Scientific Paper / Artículo Científico

UNIVERSIDAD POLITÉCNICA SALESIANA ECUADOR
INGENIUS
Revista de Ciencia y Tecnología
https://doi.org/10.17163/ings.n28.2022.03
pISSN: 1390-650X / eISSN: 1390-860X

Passive Control Tolerant to Sensing Faults in dynamic compensation devices - SVC through a hybrid strategy

Control Pasivo Tolerante a Fallos de sensado en dispositivos de compensación dinámicos - SVC mediante una estrategia híbrida

Jessica Ramírez [1,*], Leony Ortiz [1], Alexander Aguila [1]

Received: 15-05-2022, Received after review: 13-06-2022, Accepted: 17-06-2022, Published: 01-07-2022

Abstract

For this research, a passive fault tolerant control system is developed for a static reactive compensator coupled to a microgrid in connected mode, oriented to those faults that result as a consequence of common damages in their sensing systems. The proposed method uses a robust optimal controller by H∞ and artificial neural networks as a nonlinear estimation method. Simulations, validation, plant identification and controller design are carried out using a microgrid Benchmark system, programmed in Matlab/Simulink. The research shows valuable results such as: the improvement in the reliability and resilience of static compensators against sensing failures, improvements in the behavior of the output signal of the static compensator controller exposed to sensing failures and the decrease in error with respect to classic controller.

Keywords: DSTATCOM, FTC, H∞, Microgrids, NARX, Robust control

Resumen

Para esta investigación se desarrolla un sistema de control tolerante a fallos pasivos para un compensador reactivo estático acoplado a una micro-red en modo conectado, orientado a aquellos fallos que resultan como consecuencia de daños comunes en sus sistemas de sensado. El método planteado utiliza un controlador óptimo robusto por H∞ y redes neuronales artificiales como método de estimación no lineal. Las simulaciones, la validación, la identificación de la planta y el diseño del controlador se llevan a cabo por medio de un sistema Benchmark de una micro-red, programado en Matlab/Simulink. La investigación muestra valiosos resultados como: el mejoramiento en la confiabilidad y resiliencia de los compensadores estáticos ante fallas de sensad, mejoras en el comportamiento de la señal de salida del controlador del compensador estático expuesto a los fallos de sensado, disminución el error con respecto al controlador clásico.

Palabras clave: Control robusto, DSTATCOM, FTC, H∞, Micro-red, NARX

[1,*]Ingeniería Eléctrica, Universidad Politécnica Salesiana, Quito - Ecuador.
Corresponding author ✉: jramirezg4@est.ups.edu.ec

Suggested citation: Ramírez, J.; Ortiz, L. and Aguila, A. "Passive Control Tolerant to Sensing Faults in dynamic compensation devices - SVC through a hybrid strategy," *Ingenius, Revista de Ciencia y Tecnología*, N.° 28, pp. 34-43, 2022, DOI: https://doi.org/10.17163/ings.n28.2022.03.

1. Introduction

The energy needs in the earth continue to increase especially due to the rise of industries and the needs related to transportation. In this way, such requirements have led to the emergence of new forms of electricity generation through renewable energy resources and the use of networks smaller than the traditional ones called Microgrids (MG) [1–3] . MG can be understood as an small-scale electrical systems containing several distributed generators, loads, and energy storage systems [1, 4–6].

Due to the emergence of new types of loads such as electric vehicles and storage systems that work with direct current, which are connected together with alternating current loads that are the most recurrent in home networks [4]. Mixed or hybrid AC/DC type MGs have taken on special relevance for researchers, due to the feasibility offered by each type of MG, with the only need to include energy conversion devices that work with power electronics elements [7–13].

Due to their characteristics, MGs must be able to function both in connected network mode and independently, and for each mode there must be a correct operation and control, which should even be able to withstand certain problems and failures [1, 4, 13, 14].
The operations control should also consider characteristic features of certain type of generation such as wind and solar, where variability and intermittency are common; and they are aspects that should consider for an continuous, stable, safe and resilient operation of the Hybrid MR. There are differences and significant changes to a traditional electrical network, compared to features offered by MG, in especially those that operate in AC and DC. In matters related to control and the problems that could occur in the operation, such changes are directly related to the existence of distributed control operations and the existence of power flows that they are bidirectional [15, 16].

As previously indicated, one of the most relevant aspects of proper functioning of the MG is the presence of robust control; the same that should be able to withstand the existence of failures in various components of the control system and the MG.
During fault events and sensor and actuators malfunction of the various subsystems of the MG, the control systems with more traditional feedback may not be able to guarantee the system stability or performance of all components.
Therefore, there are new strategies for the management of this type of network as we can mention the fault tolerant controls (FTC) [1, 13, 14, 17]. Such strategies allow the emergence of fault-tolerant control systems (FTCS), which can overcome the aforementioned deficiencies. [18].

Fault-tolerant controls can be divided into two groups: active controls (AFTCS), which are those that contain diagnostic strategies and fault detection in real time through the use of information. Active control systems also contain reconfiguration mechanisms that allow the MG to be maintained stable and with acceptable performance even when there are failures in various system components. [1, 18, 19].

Fault-tolerant controls that are passive are instead designed to have a single robust structure, that is, they have no way of being automatically reconfigured during fault events. Another difference is that they do not consider the information that a fault detection and diagnosis system (FDD) may have. [1, 18].

Fault tolerant control systems have been studied extensively and there are several proposals that work in connected network mode and also when MG operates independently. The operation in connected mode to the conventional network is supported in the parameters of the main network and most of the proposals that have been previously established are related to the use of capacitor banks and flexible AC transmission systems (FACTS). In the case of advanced control strategies, voltage regulations are also used in the generation zones, although the controllers can be directly in the element to be controlled, as shown in Figure 1. [1], [20].

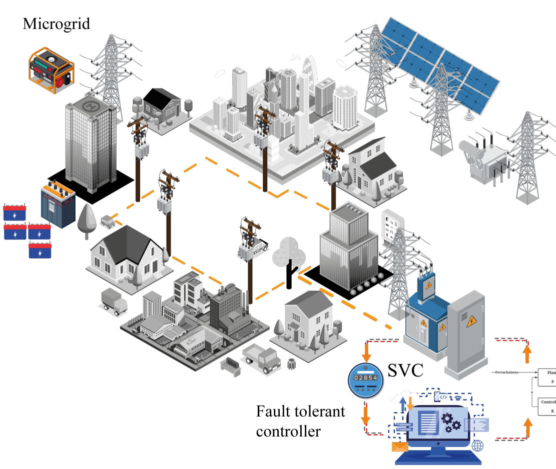

Figure 1. Fault tolerant control

On the other hand, in isolated operation, the researchers have determined that there are other needs, such as the correct choice of the generator system that becomes the frequency leader. [20].
Mainly when there is a high penetration of generation sources with renewable energies in which the inherent characteristics of intermittence and discontinuity and complicate the use of traditional MG control strategies [20].

In [20] an FTC system is presented that allows fault tolerance based on an adaptive controller based on the model through a PID control tuned by genetic algorithm and a structure with intelligence, it is stated that this structure guarantees monitoring of the conditions of the MR, which allows regulation of frequency, voltage amplitude. The existence of fault scenarios including actuator failures, sudden load connection, as well as short duration faults is proposed; which allows testing the performance of the proposed method.

In [21] an FTC strategy is presented to deal with loss of effectiveness and lock-in-place faults that occur con an SVC, the strategy used in that document use an adaptive backstepping technique with a dynamic surface control (DSC). The results of the investigation shows that the strategy can produce a good performance over signals in the closed-loop system under the occurrence of the described faults.

Other investigations center their attention on fault-tolerant controllers for a wide area control systems but doesn't center on an SVC. The controller generally finds a way to deal with faults over communications of signals to control de whole system while other investigations use static or dynamic compensations systems to control the angle of synchronous machines where robust control try to maintain the machine in good operational conditions [22].

2. Materials and methods

2.1. Microgrids

MGs are in general a revolutionary set of elements that work together to generate, transport and supply power to a set of loads in a certain geographical area that can operate in isolated or with an interconnection link with a conventional network. This implies that a MG must have generation elements and loads that seek a constant balance based on the available resources at a technological and environmental level. In general, MGs make use of generation systems that take advantage of renewable resources such as water, wind, heat or radiation from the sun. [23, 24].

Generation systems and consumption points are linked by distribution systems that can be AC or DC, as shown in figure 1, with the corresponding need to have AC/DC or DC/AC conversion elements. On the other hand, and due to the need to cover deficiencies that could arise from the implications of a complete system but with limited resources, reactive compensation systems and even storage systems can be made available, which in the long term can improve the quality of service. [25–27].

2.2. Neuronal network

A fairly simple abstract model of the functioning of an artificial neuron can be conceived, which can be seen in Figure 2.

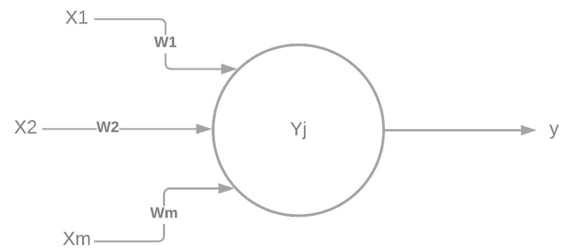

Figure 2. Artificial neuron

The artificial neuron is composed of a set of weights represented in the values W_1, W_2, W_m and that represents the synaptic connections of a real neuron, a vector x that composes the inputs and finally an output of the unit represented by y which is the result of an activation function.

An artificial neural network is the computational composition of multiple elementary processors composed of an adaptive system that, through an algorithm, is capable of adjusting its weights in order to improve performance with the use of samples. One of the main advantages of the use of artificial neural networks is the ease of use of training data through supervised or unsupervised processes. The supervised process occurs by making use of well-known input and output data, expecting that the output data of the neural network is as similar as possible to the output data that is available. Unsupervised learning makes use of a set of patterns that are valid to find structures or configurations that are present in the data [28].

2.3. Static VAR compensator (SVC)

Within the FACT type devices, the static reactive compensator falls into the category of those that have a bypass connection. The device in question consists of an inductor controlled by means of power electronics called thyristors and which receives the name of TCR [29]. Through the correct control of the TCR tripping, a variation of the reactance is achieved which, in the long term, implies a change in the consumption of reactive power at the connection point of the compensator, then it is possible to improve the power factor at said point. In this point the bus voltage is also checked [29–32].

The device is controlled by modifying the firing angle of the power elements that make up the SVC. This logic control is issued by control loops that may contain PI, PID controllers or even more robust options such as the one that will be implemented in the present investigation. [33–37]. The reactive compensation devices are used in the MR in order to compensate the power factor that is outside normal parameters [29–37]. Due to the effects of the loads connected to the system, an alteration in the power factor results in the affectation of the system voltage in the system bars [29–37].

On the other hand, it is usual that in the MG the generation systems require consumption or due to their own generation principles cause modifications in the reactive values which can cause a drop in the output voltage of the units and therefore a drop in power. The problem can be solved with the installation of an SVC [29–37].

2.4. H-infinite ($H\infty$)

It is used to achieve controllers with guaranteed performance and that are stable, the use of these models is presented as an optimization problem through which a model that meets the objective is found. One of the main advantages of the method is that it is widely applicable in multivariable systems, while part of the disadvantages include a high level of mathematical knowledge and an understanding of the system to be controlled.

The name of the method is based on the fact that the optimization is carried out on the so-called Hardy space in the positive half of the complex plane and represents the maximum value on the mentioned space, being understood as the maximum gain in any direction and at any frequency for a SISO system. It is the maximum magnitude of the frequency response. Among its uses is the reduction of the impact of a disturbance in a closed loop that can be observed as stability or performance.

The plant has inputs composed of an exogenous input that includes a reference signal, disturbances and manipulated signals. On the other hand, there are outputs between which there is an error signal that must be minimized and the measured variables that will be used as control signals in the system. By means of the measured signals and the value of K, the manipulated variables can be calculated. Expression (1) is used to formulate the problem in matrix form [17, 38, 39].

$$\begin{bmatrix} z \\ v \end{bmatrix} = P(s) \times \begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{11}(s) & P_{12}(s) \end{bmatrix} \times \begin{bmatrix} w \\ u \end{bmatrix} \quad (1)$$

It is possible to calculate the dependence of z on w by means of the lower linear fractional transformation (LFT) which is shown in expression (2), where $F_l \times (P, K)$ represents the result of the LFT that can be used to find the relation between z and w.

$$\begin{aligned} z &= F_l \times (P, K) \times w \\ F_l \times (P, K) &= P_{11} + P_{12} \times K \times \\ &\quad (I - P_{22} \times K)^{-1} \times P_{21} \end{aligned} \quad (2)$$

According to the aforementioned, it is known that the objective of the method in question requires finding a controller K such that $F_l \times (P, K)$ is minimized according to the norm H∞ being the same applicable to the design carried out by means of $H2$. There are some techniques to achieve the objective, among which the Youla-Kucera parameterization that leads to very high order controllers, methods based on the resolution of 2 Riccati equations requiring many simplifications and finally the method based on optimization with a reformulation of Riccati using linear matrices of inequalities, a method that requires few assumptions [17].

2.5. Fault tolerant controller design

The control signal is manipulated directly by the controller, which replaces a traditional PI type controller that was part of the control system and whose performance will be compared with the H∞ controller.

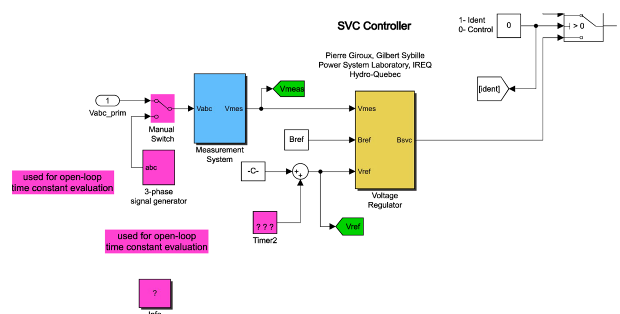

Figure 3. Controller zone

Figure 3 illustrates the area of the controller into which the robust controller is inserted. It can be seen that the variables that are measured are those that correspond to voltage signals in addition to having values that correspond to references necessary to generate adequate control signals.

On the other hand, figure 4 shows the way in which the designed controller is placed inside the voltage regulator considering the need to reduce the error to 0. The error corresponds to those values that result from the difference between the voltage measured and the reference voltage in addition to subtracting the value corresponding to the control signal in this case represented by the $Bsvc$. It is understood that the controller acts directly on the control signal.

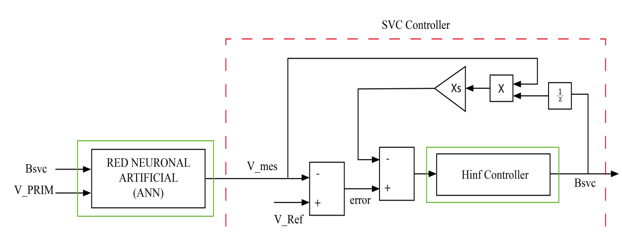

Figure 4. Voltage regulator design

2.6. Problem formulation

A controller is said to be fault tolerant when this controller is capable of maintaining the control objectives despite the fact that it is subject to the occurrence of faults, the faults in question can be additive or non-additive faults depending on the alteration that they cause. These alterations to the measurements that in the long term create modifications in the equations of the space of states. While non-additive or multiplicative faults cause changes in the terms of the state space.

Fault tolerance can be achieved by passive or active strategies, in some cases being able to maintain the controller with changes in its parameters, while in other cases the control laws can be reconfigured [1, 13].

3. Results and Discussion

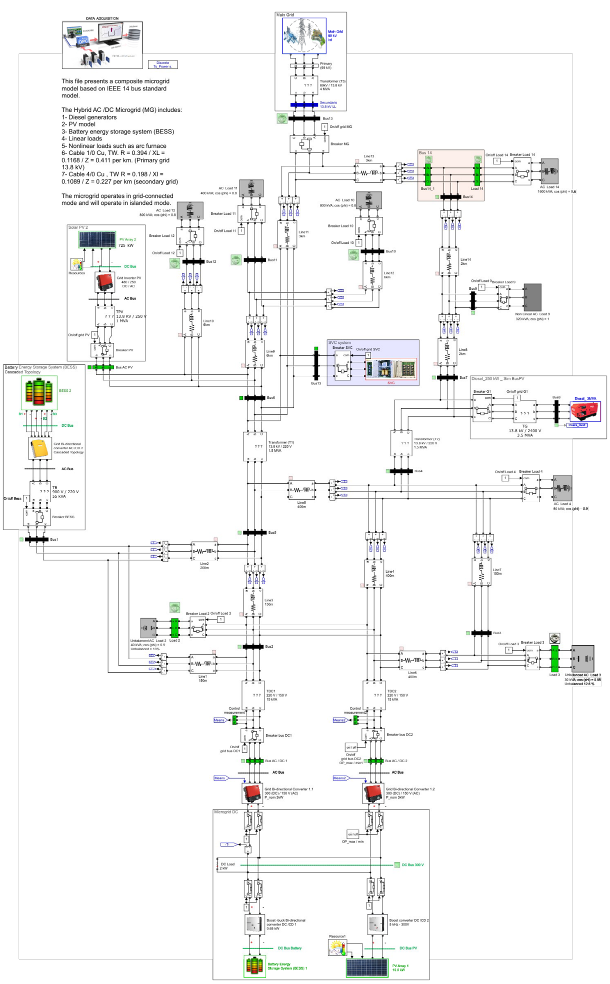

Figure 5. Microgrid Diagram

3.1. Study case

For the present study, the use of a benchmark-type test system is proposed, which represents an MG of 14 bars composed of 2 energy storage systems, 2 photovoltaic generation plants, 1 diesel generator, an one interconnection point with a conventional network. In addition to linear and non-linear loads and finally an SVC, the mentioned model can be seen in Figure 5 [3].

The controller is subjected to simulations to obtain a detailed model of the plant through the use of state spaces, the simulation process yields a plant of the SVC controller. The proposed method is tested with the occurrence of non-malicious sensing failures of incipient and abrupt type in the primary of the control system, the fault tolerant controller designed by means of the H∞ methodology is implemented within of the SVC.

3.2. Results

The controller that is obtained through the design process proposed in this document yields the parameters for the controller according to what is shown by expression (3), where A, B, C and D represent the arrays that form the state space that describes the voltage controller region of the SVC.

$$
\begin{aligned}
A &= \begin{bmatrix} -2.85e^{-3} & -437.52 & -200.38 \\ -189.32 & -108.03 & -119.03 \\ -31.96 & 10.56 & -21.65 \end{bmatrix} \\
B &= \begin{bmatrix} -2.25e^{+3} \\ -9.54e^{+3} \\ -2.56e^{+3} \end{bmatrix} \\
C &= \begin{bmatrix} -2.68e^{-17} & -6.32e^{-17} & 3.62e^{-19} \end{bmatrix} \\
D &= 0
\end{aligned}
\tag{3}
$$

On the other hand, the implemented neural network is designed to work with 2 inputs, each layer has a total of 10 neurons in its hidden layer while each one has 3 output neurons. There are 2 NARX type systems available and each one is used independently to work with the primary and secondary signals. Based on what was stated in the previous chapters, the simulations corresponding to the faults are developed. The occurrence of the fault is planned with an occurrence time of 0.4 seconds of the simulation. Once the MR has already found stability at its point of operation. The faults occur according to what is explained by different factors that trigger alterations in the signals acquired from the primary, the faults tested are incipient according to what is shown in figure 6 and 9, another of an abrupt type that is displayed in figure 7.

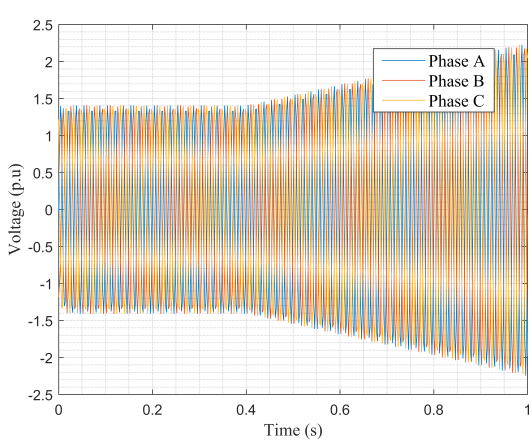

Figure 6. Incipient failure in primary

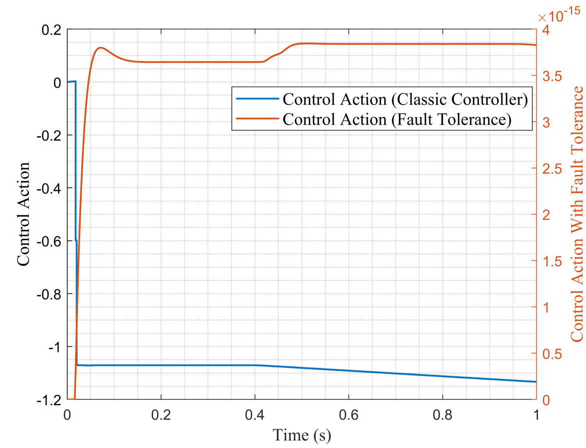

Figure 8. Control action: incipient failure

It can be seen that the abrupt failure that occurs at 0.4 seconds of simulation causes an output with a value of 0, which suggests a disconnection of the voltage sensor involved.

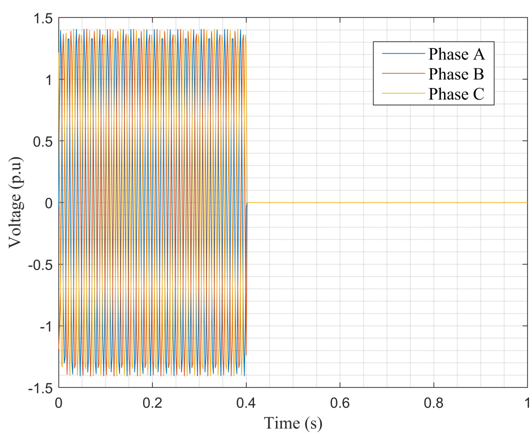

Figure 7. Abrupt failure in primary

The signals shown above were tested in order to verify how a sensing failure can cause undesired changes in the control signals of devices linked to said signals. In this specific case the control signal that triggers the triggering of the detection devices power involved in the operation of SVCs. The signals were introduced in the controller with a PI method and also with the robust controller.

3.3. Incipient failure

Figure 8 shows a comparison of the performance of both control methods and how they develop before the occurrence of the incipient failure.

It can be seen that the control action resulting from both methods is completely different in form and magnitude.The control action resulting from the PI controller has a magnitude that varies between 0 and -1.2 approximately, while the control action resulting from the designed controller with H∞ varying between 0 and $4x10^{-15}$. These magnitudes are altered by the reference points to which the system is subject prior to 0.4 seconds of occurrence of the fault and once the fault occurs immediately the control action is modified.

For a better understanding of the behavior, Figure 9 is presented, which illustrates the error value that occurs with each control action, which should be minimized. It is observed that when the fault occurs, the behavior of the control action of the controller PI tends to a constantly growing divergence, while in the case of the controller built in the present investigation, the error tends to change but the change is minimal compared to the more traditional control action.

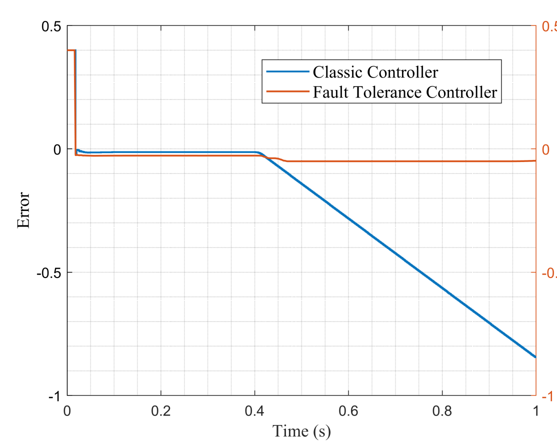

Figure 9. Error: incipient failure

Figure 10 shows the behavior of the output voltage (p.u) in phase A after the signal is processed by the controller H∞ and a stage composed of an artificial neural network. Once the fault occurs, the voltage tends to have a fluctuation as an expected effect without this modification being significant, since it has a variation of 0.02 units with respect to the pre-fault condition.

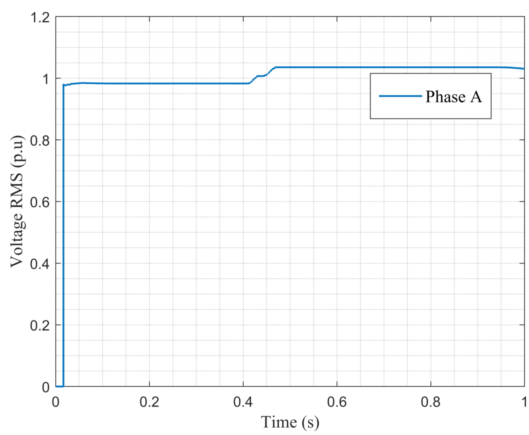

Figure 10. Voltage RMS (p.u), phase A: incipient fault

3.4. Abrupt failure

In a similar way to what was reviewed with the incipient failure, the results obtained are presented for the case in which the failure is of the abrupt type, Figure 11 shows the behavior of the control action subject to the abrupt failure.

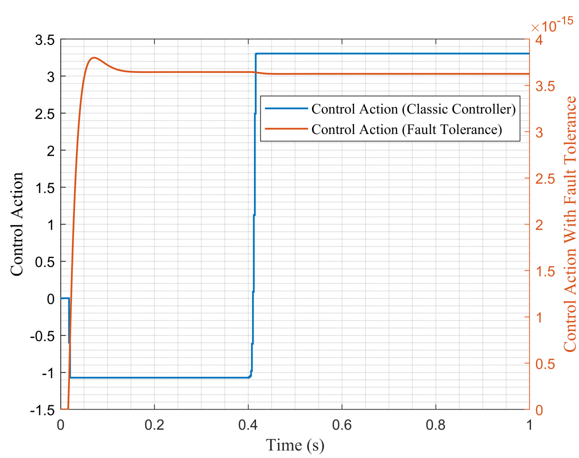

Figure 11. Control action: abrupt failure

It can be visualized again that the control action with a traditional controller has a variation between -1.2 and 3.5 units, having a sudden change at 0.4 seconds in the occurrence of a fault. On the other hand, the control action with the use of the H∞ system is maintained in the interval between 0 and 4x10-15 with a behavior similar to that obtained in the previous fault studied, the controller even shows a lower fluctuation after 0.4 seconds from incipient failure.

Figure 12 corresponding to the error produced as an effect of the control action with both controllers is also presented. Once again it is evident that the error caused by the controller H∞ is much lower than that produced by the PI controller after the occurrence of the fault, the PI controller again causes a divergence in the error, although in this case the error stabilizes in a short period of time.

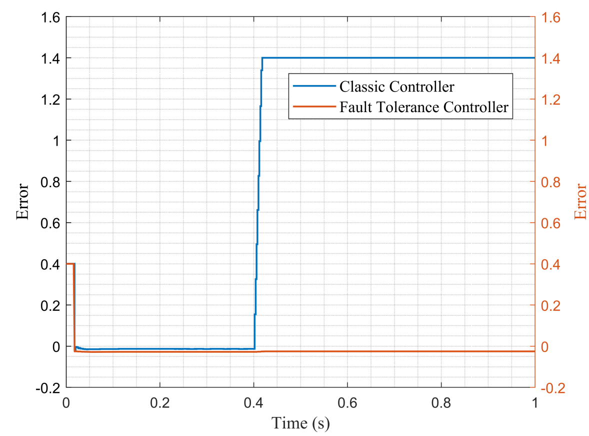

Figure 12. Error: abrupt failure

As previously reviewed, the RMS voltage value in phase A is plotted as an effect of the implementation of the robust controller, the result is shown in Figure 13.

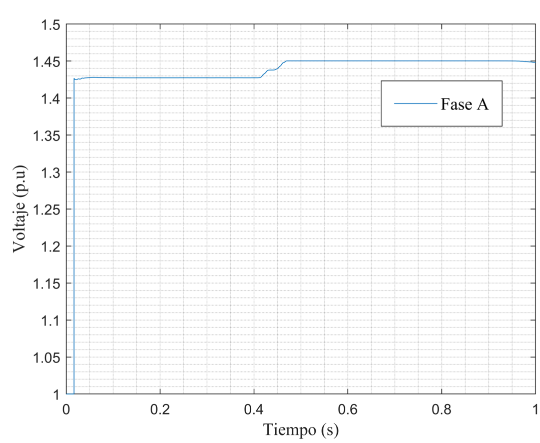

Figure 13. Voltage RMS (p.u), phase A: abrupt failure

Since the error produced by the control action is small the variation that occurs in the voltage is also small which validates the robustness of the controller in the event of sensing failures.

4. Conclusions

It is verified that implementing a fault tolerant controller designed by means of H∞ improves the capacity of the controllers to support alterations produced by failure events in the controller input, the performance is much better than a conventional PI type controller. The new controller strategy is effective to maintain the stability action without significant changes.

The operation of the controller designed by means of simulation in software specialized in simulation of dynamic systems Simulink/Matlab is successfully tested. The software allowed to carry out simulations in order to carry out the identification of the system in addition to the controller design and its validation in a Microgrids implemented by means of a Benchmark system.

The designed passive sensing fault-tolerant control system shows better performance in the event of an abrupt fault compared to an incipient fault, the designed parameters of the controller were successfully calculated, although in both cases it is significantly better than a traditional controller.

The correct performance of an artificial neural network is achieved as a previous step to the introduction of a measured signal in the controller involved, the signal that is produced by a sensing error is processed by an artificial neural network to later introduce the signal in the controller.

It is proposed to introduce the methodology of this academic article for the development of robust controllers that can withstand malicious failures and the occurrence of other types of failures as well as in different types of devices that require a robust control action. On the other hand, it is proposed to carry out comparative research with selection algorithms that allow selecting the best control action that is the result of different methodologies to improve its performance.

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