DC busbar (V_{dc}) depending on system state variables. For field voltage variations (V_{fd}), the system responded linearly. As for variations in the load (P_o) and angular speed (w), the system responded as nonlinear form. Combinations of these behaviors give the system a nonlinear relationship between the generated voltage and the state variables of the system, as noted by the format of the response surface. Thus, the controller adopted should be able to deal with this non-linearity and to maintain the level of generated voltage in the operating range.

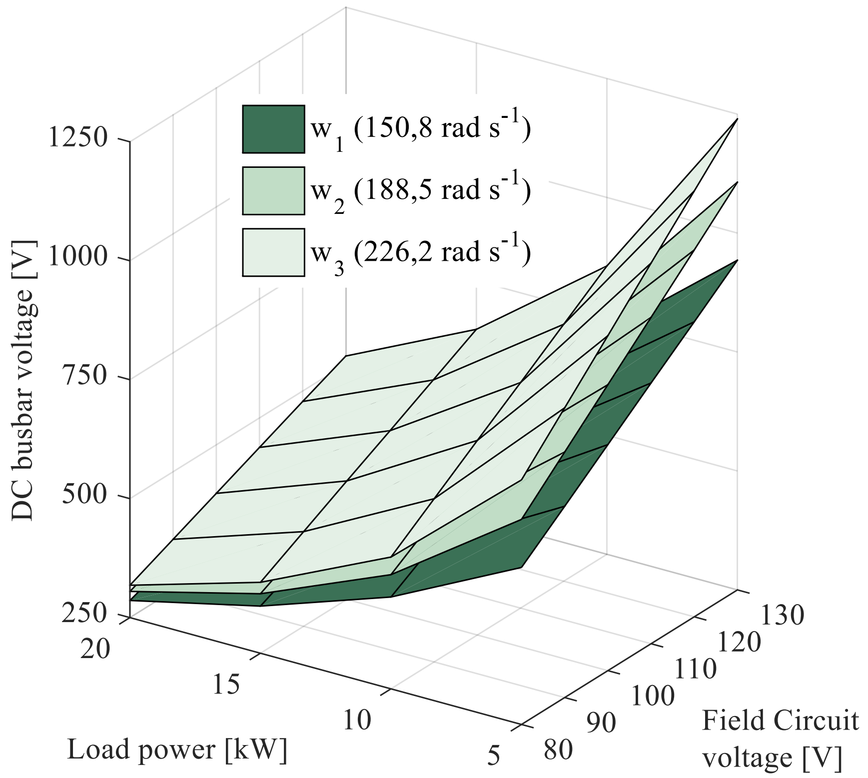

FIGURE 3. Surfaces of the voltages values on the DC busbar during the steady state of the system in open loop and constant angular speed.

For the power generation system to work properly it is necessary to define the ideal operating condition and limits of its variables. Table 1 shows the nominal values and the maximum and minimum values assigned to variables, based on the synchronous generator of 20kW adopted.

TABLE 1. System operation variable; nominal, maximum and minimum values.

System Variables	Nominal values	Maximum values	Minimum values
$\mathbf{P_o}$	20.0 kW (100%)	20.0 kW (100%)	0.0 kW (0%)
w	188.5 rad s^{-1} (100%)	235.6 rad s^{-1} (125%)	141.4 rad s^{-1} (75%)
$\mathbf{V_{fd}}$	135.0 V (100%)	200.0 V (148%)	N.A. [1]
$\mathbf{V_{dc}}$	515.0 V (100%)	566.5 V (110%)	463.5 V (90%)

P_o, load power; w, angular speed of the SG rotor; $V_{fd,}$ voltage in the field circuit; and V_{dc} voltage on the DC busbar of the inverter circuit.
(1) The minimum V_{fd} value is not applicable, as it is an actuated variable of the system.

In the proposed system, it was opted for the use of a fuzzy controller, where the independent variables of the system are P_o and w. The actuated variable is V_{fd} and the controlled variable is V_{dc}, which behavior determines the correct operation of the system.

Unlike a PID controller, the fuzzy controller is able to absorb the system complex dynamic (nonlinearities) and operate over a wide operating range (GARCIA et al., 2014), necessary feature for system control (JADRIĆ et al. 2000).

The difficulty in designing a fuzzy controller is in developing the rules bases and the impossibility of the analysis of the system stability without the use of simulations or experimental tests. Therefore, the construction of the mathematical model of the generation system is essential for the design and testing with the fuzzy controller. Yet for the determination of fuzzy variables and the construction of the basic rules, we adopted as reference the models proposed by LI & GATLAND (1996).

LI & GATLAND (1996) studied different architectures of fuzzy controllers using two rules bases for the design of controllers of the proportional integral type (PI), proportional derivative (PD) and proportional integral derivative (PID). The studied controllers are of multiple inputs and single output (MISO). During operation of the controller variables are converted by membership functions, in the process called fuzzification. The reverse process, the defuzzification converts the controller's response back to a single output value of the manipulated variable. The identification of each membership function is done by name, called linguistic variables that facilitate the process of construction and interpretation of the rule set. The linguistic variables used are:

- NL (Negative Large);
- NM (Negative Medium);
- NS (Negative Small);
- ZR (Zero);
- PS (Positive Small);
- PM (Positive Medium),
- PL (Positive Large).

Figure 4 illustrates a set of seven membership functions of a fuzzy variable.

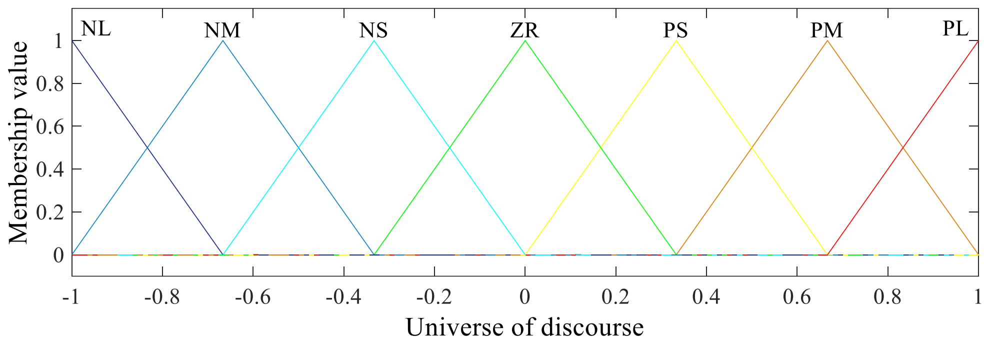

FIGURE 4. Membership functions of a fuzzy variable.

Figure 5 illustrates two bases of rules proposed by LI & GATLAND (1996), as follows: (A) rules base for the proportional integral type controller; and (B) rules base for proportional derivative type controller. Each of the three variables utilizes seven membership functions. Since each rule base has two input variables, it has a total of forty-nine output combinations.

(A) Error

Derived Error	NL	NM	NS	ZR	PS	PM	PL
PL	ZR	PS	PM	PL	PL	PL	PL
PM	NS	ZR	PS	PM	PL	PL	PL
PS	NM	NS	ZR	PS	PM	PL	PL
ZR	NL	NM	NS	ZR	PS	PM	PL
NS	NL	NL	NM	NS	ZR	PS	PM
NM	NL	NL	NL	NM	NS	ZR	PS
NL	NL	NL	NL	NL	NM	NS	ZR

Entry: Actuation

(B) Error

Derived Error	NL	NM	NS	ZR	PS	PM	PL
PL	NS	NS	NS	PS	PL	PL	PL
PM	NS	NS	NS	PS	PL	PL	PL
PS	NM	NS	NS	PS	PM	PL	PL
ZR	NL	NM	NS	ZR	PS	PM	PL
NS	NL	NL	NM	NS	PS	PS	PM
NM	NL	NL	NL	NS	PS	PS	PS
NL	NL	NL	NL	NS	PS	PS	PS

Entry: Actuation

FIGURE 5. Fuzzy rules bases proposed by LI & GATLAND (1996).

The design process and controller tuning was carried out in three stages. In the first stage was tested the controller, fuzzy PI, fuzzy PD and simplified fuzzy PID, proposed by LI & GATLAND (1996), using as state variables the V_{dc} error and its derivative, the membership functions of Figure 4 and rules bases illustrated in Figure 5. In stage two, the controller with better performance of stage one has been adapted to enhance its performance in the system, through modifications on the rules bases and the variables of the fuzzy controller. Finally, in stage three, the controller has again been modified to include the rotor angular speed as a state variable. In stages one and two, all controllers underwent the same angular speed disturbances (w) and load power (P_o), applied simultaneously. Figure 6 illustrates the disturbances in w and P_o applied to the generation system simulations, for adjustment of the controllers.

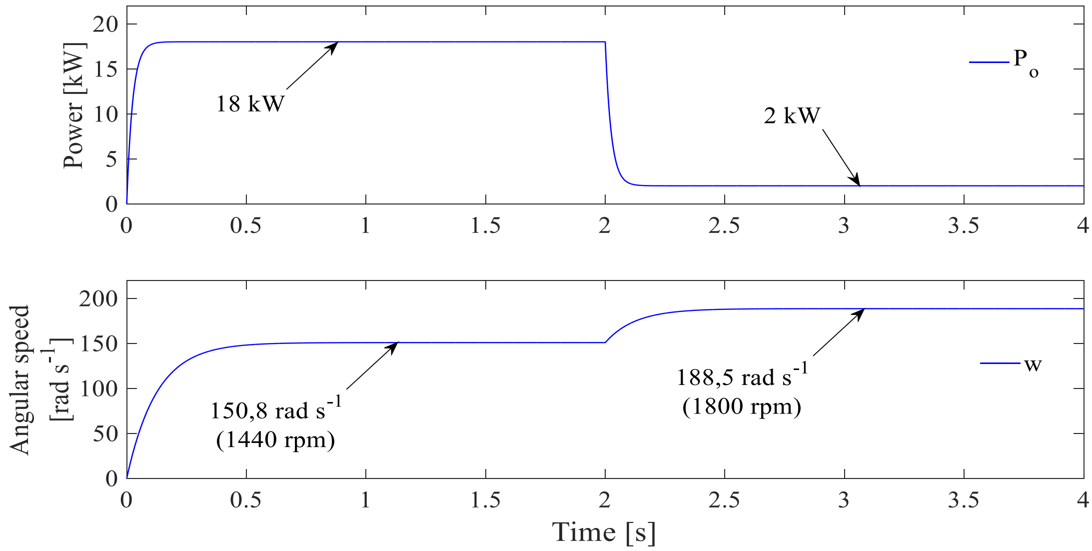

FIGURE 6. Disturbances in w and P_o applied in the simulations of the generation system for controllers adjustment.

In Figure 6, the adopted disturbances simulate the system starting in zero state to a high level load, with the system operating below the nominal angular speed drive followed by relief of the load and increase of the angular speed drive. This sequence was adopted by the occurrence of simultaneous variations of w and P_o in two critical scenarios for the operation of the system.

In the simulations of the third stage was used the same sequence of disturbances in the load power (P_o), while the angular speed (w) is maintained constant during the entire simulation period. In the first scenario (w1), the angular speed was maintained at its maximum operating value of 235.6 rad s^{-1} (2250 rpm) and the second scenario (w2), the angular speed was maintained at its minimum operation value of 141.4 rad s^{-1} (1350 rpm).

For the evaluation of the controllers, performance indexes were generated for the simulations that were compared and used to select the fuzzy controller. The evaluated indexes were: integral of absolute error (IAE) and the integral of time multiplied by absolute error (ITAE). The indexes were calculated with the normalized values of the V_{dc} error and time in seconds unit (s), recorded in the same simulation period.

RESULTS AND DISCUSSION

The next results correspond to the first design stage of the fuzzy controller of the electric power generation system. In this stage it was used architectures developed by LI & GATLAND (1996). Figure 7 illustrates the mathematical model block diagram of the system with the fuzzy controller for the PI and PD architectures by LI & GATLAND (1996), and kp the scaling factor of voltage error, kd the scale factor of the voltage derived error and ksi the scale factor of the controller integral output.

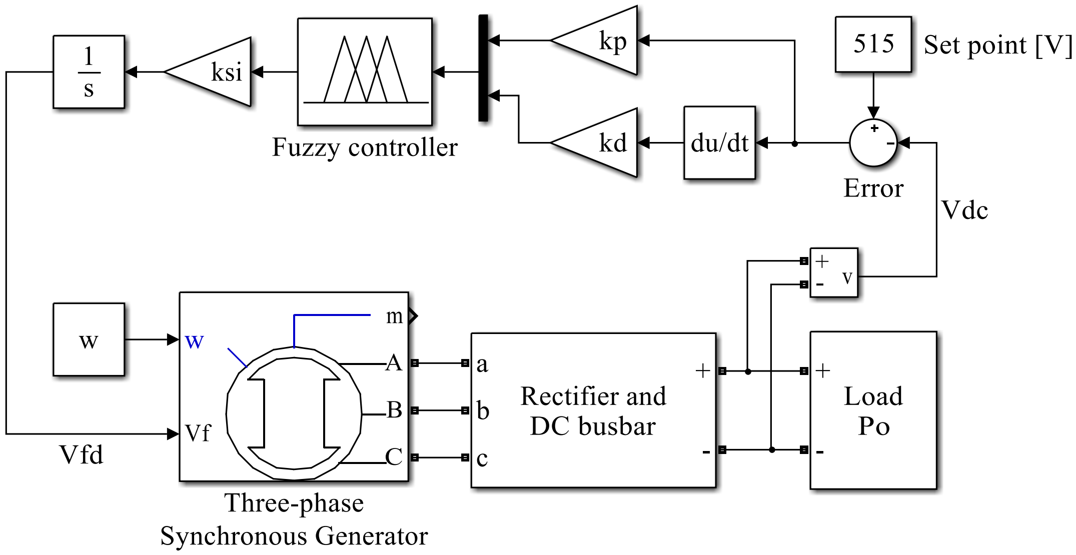

FIGURE 7. Block diagram of the mathematical model of the system with fuzzy controller for PI MISO and PD MISO architectures.

Figure 8 shows the mathematical model block diagram of the system with fuzzy controller, for simplified PI MISO architecture from LI & GATLAND ((1996). This architecture uses a single basic rule (PI or PD) and the actuation is the sum of full and proportional outputs of the controller. In Figure 8, ksp is the scale factor of the controller proportional output.

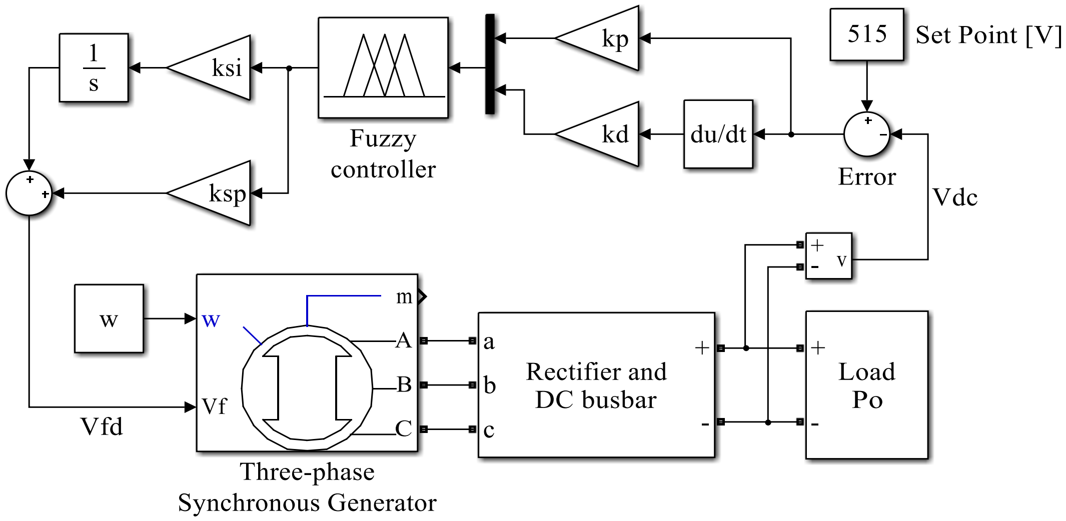

FIGURE 8. Block diagram of the mathematical model of the system with fuzzy controller for simplified PID MISO architecture.

In the proposed system, the switching of the rectifier diode bridge generates high frequency transitions in the output voltage levels for the DC busbar. These voltage oscillations in the system end up hindering the use of the derivative of the error as controller input variable, making the system more susceptible to instability. In order to maintain system stability, the controller derivative actuation was minimized. Thus, after adjusting the scaling factors, it was noted that component of derived error exerted little or no influence on actuation of the fuzzy controllers PID MISO.

In the second project stage, the fuzzy controller simplified PID MISO architecture, of first stage was changed to the exclusion of the derivative component of the error and addition of another exit. It was used an output for proportional actuation and the other for integral actuation. The result is a PI fuzzy controller of single input and multiple outputs (SIMO). Figure 9 illustrates the mathematical model block diagram of the system with the PI fuzzy controller SIMO.

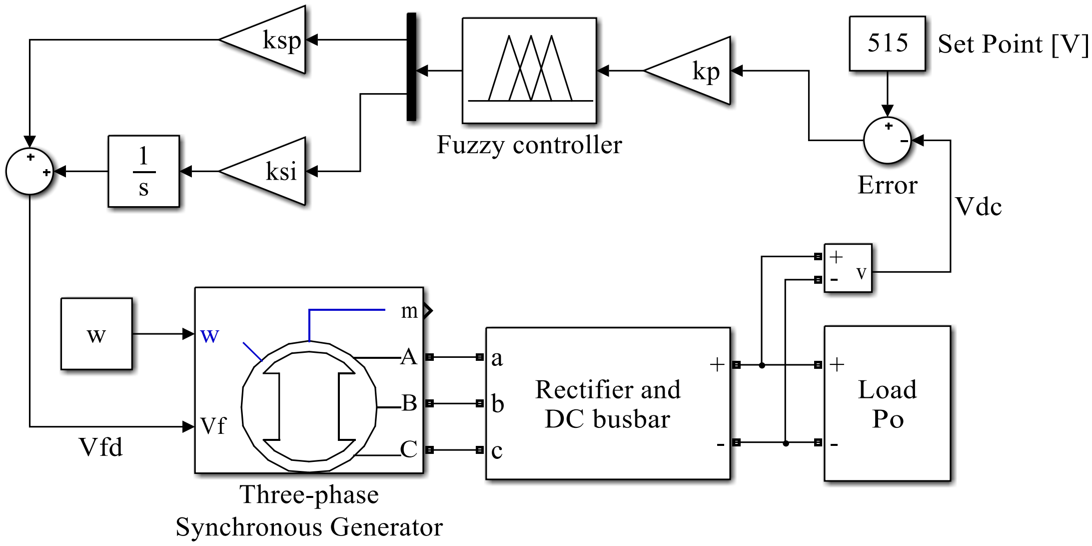

FIGURE 9. Block diagram of the mathematical model of the system with fuzzy controller for PI SIMO architecture.

Figure 10 illustrates the rules base established. On the development of the rules base, the desired goal was to reduce the excessive accumulation of actuation by the integrator during the rise of the V_{dc} value and drastically reduce its value if V_{dc} exceeds the nominal operating voltage. To this end, it was used different strategies for integral actuation on positive errors and negative errors.

	Error						
	NL	**NM**	**NS**	**ZR**	**PS**	**PM**	**PL**
Proportional Actuation	NL	NM	NS	ZR	PS	PM	PL
Integral Actuation	NL	NL	NL	ZR	PS	PS	PM

FIGURE 10. Fuzzy rules base for PI SIMO controller.

Table 2 contains the scale factors of the variables of the fuzzy controllers obtained in the first and second design stage.

TABLE 2. Scale factors of the variables of the fuzzy controllers in the first and second design stages.

Fuzzy Controller	kp	kd	Ksp	Ksi
PI MISO	1.961×10^{-3}	0.1	N.A.	0.015
PD MISO	7.767×10^{-3}	0.1	350	N.A.
PID MISO and PI rules	22.844×10^{-3}	0.1	120	0.025
PID MISO and PD rules	22.844×10^{-3}	0.1	120	0.025
PI SIMO	22.844×10^{-3}	N.A.	120	0.025

Figure 11 illustrates the recorded values of V_{dc} in the system simulations with the controllers on the first and second design stages. The corresponding curves for PID MISO controllers appear overlapped.

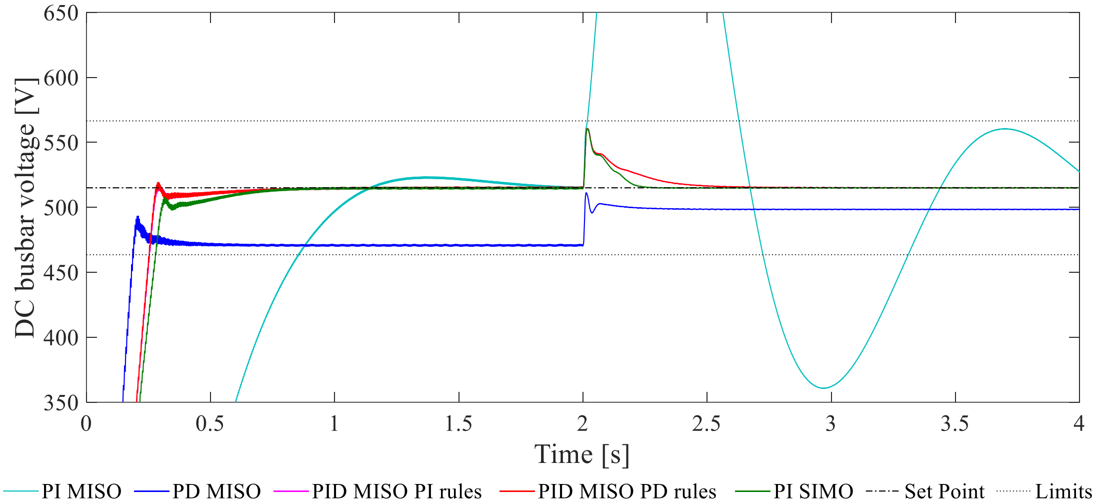

FIGURE 11. V_{dc} value acquired in simulation system with the controller on the first and second design stage.

Table 3 shows the performance indexes IAE and ITAE of the fuzzy controllers on the first and second stages of the project.

TABLE 3. Performance indexes IAE and ITAE of fuzzy controllers in the first and second design stages.

Fuzzy controller	IAE	ITAE
PI MISO	1013.60	1479.20
PD MISO	332.06	368.82
PID MISO with PI rules	177.17	45.49
PID MISO with PD rules	176.76	45.42
PI SIMO	182.37	38.85

The obtained results in the first two design phases can be observed that both architectures of the fuzzy control PID MISO and fuzzy PI SIMO, kept V_{dc} within the established limits. In comparison, the fuzzy controller PI SIMO showed an increase in the IAE, about 4%, and a reduction in ITAE of approximately 14%. Despite of the IAE increase, the new strategy demonstrated to be effective in reducing V_{dc} stabilization time during the rapid transition on P_o, which explains the decrease in ITAE index, as shown in Figure 11.

In the third project, entering the angular speed (w) as a state variable, it was possible to design rules to compensate the actuation on the controller due to w. The strategy adopted for the design of the rules was to reduce the controller actuation when angular speeds were higher than nominal and increase when in angular speeds were lower than the nominal. The new fuzzy controller PI MIMO (Multiple Input Multiple Output), start receiving the angular speed error, which was calculated on the nominal value of the rotor drive of 188.5 rad s^{-1} (1800 rpm). Figure 12 illustrates the mathematical model block diagram of the system with the fuzzy controller PI MIMO being kw the scale factor of the angular speed error.

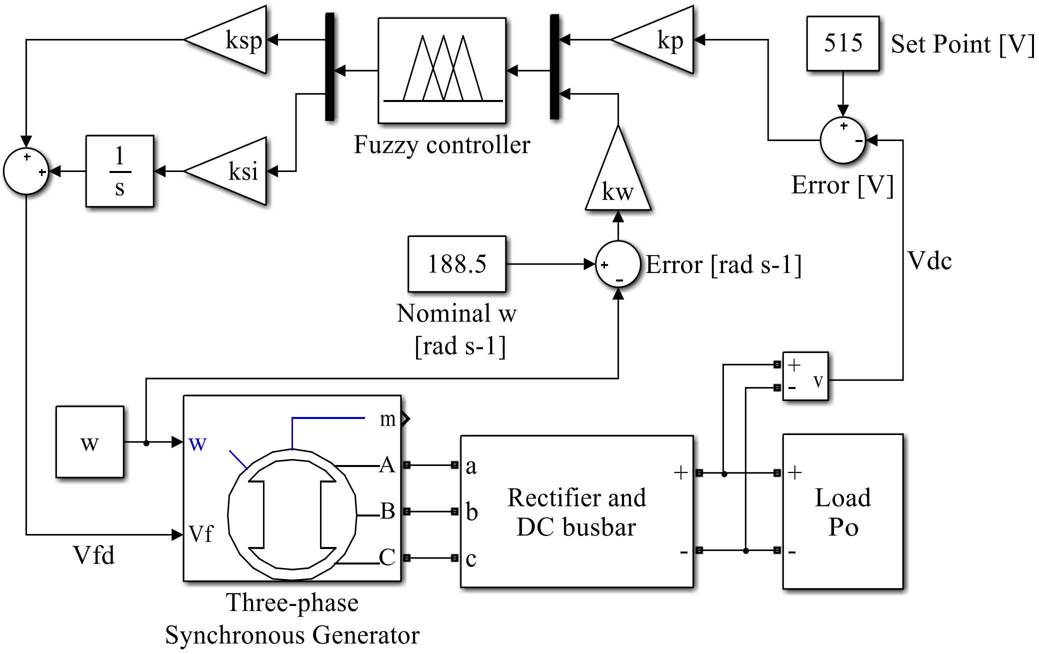

FIGURE 12. Block diagram of the mathematical model of the system with fuzzy controller for PI MIMO architecture.

Figure 13 illustrates the rules created for the fuzzy controller PI MIMO, with: (A) rules base to the output of proportional action; and (B) rules base for integral action. Thirty-five rules were created to the output of proportional action and thirty-five rules to output of integral actuation, totaling seventy rules for the controller.

(A) Voltage Error

Speed Error	NL	NM	NS	ZR	PS	PM	PL
PM	NL	NL	NM	ZR	PM	PL	PL
PS	NL	NM	NS	ZR	PS	PM	PL
ZR	NL	NM	NS	ZR	PS	PM	PL
NS	NL	NM	NS	ZR	PS	PM	PL
NM	NM	NS	NS	ZR	PS	PS	PM

Entry: Proportional Actuation

(B) Voltage Error

Speed Error	NL	NM	NS	ZR	PS	PM	PL
PM	NL	NL	NL	ZR	PS	PS	PM
PS	NL	NL	NL	ZR	PS	PS	PM
ZR	NL	NL	NL	ZR	PS	PS	PM
NS	NL	NL	NL	ZR	PS	PS	PM
NM	NL	NL	NL	ZR	PS	PS	PM

Entry: Integral Actuation

FIGURE 13. Fuzzy rules bases for PI MIMO controller.

Table 4 contains the scale factors of the variables of PI MIMO controller.

TABLE 4. Scale factors of the variables of PI MIMO controller.

Fuzzy controller	kp	kw	ksp	ksi
PI MIMO	22.844×10^{-3}	10.610×10^{-3}	120	25×10^{-3}

Figure 14 illustrates the values recorded in the V_{dc} system simulation with PI MIMO controller.

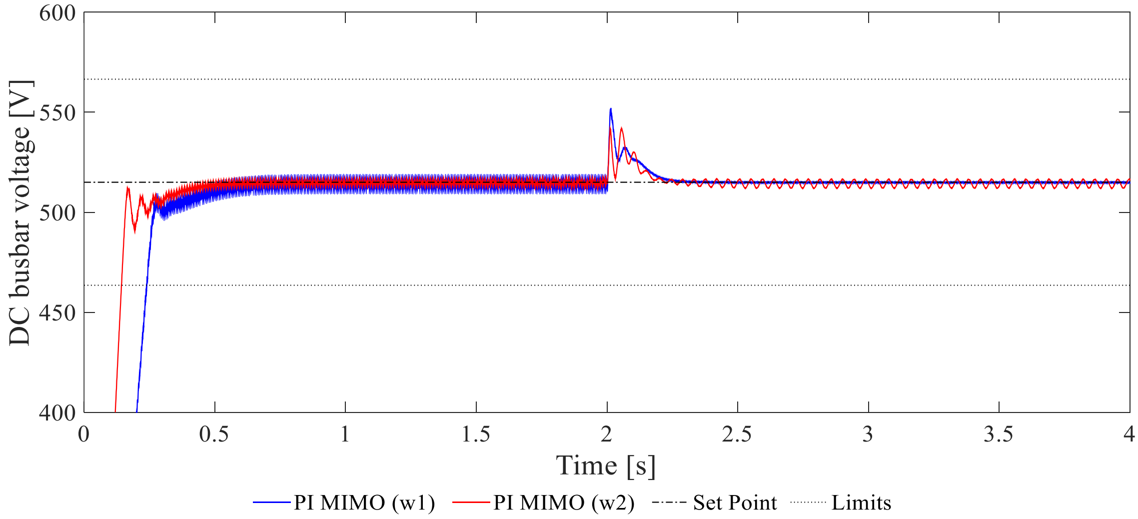

FIGURE 14. V_{dc} acquired value in system simulations with the PI MIMO controller.

In Table 5 are the performance indexes IAE and ITAE of the fuzzy PI SIMO and PI MIMO controllers of the third stage, after the simulation of both controllers for the two w scenarios, being: w1 of 235.6 rad s^{-1}; and w2 of 141.4 rad s^{-1}.

TABLE 5. Performance indexes IAE and ITAE of fuzzy controllers in third design stage.

Fuzzy controller	IAE (w1)	IAE (w2)	ITAE (w1)	ITAE (w2)
PI SIMO	93.52	144.65	30.68	31.33
PI MIMO	93.16	144.01	30.69	31.20

The data in Table 5 show similar values on the performance indexes for both controllers. However, during the simulations with the fuzzy controller PI MIMO was possible to note that the change on the actuation sensitivity impacted in the system stability, causing oscillations in the DC busbar voltage. The solution was to reduce the kw value. This reduction diminished the influence on the angular speed drive error in the controller output actuation, which explains the similar results of two control architectures on the third stage of the project.

Given the results, the architecture chosen for the control of the on board power generation system was the fuzzy PI SIMO, which kept the operating system within the limits established during the simulations using a single state variable, a small number of rules and a simple architecture compared to the controller proposed by JADRIĆ et al. (2000). Although this architecture does not consider directly the angular speed drive, when changing w, consequently, there is a change in generated voltage. Thus the fuzzy controller PI SIMO is indirectly sensitive to the error from the angular speed.

CONCLUSIONS

The chosen controller for the system operation was the fuzzy PI SIMO, which combines intelligent control strategies in association with strategies specifically developed for the system behavior under operating conditions established, in a simple architecture and a small number of rules. Finally, the simulations show the system's ability to operate on load disturbances and drive speed, keeping the DC busbar voltage within the established limits.

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