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Emergency Control Strategy based on Wide Area Synchronized Measurements for Transient Stability Enhancement

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Abstract

This paper introduces a measurement based fuzzy logic controller for stabilizing large interconnected power systems after the occurrence of severe disturbances. This proposed fuzzy controller uses Wide Area Phasor Measurements as inputs and triggered by a transient instability prediction scheme developed earlier. The effectiveness of the proposed algorithm has been demonstrated on the Venezuela Power System. Simulation results demonstrate that appropriate control actions can be determined as early as 100 ms after a major fault leaving enough time to stabilize the power system.

Key words: Transient Stability, Phasor Measurement Units, Wide Area, Emergency Control, Fuzzy Logic, Load Shedding and Generator Tripping.

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1. Introduction

Monitoring the operating state of a power system and assessing its stability in real time has been recognized as a task of primary importance to prevent blackouts (Karlsson, D., & Lindahl, S. (2004)). Among various instabilities, transient (or large disturbance rotor angle) instability is a very fast phenomenon that need fast recognition to allow sufficient time for emergency control actions. Due to the fast nature of the instability, drastic control actions such as load shedding, generator shedding, and system separation may be necessary to stabilize the disturbed power system. Most of the blackouts that have occurred in the last few decades are originated by the combination of unexpected events (low probability of occurrence) and inappropriate protection and control actions (U.S.-Canada Power System Outage Task Force (2004)).

Synchrophasors provide phasors of the voltage and current measurements taken at geographically different locations synchronized with high precision to a common time reference. This is achieved by time synchronizing the sampling of signals and time tagging the phasors using the global positioning system (GPS). Synchrophasors, together with modern communication and computation technology facilitate the monitoring of the state of a power system, including the phase angles of bus voltages (Adamiak, M. G., Apostolov, A. P., Begovic, M. M, Henville, C. F., Martin, K. E., Michel, G. L., Phadke, A. G., & Thorp, J. S. (2006)).

When a power system is subjected to a large disturbance such as a fault, or loss of generation or major transmission line, the sudden change in the electrical output of large synchronous generators can cause them to accelerate or decelerate leading to rotor angle or frequency instability. The mechanical inertia of the generators plays a key role in the response of the power system after such a disturbance.

The wide area measurement technology provides a reliable platform for the development of fast monitoring, control and protection applications against such system wide instabilities (Phadke, A.G. (1993)). Prior to the introduction of this technology power system measurement and control was performed by local signals. In most instances, monitoring, control and protection based on local signals is unsatisfactory for system wide disturbances. Slow updating and poorly synchronized SCADA signals are also not satisfactory for response based special protection systems (SPSs) (Phadke, A.G., & Thorp, J. S. (2008)). Response based special protection systems are alternative to the conventional event based special protection systems that respond to pre-selected set of disturbances. Rather than responding to specific events, response base SPSs take actions in response to abnormal situations detected through system variables such as voltages and power flows. It is well known that transient instability can occur very fast, sometimes within a second, thus any response based SPS must retain the speed of event based SPSs.

In this paper, a novel emergency control strategy to enhance the transient stability using fuzzy logic theory based on wide area phasor measurement technology is proposed. This new approach is conceived as part of an integrated special protection scheme to preserve the safe operation of the grid undergoing to critical disturbances. The technique uses the post-disturbance voltage magnitude and frequency measurements taken using the phasor measurement units (PMUs) installed at strategic locations of a multi-machine power system. The algorithm was tested for Venezuelan power system using time-domain simulations.

2. Wide Area Synchronized measurement based Emergency Control

Special protection systems should initiate appropriate control actions when an impending transient instability is predicted. When the transient stability status prediction scheme indicates that the system is unstable, the power system is either operating in or soon moving into the emergency state. The system will become unstable and move into an in-extremis state unless appropriate control actions are triggered, forcing the system to return to the alert state (C. W. Taylor, D. C. Erickson, K. E. Martin, R. E. Wilson and V. Venkatasubramanian (2005)).

Different philosophies of power system control against disturbances are illustrated in Fig. 1. Continuous control where the control actions are of continuous nature is applied for dealing with issues such as small disturbance rotor angle stability (steady state or small signal stability).

The small disturbance rotor angle stability is usually maintained through continuous adjustment of control variables, for example excitation current of a generator or output of a FACTS device, using an appropriate feedback controller.

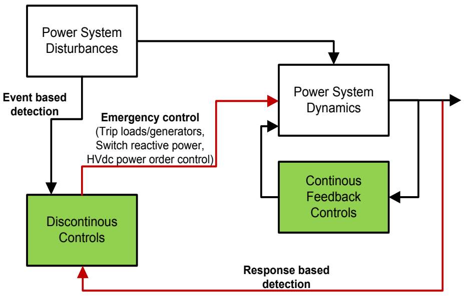


Fig. 1. Power system stability controls (adapted from C. W. Taylor et al. (2005))

On the other hand, emergency control systems generally referred to as wide area control systems or WACS, take control actions that are of discontinuous nature. These emergency control solutions are system-dependent because they will be developed based on the available infrastructure such as HVdc links, FACTs devices, and braking resistors among others. WACSs monitor a power system using wide area measurement technology, which includes synchrophasors obtained from PMUs. These systems detect abnormal conditions from the changes in the monitored power systems variables, and therefore known as response based controllers.

The emergency control technique proposed in this paper is designed for preventing transient instability in power grids that are principally dependent on ac transmission. This is the case for most of the electric power grids around the world. The emergency controller is triggered by a transient stability status prediction scheme (Rajapakse, A. D., Gomez, F. R., Nanayakkara, K. Crossley, P.A., & Terzija, V. V. (2010). and (Gomez, F. R., Rajapakse, A. D., Annakkage, U. D., & Fernando, I. T. (2010)). This transient stability predictor can accurately establish the stability status (whether the system is going to lose the synchronism due to the disturbance) following a major fault. Once an imminent instability condition is predicted, some emergency actions needed to be taken to preserve the stability of the grid. If no further action is taken, then the system may break apart due to uncontrolled tripping of generators (from out of step protection) and formation of islands which are unstable. The controller proposed in this paper uses a fuzzy logic system to select suitable control actions, namely load shedding and generation tripping, following a critical disturbance.

3. Generator and Load Shedding Scheme for the Venezuelan Power System

Two of the most effective control actions that could be taken to reduce the power imbalance in different areas due to network disturbance are: (i) the tripping of generation in areas where there is a surplus of power and (ii) the shedding of loads in areas where a deficit of power exists. Generator tripping and load shedding are the fastest actions that can be taken to reduce a major power imbalance resulting from a disturbance, although these actions should be taken only as the last resort to prevent further damage. The selective tripping of generators for transmission line outages has been used extensively to improve stability. The action of the WACS against transient instability requires a response within fraction of a second, thus there is no time for human operators to intervene (Rajapakse, A. D., et al. (2010)). Design of automatic control against large disturbances such as faults using conventional linear control approaches is difficult due to nonlinear nature of the power system. Fuzzy logic control offers a way of dealing with modeling problems and uncertainty by implementing linguistic, informally expressed control laws derived from expert knowledge. Thus a fuzzy logic based approach is used for the design of the proposed emergency control scheme.

3.1. Structure of the proposed control system

A block diagram of the complete WACS proposed in this research is presented in Fig. 2. The scheme consists of three stages: (i) a disturbance detecting trigger mechanism, (ii) a stability prediction scheme and (iii) a discontinuous emergency control strategy. The near real-time measurements of the system are obtained using conventional measurement transformers and the waveforms are sampled in a PMU where the phasors of the voltages and the currents as well as the local frequency are computed. These phasor measurements are transmitted to a phasor data concentrator (PDC). It was assumed that measurements are taken at a rate of 60 phasors/second. Applications such as the proposed WACS get the required data from the PDC.

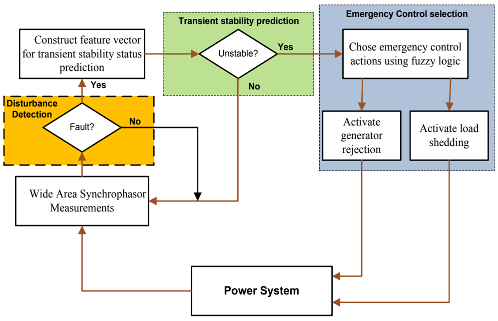


Fig. 2 Overall structure of the wide area control system

A disturbance detector is employed to detect the occurrence of a fault and the instant of its clearing to initiate preparing input feature vectors for predicting the transient stability status. If the predictor indicates a transient instability, the fuzzy logic based emergency controller chooses the suitable actions and gives commands to relevant actuators.

3.2. *Disturbance detection and instability prediction*

Although the proposed control system monitors the power system continuously, the transient stability status prediction is activated only after detecting a major fault. Once, a major fault happens, the voltage magnitudes measured at the buses close to the fault depress. This can be used to detect the occurrence of a major fault in the system. In the disturbance detection system used in this research (shown in Fig. 3) if the voltage magnitude in any of the monitored bus drops below 0.7pu (Vdip = 0.7pu), for more than 4 consecutives measurements (four cycles), a fault is assumed. Once the faulty element is isolated by the action of local protection, the voltage starts to recover. The fault is assumed cleared, if the voltage dip starts to recover at a rate faster than 40% (k=0.6) per measurement period at the bus where the minimum voltage was observed. When this condition is satisfied, construction of the input feature vector to be used for the SVM binary classifier is initiated. These thresholds and time delays were determined through a trial and error approach using numerous simulation data.

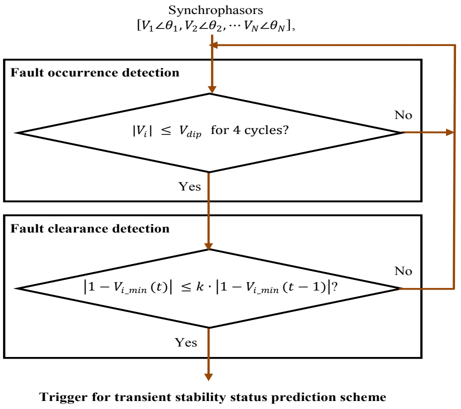


Fig. 3 Disturbance detection logic

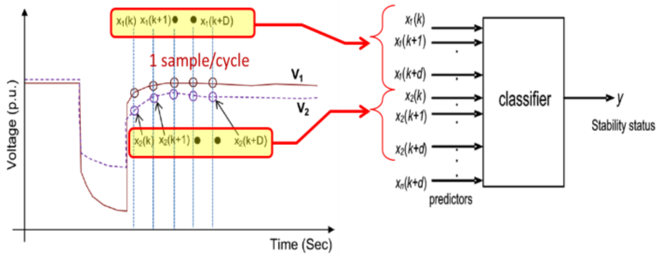


Fig. 4 Transient instability predictor

A support vector machine (SVM) classifier is trained to predict whether the power system is going to be unstable following the clearance of a fault. Feature vectors for the classifier are synchronously measured voltage magnitudes at selected locations in the power system. A selected number of consecutive measurements at each location, taken immediately after the fault clearance are required for this purpose. The concept of the stability predictor is shown in Fig. 4. Details of the design of this classifier and its performance evaluation can be found in previous publication of the authors, and therefore not repeated here.

3.3. *Fuzzy logic based emergency control*

The emergency control system was developed for the Venezuelan power system shown in Fig. 5. As mentioned previously, voltage magnitudes, voltage phase angles, and bus frequency all undergo changes during a disturbance leading to transient instability, and therefore are indicators that can be used as inputs of an emergency controller. PMUs can provide accurate and time tagged measurements of all these quantities. Fifteen (15) PMUs locations determined during the testing of the transient stability status prediction stage are used in the emergency control as well. The measurements at these locations demonstrated good overview of the grid and the instability conditions could be predicted with accuracy over 95%. These 15 PMUs were placed on the high voltage (230 kV, 400 kV and 765 kV) buses close to large generation or load centers. The main 12 PMUs associated to the backbone of the Venezuelan system are shown on the simplified network diagram in Fig. 5.

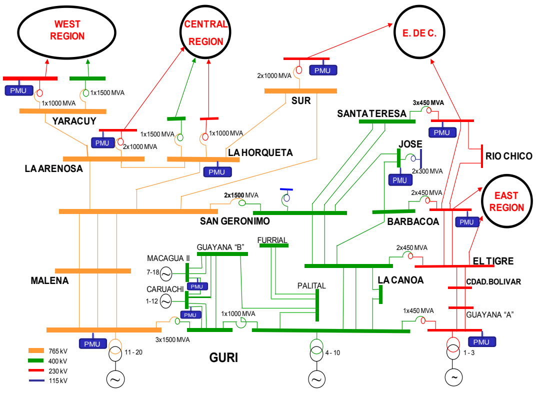


Fig. 5 Simplified single line diagram of the Venezuelan power network

The voltage phase angles can indicate the stress at various localities in the system. Although phase angles are a key variable for identifying the areas where generation needs to be reduced, they are slow varying compared to the voltage magnitudes and the frequency. Also in case of identifying where the load has to be reduced, the voltage phase angles are less effective. Voltage magnitudes vary considerably and rapidly during the initial part of the disturbance can also indicate deficit of generation, although the low voltages could also mean deficit of reactive power or voltage stability problems.

The proposed load shedding and generator tripping scheme shown in Fig. 6 utilizes a fuzzy inference system to determine the required emergency control actions. A separate fuzzy system is employed for each monitored area (all of them are implemented on one centrally located controller). The frequency and voltage magnitudes at that given area are acquired through wide area PMU measurements and the corresponding fuzzy values are computed. Using a fuzzy rule base, three fuzzy measures indicating the requirement for load shedding (LS), requirement for generator tripping (GT) and the requirement for no action (NA), are computed for each area. The proposed philosophy does not allow simultaneous load shedding and generation tripping within the same area.

3.4. Fuzzy logic system for evaluating control actions

The input signals (voltage magnitudes and bus frequency) are first characterized by linguistic variables using fuzzy set notations, through the fuzzification. Usually, at a given instance, more than one fuzzy rule is applicable, and therefore, the final values of the fuzzy measures are computed by combining all applicable rules through a fuzzy inference method. This fuzzy logic controller was implemented in Matlab using Fuzzy Logic Toolbox.

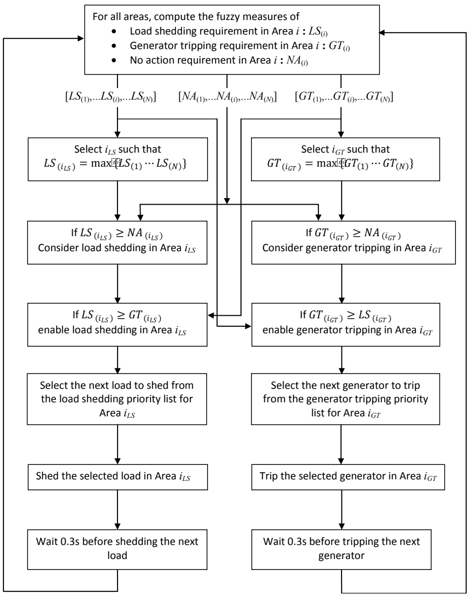


Fig. 6 Proposed fuzzy based emergency control strategy

3.5. Fuzzification

Fuzzification is the process where the crisp quantities are converted to fuzzy values by using fuzzy membership functions (Driankov, D., Hellendoorn, H., & Reinfrank, M.(1996)). In Fig. 7, the input membership functions used in this emergency controller are presented. The labels corresponding to the linguistic variables are: L=low, N=normal and H=high. These linguistic variables are used to construct the fuzzy rules that describe the relationship between the inputs and the outputs. The fuzzy memberships of the outputs, those of the three possible the control actions (LS, GT, NA), are presented in Fig. 8. The labels corresponding to the linguistic variables are: Z= zero, L= low and H= high.

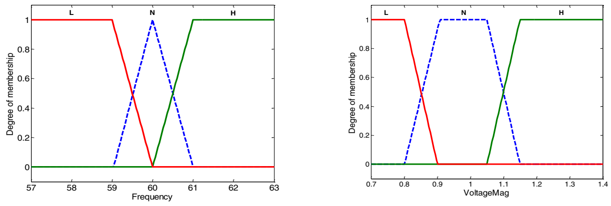
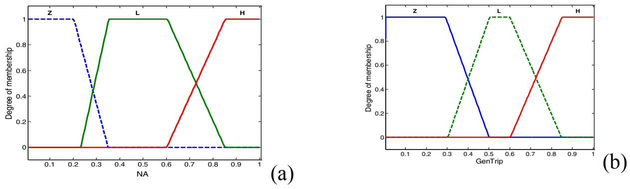


Fig. 7 Input membership functions used in the proposed scheme



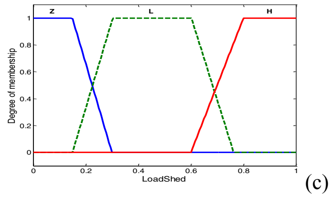


Fig. 8 Output fuzzy membership function for (a) the non-action output, (b) the Generator Trip Scheme and (c) the Load Shedding

3.6. Fuzzy inference and defuzzification

The fuzzy inference system (FIS) tries to formalize the reasoning process of human language by means of fuzzy logic (that is, by building fuzzy IF-THEN rules). These rules will determine the output of the controller according to the fuzzified values measured in the input. The rules are of the following nature:

If the frequency (f) is low (L) and the voltage magnitude (V) is low (L), then the load shedding requirement (LS) is high (H).

The most common defuzzification method is the centroid method or the center of area method. Based on the product–sum inference and centroid defuzzification, the output of the fuzzy control requirement is computed. The fuzzy system was implemented and evaluated using Matlab Fuzzy Logic Toolbox (Sivanandam, S. N., Sumathi, S., & Deepa, S. N. (2007)).

The voltage magnitudes and frequency are gathered from the PMUs at each control point (Taylor et al. (2005)). According to the measured voltage magnitude and the frequency of a monitored bus, certain rules will be applied. Based on the applicable fuzzy rules, three outputs (LS, NA and GT) are produced. This is repeated for each monitored bus, and for Venezuelan power system, 15 points were used.

4. Results and controller's performance

In this section, the proposed fuzzy logic based emergency control strategy is tested on a dynamic model of the Venezuelan Power Electric Network simulated in the TSAT software. In order to simulate the emergency control actions in runtime, a User Defined Model (UDM) was implemented in TSAT to perform the tripping of loads and/or generators. However, the fuzzy control system was implemented outside of TSAT, using MATLAB Fuzzy Systems Toolbox. Thus, first the simulation was run without the control action, and variations of the frequency and the voltage were obtained. Then these variations are input to the controller implemented in MATLAB. The decision of the fuzzy controller is incorporated to a second (or multiple) simulation run through the UDM to obtain the results with emergency control action. Since the control actions are discontinuous, this approach is applicable.

The effectiveness of the emergency control strategy was validated considering a high power interchange scenario. A three-phase to ground fault was applied on a 765 kV transmission line carrying 1395.7 MW from the Southern generation center (Guri Power Plant and Malena Station) to the northern load centers. After clearing the fault, the Western region of the grid suffers a lack of generation to supply the local loads. Although there are few small generating plants in the Western region, the electrical power output that can be delivered by those generators is curtailed due to prevailing low voltages in the Western region. In order to prevent the loss of synchronism of some of the critical machines in the Western region, some load need to be shed. The rest of the system is able to redistribute the power flow to maintain a safe operation.

The voltage magnitudes and bus frequencies corresponding to this contingency are presented in Fig. 9. Once the fault is cleared, the overloaded buses in the Western region can be clearly identified. The synchronous machines located at Guri 765 kV generation station experience large frequency excursions due to the export reduction originated by the loss of a major transmission line. The frequency in the Southern region reaches a maximum of 60.8 Hz before returning to the acceptable range during the subsequent oscillations.

The curves in correspond to the 15 locations monitored using PMUs, and they do not directly show transient instability (Gomez, F. R et al. (2010)). However, the top graph in Fig. 10 which shows the rotor angles of all the generators in the system indicate that there are two generators that loose the synchronism as a result of the fault. Although the phase angles of the monitored buses do not directly indicate this, the transient stability status prediction scheme could correctly predict using only the 15 monitored bus voltage magnitudes that this contingency is leading to loss of synchronism of some of the generators (Gomez, F.R, et al). The buses which show a prolong undervoltage condition in Fig. 9 are in the same area as these two unstable generators are located.

Table 1. Fuzzy Decision Variables

AREA #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LS	0.59	0.53	**0.61**	0.59	0.50	0.54	0.58	0.57	0.55	0.55	0.53	0.11	0.54	0.27	0.59
GT	0.23	0.29	0.20	0.21	0.31	0.28	0.24	0.26	0.28	0.23	0.25	0.28	0.21	0.20	0.23
NA	0.35	0.37	0.37	0.38	0.39	0.36	0.34	0.33	0.33	0.40	0.42	0.77	0.44	0.73	0.35

The requirements for different control actions under this faulty condition, as obtained from the fuzzy logic system, are summarized in Table 1. These values correspond to measurements taken about 100 milliseconds after clearing the fault. Taking a control decision based on the measurement obtained immediately after clearing the fault is not appropriate, since the voltages are still recovering. Therefore, control decision was made based on the measurements gathered after about 100 milliseconds from the trigger signal. This requires addition of further 100 ms delay to represent the time taken by these measurements to reach the central controller.

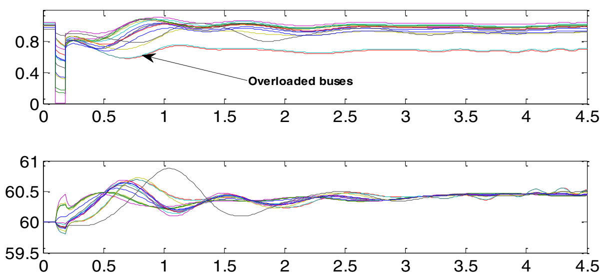


Fig. 9 Voltage magnitude and frequency trajectories after a contingency leading to transient instability problems

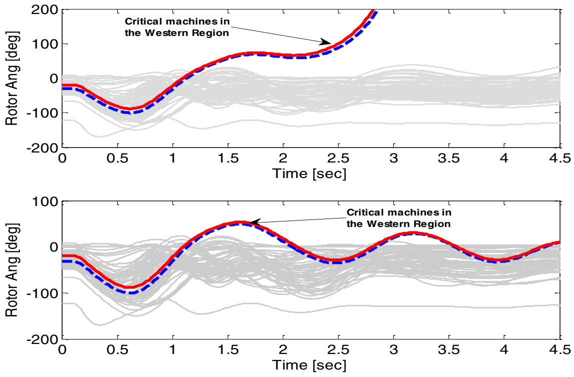


Fig. 10 Rotor angles trajectories with and without emergency control schemes

The highest requirement for load shedding was given by the controller associated with bus 3 (LS (3) = **0.61**). At the same time point, the requirement for no action associated with the same bus, NA(3), was 0.37. Since LS(3) > NA(3), a decision was made to shed loads in the region close to bus 3. Then LS (3) is compared with GT (3) and since LS(3) > GT(3), load shedding is confirmed. For this contingency, the requirement for generator tripping (GT) is smaller than the requirement for no action (NA), for all the buses. So generator tripping is not considered as an emergency control action for any area. Similar control requirements indexes reinforce a specific control action at a particular region. Further time delay of 200 ms was added before actually shedding the loads, in order to account for the time required for conveying the control decision to the breakers and operating time of the breakers. Thus a total time delay of 400 ms was assumed from the trigger signal to the time of execution of the control action. The effect of the control action on the system's enhancement is illustrated in Fig. 11. The two stages of load shedding improved the voltage profile after the disturbance and the voltage phase angle returned to a new operating point.

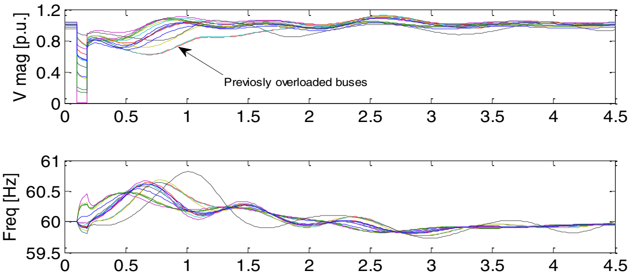


Fig. 11 Voltage magnitude and frequency trajectories after executing the load shedding

Variations of the values of the output fuzzy measures corresponding to bus # 3 are plotted in Fig. 12. These correspond to the variations throughout the complete disturbance. After the fault that occurs at 0.1s, the value of the fuzzy requirement for load shedding, LS, increases above the restrain provided by the value of fuzzy requirement for no action, NA. Even though the restrain NA is overtaken by LS immediately after the fault, decision on the control action is made based on their values at a point 100 ms is after the fault clearing time. Furthermore, no action will be taken unless the stability status of the system is predicted to be unstable.

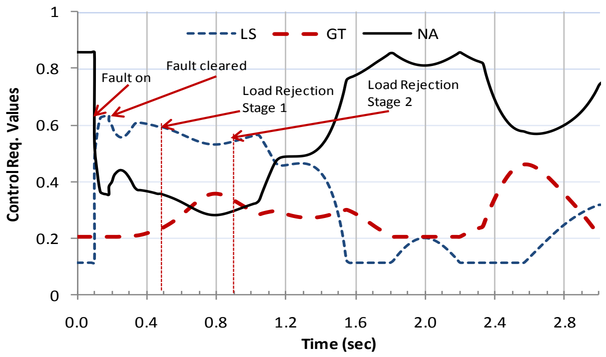


Fig. 12 Fuzzy output for the control area associated to bus # 3

Once, the controller is enabled after receiving the transient instability status, the first stage of load rejection occurs at 0.5 seconds (after the 400 ms time delay described previously). The controller continues to monitor the situation after the load has been shed. After the removal of the load with the highest load shedding priority, the load shedding requirement (LS) still remains higher than the no action (NA) signal. Consequently, a second load stage is shed at 0.9 s in the North Ring (Anillo norte), a load is located at Cuatricentenario 230 kV bus. Following this second load shedding, the system recovers and the restrain signal (NA) overtakes the load shedding (LS) requirement.

5. Conclusion

An emergency control scheme for transient stability enhancement was proposed and its validity was demonstrated by applying the algorithm to the Venezuelan power grid. The early prediction of the transient instability condition enables activation of emergency control actions in a timely manner to prevent the transient instability. The appropriate post-contingency corrective actions can be selected using the proposed fuzzy system to avoid the loss of synchronism. Decisions are based on the wide area measurements made within few tens of milliseconds after the fault.

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