A FUZZY LOGIC-BASED LOAD FREQUENCY CONTROLLER

by

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Abstract: *The well known and widely used power system model for the Load Frequency Control (LFC) problem is extremely linearized and approximated. Over the last three decades, extensive research efforts have used such a model as a base for studying several control schemes in this field. Unfortunately, documented reports have proved that there exist many power systems worldwide suffering from severe load-frequency fluctuations. Beside approximation and linearization, the uncertainty of the model parameters may constitute the main reasons of LFC failure. Unlike common control schemes, this paper presents a Fuzzy Logic-Based Load Frequency Controller. A Variable Structure Fuzzy Controller (VSFC) will be developed to suite the power system model for both wide range of parameter uncertainties and different types of disturbances. The performances of the proposed VSFC are compared with a conventional LFC for a variety of system parameters and transient disturbances. This may highlight the effectiveness of the proposed controller not only solving the LFC problem but also in providing sufficient damping of the frequency oscillations. Another important objective of this paper is that it presents an easy tutorial to demonstrate the use of readily available computer software(MATLAB, SIMULINK, and Fuzzy Logic Toolbox) in the analysis and design of Load Frequency Control systems.*

1. INTRODUCTION

In order to ensure acceptable quality of power supplies, the load frequency deviations have to be constrained within minimum tolerance. For this purpose, massive number of Load Frequency Control (LFC) techniques are proposed over the last three decades[1-10]. The literatures in this field are still showing continual interest for designing LFC systems. In the late 60s and early 70s, integral control system was proposed[1,2]. The integral gain was chosen according to conventional transfer function analysis and the critical gain was able to minimize frequency deviations for a single area power system. Tedious trial and error procedures were needed if the algorithm is applied even for two dissimilar areas. For detailed multi area power systems, it is not possible to apply this method for the design of LFC system.

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Optimum control schemes have been introduced to overcome the shortages of integral control. An Algorithm based on minimizing the square errors of a cost function describing the power system frequency deviations and tie line powers[3-6] was developed. The Algorithm was applied to a two area power system giving better results. The necessary weighting matrix parameters, were chosen as a result of comparing the Eigenvalues before and after the application of the optimum control scheme. Such parameter selection will be ,of course, very problematic for a multi area power system.

Indeed, some power system data such as frequencies and tie line powers which are required to determine the control signals are only available in discrete manner. Hence, further considerations were required for practical implementation of the above continuous LFC methodologies. Also, some states couldn't be available for measurement. Few works have been done concerning discrete-time LFC and in most of them significant system non-linearties, e.g., generation rate constraints have been ignored. Discrete LFC techniques and state estimation methods were proposed to solve such problems[7-8,11-13]. However, these proposals were also based in complex mathematics and may require optimization techniques to select the necessary weighting matrices. Other complications may be arisen in creating the initial ratios of the performance indices especially for a multi area power system[7].

To consider the system non-linearity and parameter uncertainties, robust LFC systems have been proposed[9,10,14]. In reference [9], a method based on solving the Riccati-equation has been presented, and the controller is designed for the bounds of the model parameters. From the author's experience in this field, and the analysis of this study, some initialization values of the weighting matrix may lead to system instability. Also, it is found that the results are characterized with very high over shoot, especially, in case of taking generation rate constraints in account. Performance of multi area power system shows that the system presents larger overshoots and longer settling times. A LFC technique based on the well known modal analysis methods is also developed[14]. A selective modal analysis was used to find out the most effective state for feeding back the integral controller. Unlike the conventional pole assignment techniques in which "P-1" pole pre-specifications are needed in order to stabilize a "P" closed loop system, the proposed method requires only one selected pole pre-specification for every controller parameter. This allowed more freedom left for the rest of the closed loop system poles and, consequently, keeping the system physics less changed. The technique has been applied with considering generation rate constraints and the controller has been designed based on the bounds of the model-parameters.

Such bounds, as taken from the literature, were put down in the range of ± 20% of the nominal parameters[12,13]. Practically, the actual model-parameters may be entirely away from such bounds. In view of that, this paper presents a Fuzzy Logic-Based Load Frequency Controller. A Variable Structure Fuzzy Controller (VSFC) will be used to suite the power system model for both wide range of parameter uncertainties and different types of disturbances. The performances of the proposed VSFC are compared with a conventional LFC for variety of system parameters and transient disturbances. This may highlight the effectiveness of the proposed controller in providing sufficient damping of the frequency oscillations. The controller will be implemented through the recent Fuzzy Logic Toolbox[15] of the latest MATLAB version[16-18]. This Toolbox provides a seamless comfortable way of selecting the membership functions, writing the fuzzy rules, and above all a powerful Graphic User Interface GUI. Also, the Toolbox enables the user to practically interface his own Hardware via the so called Real Time Workshop (RTW) which is conducted to SIMULINK in conjunction with the modern Hardware-In-the Loop (HIL) facility provided recently by Hardware manufacturers[19-24]. The carried out work of this paper represents also a valid tutorial to demonstrate the application of the above readily available software in the analysis and design of control system for industrial processes.

2. THE LOAD FREQUENCY CONTROL MODEL:

A schematic diagram representation of LFC system is shown in Fig.(1-a). For a single area system connected via tie lines to other areas like those of Fig.(2), following equations formulate the model :

1. Speed-governing system:

$$\Delta X_E(S) = \frac{K_G}{1+ST_G}\left[\Delta P_C(S) - \frac{1}{R}\Delta F(S)\right] \qquad (1)$$

Details of derivation of this equation are illustrated clearly in Fig.(1-a)

2. Turbine:

$$\Delta P_G(S) = \frac{K_T}{1+ST_T}\Delta X_E(S) \qquad (2)$$

This equation is based on the fact that the resulting generator power change ΔP_G will be proportional to the governor signal change ΔX_E . Consequently, a simple representation of a turbine with time constant in the practical range of 0.2 ~ 2.0 seconds[1-4] has been considered to be adequate in this study.

3. Power system:

$$\Delta P_{Gi} - \Delta P_{Di} = \frac{d}{dt}W_{Kin,i} + D_i \Delta F_i + \Delta P_{tie,i} \qquad (3)$$

The power system representation in this way is based on several assumptions:

(1)The synchronous machine operates within an area containing an infinite number of generators which are connected together to perform a power system having very stiff buses as shown in Fig. (2).

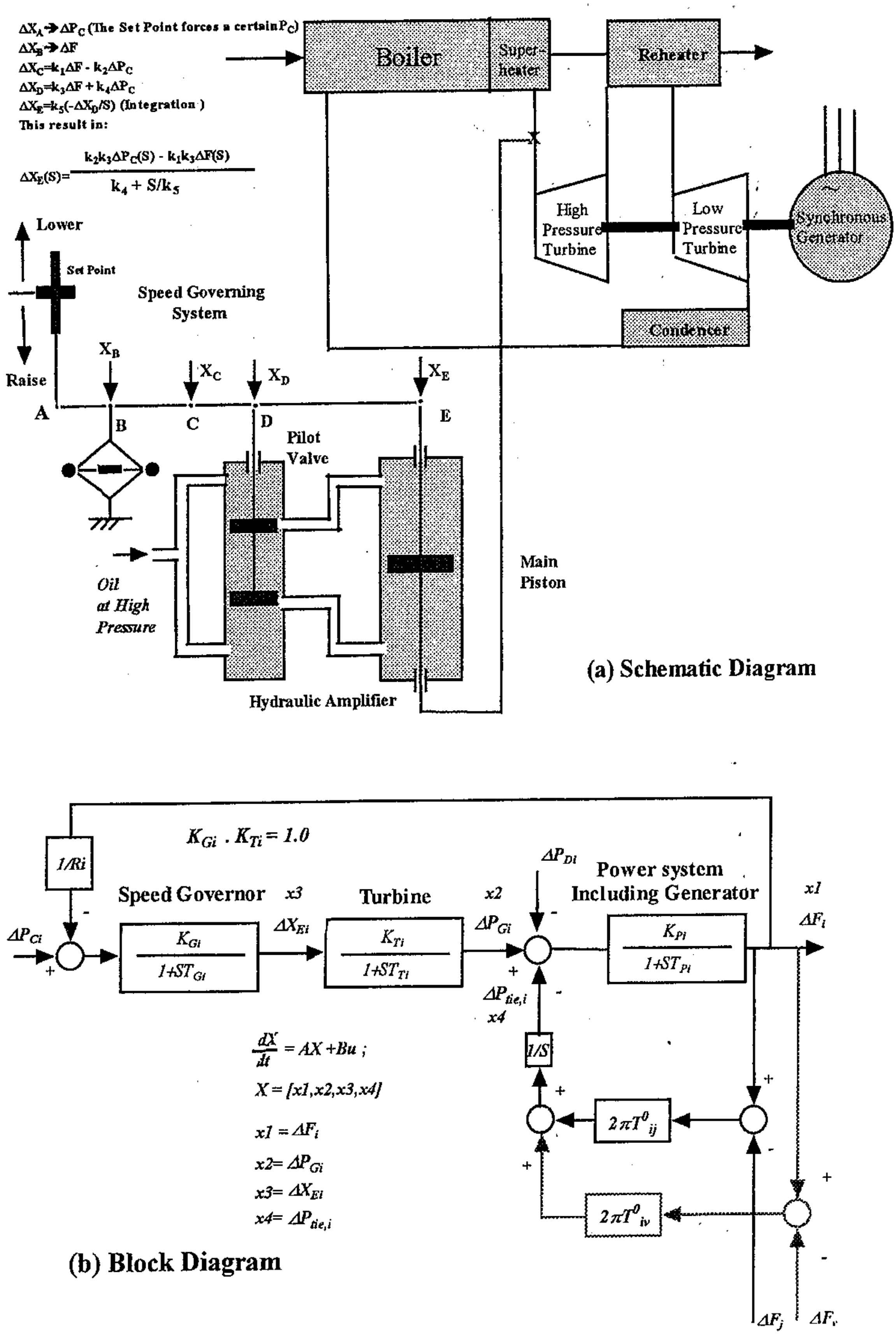

Figure (1) Load Frequency Control Model : a- Schematic Diagram, b-Block diagram

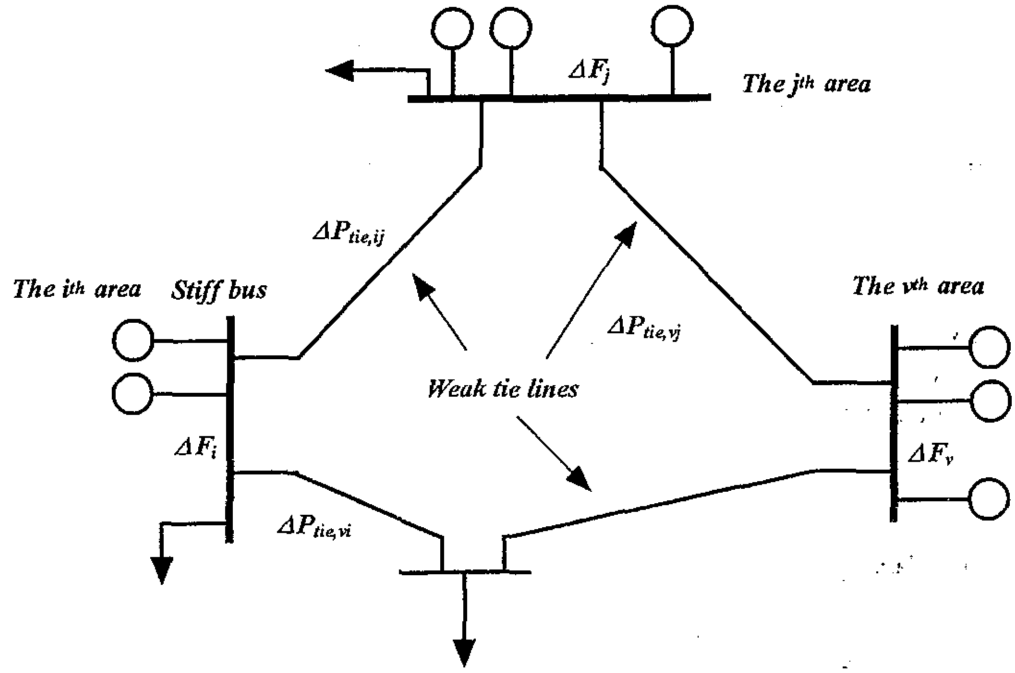

Figure (2) Representation of the power system as interconnected areas

This leads to the assumption that in case of small perturbations these machines will swing in coherence which means that the buses frequency-changes ΔF_i will be identical.

(2)This area is connected via relatively weak tie lines to another areas each of which swing in coherence and their buses will have a different frequency-changes ΔF_j, ΔF_v due to the same perturbation.

(3)After the small perturbation, due to a change in the area power demand ΔP_{Di}, the speed governor will react with a change in the generated power ΔP_{Gi} and the net power surplus (ΔP_{Gi}-ΔP_{Di}) will be absorbed by the system in the form of the three terms found in the right side of equation (3). From these terms, the 1st and 2nd terms are too small in comparison with the 3rd one. This is due to the fact that the first term which represents the change in the kinetic energy of the i^{th} area varies as the square of the speed or frequency, and for small perturbations this squared value will be neglected. Also the value of Di in the second term for a 2000 MW total area capacity with nominal load P_{Di} =1000 MW and inertia constant H=5.0 Seconds will equals:

$\frac{\partial P_D}{\partial F}$=(1000/(60*2000))=0.00833 MW/Hz, which when multiplied by ΔF can be neglected.

Accordingly, eqn. (3) can be reduced to:

$$\Delta P_{Gi} - \Delta P_{Di} = \Delta P_{tie,i}\,, \qquad (4)$$

where ,

$$\Delta P_{tie,i=} = \sum \Delta P_{tie,iv} = T_{iv}^{0}(\Delta\delta_i - \Delta\delta_v)\,; \qquad (5)$$

$T_{iv}^{0} = P_{\max,iv}\cos(\delta_i^0 - \delta_v^0)$ is the synchronizing coefficient.

But, $\Delta F_i = \dfrac{1}{2\pi}\dfrac{d}{dt}\Delta\delta_i$ then Eq. (3) can be written as:

$$\Delta P_{Gi} - \Delta P_{Di} = 2\pi T_{iv}^{0}\left(\int \Delta F_i dt - \int \Delta F_v dt\right) \qquad (6)$$

(4) A decoupling between the power-frequency and the reactive power-voltage control channels may exist based on the relative speed of response of these two loops to the changes of the load-frequency and the terminal voltage in case of disturbances.

3. FUZZY LOGIC CONTROLLERS

3.1. Background And Definitions:

In 1990, C.C. Lee published a valuable survey paper about fuzzy logic in control systems[25]. The paper was aimed to introduce systematic procedure for the design of fuzzy logic control methodology and point to the problems which need further research. In that time some issues of fuzzy logic controllers were not clearly stated. Accordingly, the second part of this paper was essentially interested in highlighting the main idea, concepts, and terminology of fuzzy logic control. One decade later, fuzzy logic control has proved to be one of the most active and fruitful areas of research. The attraction of fuzzy logic, in general, lays in the fact that it can yield a controller which acts in a manner similar to human language. The theory of fuzzy logic and fuzzy logic control can be found anywhere in the literature, however reference [26-30] can be very helpful. It is also important to be aware of the physical system to be controlled using fuzzy logic control. This will simplify the steps leading to an efficient and reasonable fuzzy logic control. In summary, the so called Mamdani's fuzzy inference method [15,25-30] is the most commonly seen fuzzy methodology. Mamdani's method was among the first control systems built using fuzzy set theory. Typical steps of this methodology can be summarized as:

Step 1. Fuzzification: The operation that compares input variables with membership functions of the premise part to obtain the membership values.

Step 2. Weighting: Once the inputs have been fuzzified, we know the degree to which each part of the antecedent has been satisfied for each rule. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number will then be applied to the output function.

Step 3. Implication: Simply the usage of "OR" or "AND".

Step 4.Aggregation: This is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set.

Step 5. Defuzzification: Since the aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set.

3.2. The Fuzzy Logic Toolbox:

The Fuzzy Logic Toolbox is a collection of functions built on the MATLAB numeric computing environment [15]. It provides tools for one to create and edit fuzzy inference systems within the framework of MATLAB, or if one prefers he can integrate his own fuzzy systems into simulations with Simulink, or one can even build stand-alone C programs that call on fuzzy systems he builds with MATLAB. This toolbox relies heavily on graphical user interface (GUI) tools to help accomplish one's work, although one can work entirely from the command line if he prefers.

The toolbox provides three categories of tools:

- Command line functions
- Graphical, interactive tools
- Simulink blocks and examples

The first category of tools is made up of functions that one can call from the command line or from his own applications. Many of these functions are MATLAB M-files, series of MATLAB statements that implement specialized fuzzy logic algorithms. One can view the MATLAB code for these functions using the statement type function_name. One can change the way any toolbox function works by copying and renaming the M-file, then modifying his copy. One can also extend the toolbox by adding his own M-files. Secondly, the toolbox provides a number of interactive tools that let one access many of the functions through a GUI together. The GUI based tools provide an environment for fuzzy inference system design, analysis, and implementation. The third category of tools is a set of blocks for use with the Simulink simulation software. These are specifically designed for high speed fuzzy logic inference in the Simulink environment.

As an example which indicate how to implement the toolbox to build a Fuzzy Inference Systems (FIS) for general case can be easily indicated from the following graphs of Figs(3-6). It is clear from these figures that it is possible to use the Fuzzy Logic Toolbox without bothering with the GUI tools at all. For instance, one can also build a system entirely from the MATLAB command line. Probably the trickiest part of this process is learning the shorthand that the FIS. Each variable, input, or output, has an index number, and each membership function has an index number. The rules are built from statements like this:

if input1 is MF1 or input2 is MF3 then output1 is MF2

This rule is turned into a structure according to the following logic: If there are m inputs to a system and n outputs, then the first m vector entries of the rule structure correspond to inputs 1 through m. The entry in column 1 is the index number for the membership function associated with input 1 (refer to Fig(6). The entry in column 2 is the index number for the membership function associated with input 2, and so on. The next n columns work the same way for the outputs. Column m + n + 1 is the weight associated with that rule and column m + n + 2 specifies the connective used (where AND = 1 and OR = 2).

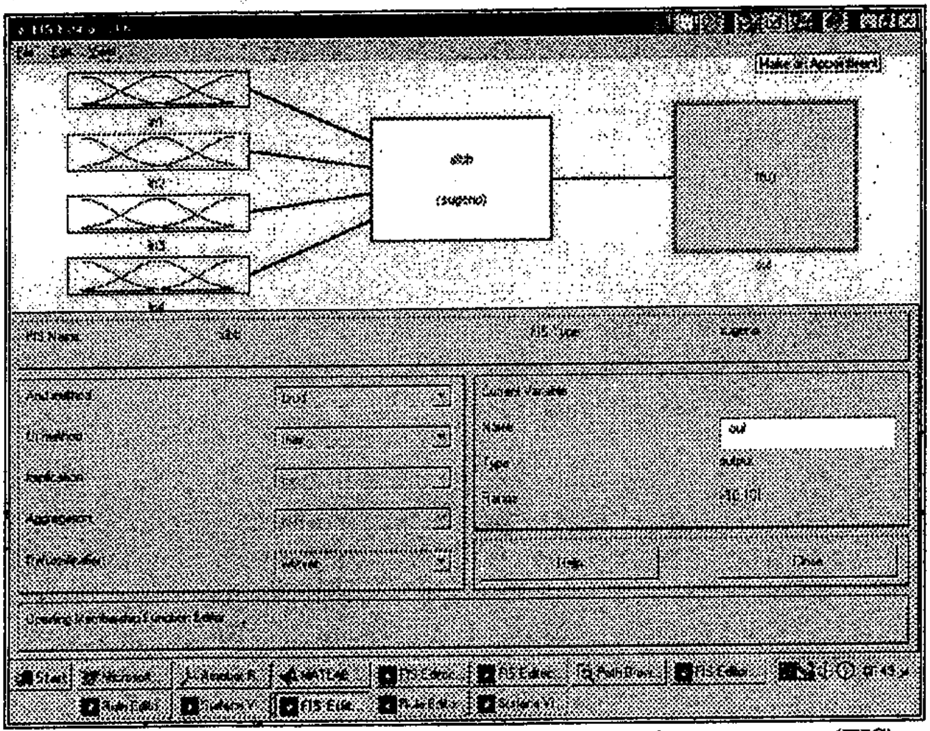

Figure (3) A general case representation of fuzzy inference system (FIS) indicating inputs, outputs, and rules.

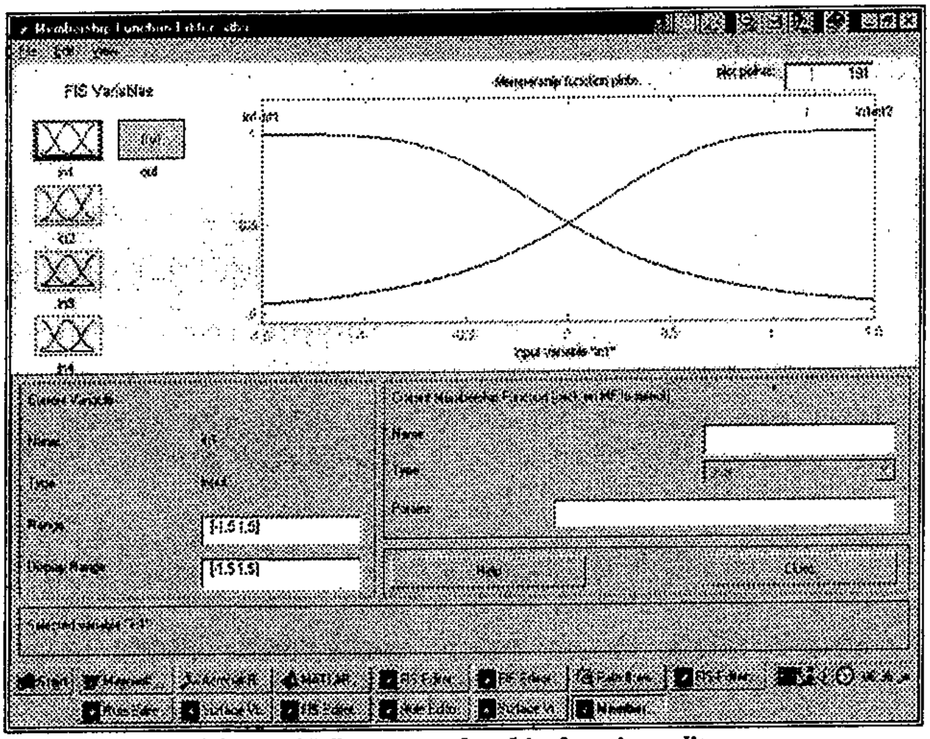

Figure (4) Input membership function editor

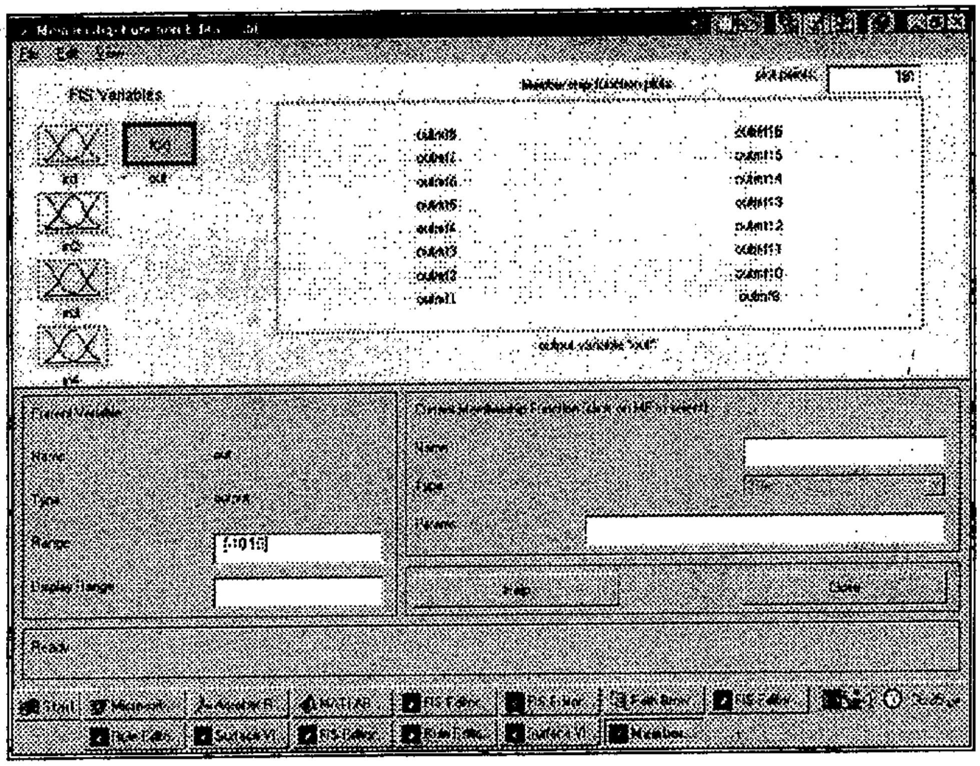

Figure (5) Output membership function editor

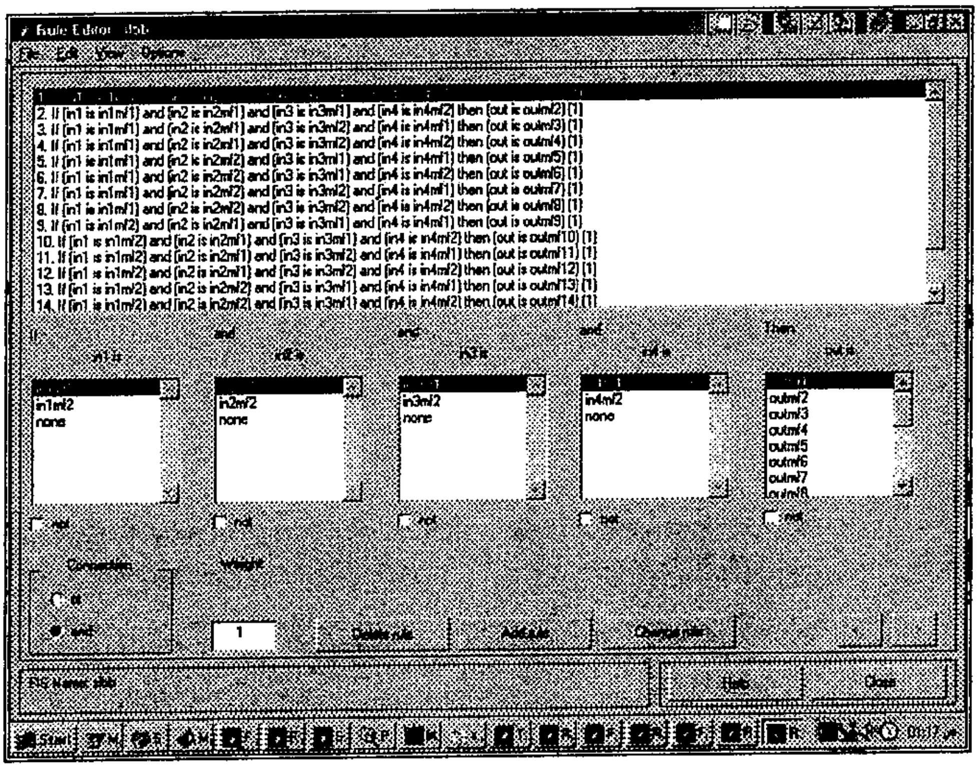

Figure (6) Fuzzy logic rule editor

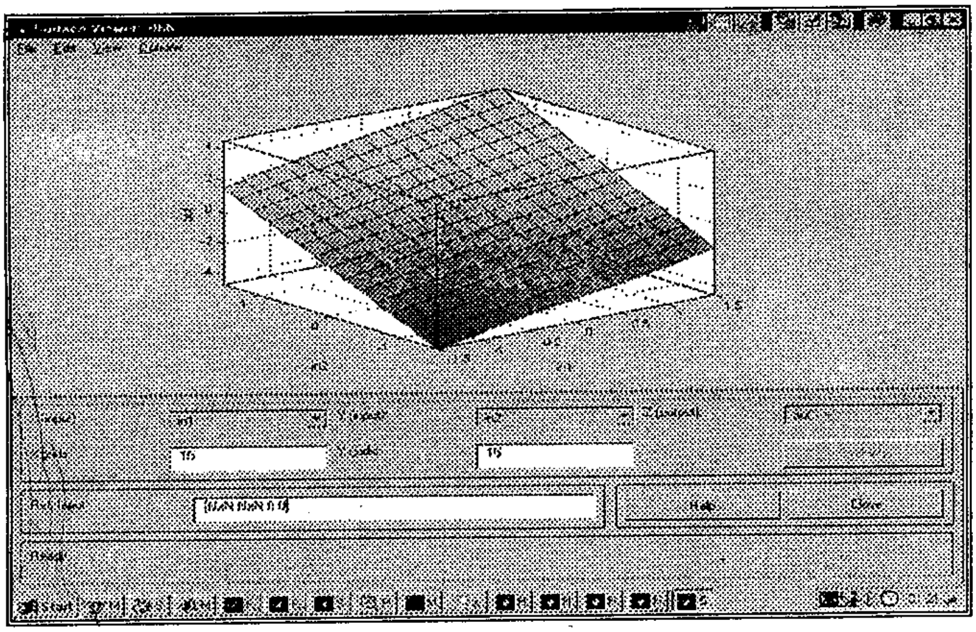

Figure (7) The FIS surface viewer

3.3. Design Of Fuzzy Logic Load Frequency Controller:

The above model shown in Figs.(1,2) has been extensively used by power system engineers until now for the dynamic study of LFC problem. However, in the recent years, several studies have proved that the above model is only valid if the power system parameters are certain nominal values[12,13]. For certain model, it has been proven that any simple controller can provide enough damping for the frequency fluctuations. This can be evident from the results given in Fig.(8).

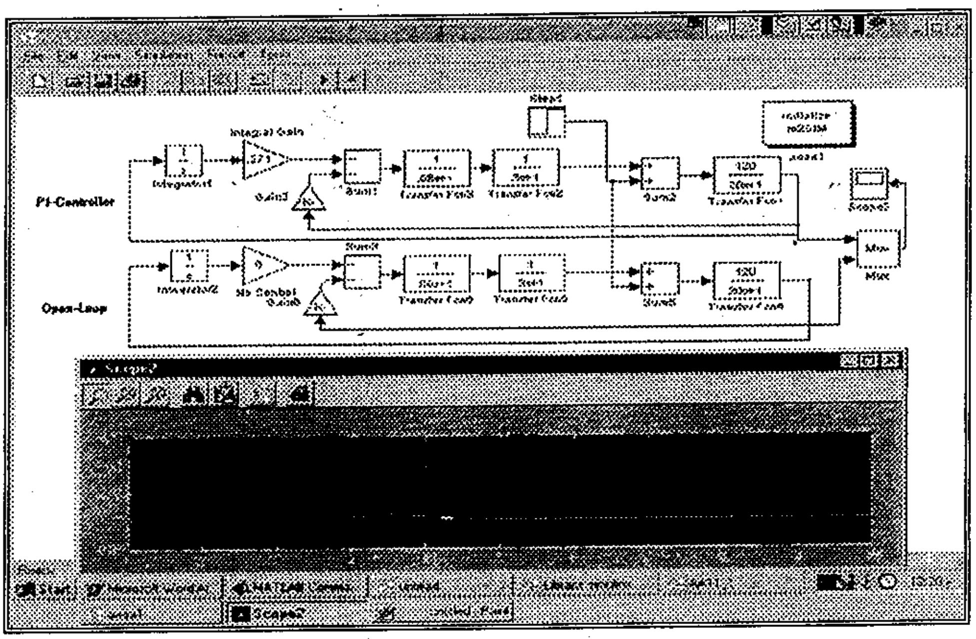

Figure (8) Successful application of conventional LFC for damping frequency oscillations

Unfortunately, the true power system parameters are uncertain and vary essentially than those nominal parameters[12-14]. This is basically due to operating conditions changes, or poor knowledge of the actual parameter values or, principally, due to the drastic approximation in modeling the system. In order to assure this criticism the above model is simulated for different values of the system parameters(+20%T_G,+20%T_T,-20%T_P,-20%K_P) and the results are given in a comparative form between the case where the model parameters are nominal and the case where uncertainty of only ±20% is assumed. The open loop (Uncontrolled case)simulation results are shown in Figs.(9,10) and it is obvious from these results that a conventional power-frequency controller based on Fig.(9) must fail if the system parameters are only ±20% uncertain compared with the nominal values.

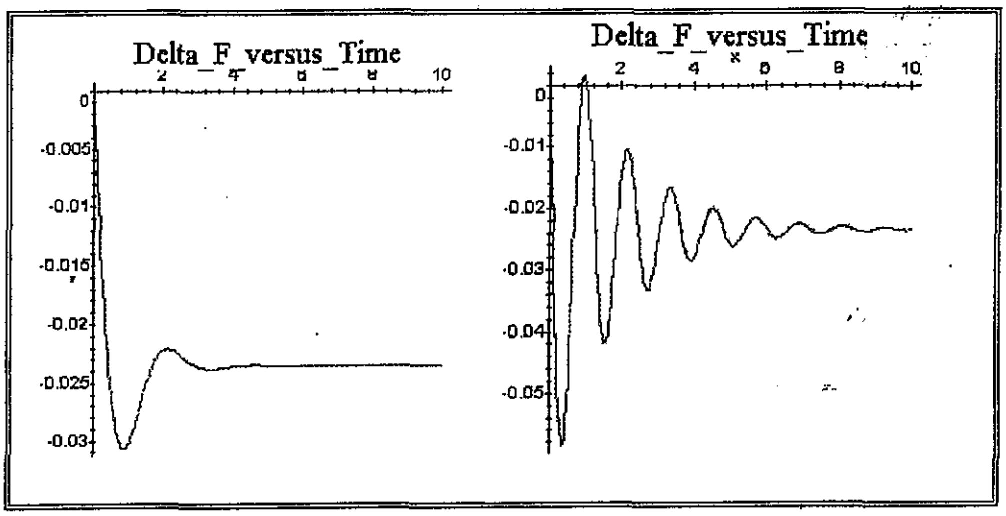

Figure (9) Open Loop (Uncontrolled case) Simulation of the LFC Model with nominal parameters (Left curve) & ±20% (right curve) respectively

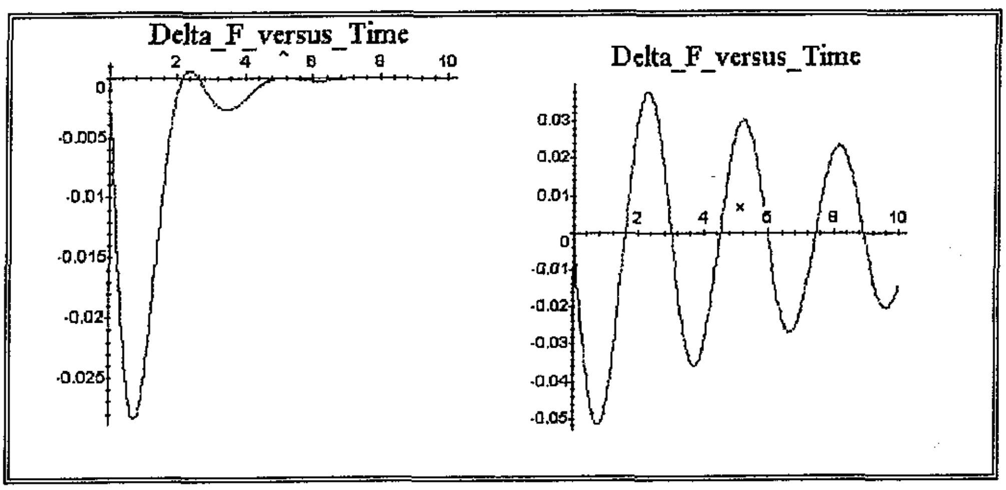

Figure (10)Closed Loop (Controlled case) Simulation of the LFC Model with nominal parameters (Left curve) & ±20% (right curve) respectively

The purpose of this paper, principally, is how to solve the problem of generating appropriate membership functions whatever the grade of disturbance may be. In the early work of Malik and Hassan [31] , a tuning technique is proposed to solve this problem in the work of Hiyama, [32,33]. Unfortunately, beside the complications of this approach due to its extra rule which is determined based on phase plane, the added parameter "R" (refer to their papers) is a function of a previous disturbance which is basically unpredictable and only (refer to the results in [31]) theoretical results can be satisfactory. Therefor, this paper presents a new approach to solve this problem. The idea of this approach is to use a self organized fuzzy logic-controller to damp the frequency oscillations regardless the disturbance type beside considering the power generation constraints and the parameter uncertainty. A novel strategy is shown in Fig.(11) to supplement an input signal to the system via fuzzy logic control which will be multiplied with an error signal from the generated power. The later signal provide the ranges adjustment of the membership functions in accordance to the disturbance type. Such proposal can be considered as a Variable Structure Fuzzy Controller (VSFC) since the membership functions vary continuously. The Matlab Fuzzy Logic Controller toolbox, which is previously explained in sections 3.1 and 3.2., is used to implement this approach and a Simulink block diagram for the previously mentioned power system of Fig.(2) is performed and shown in Fig.(11).

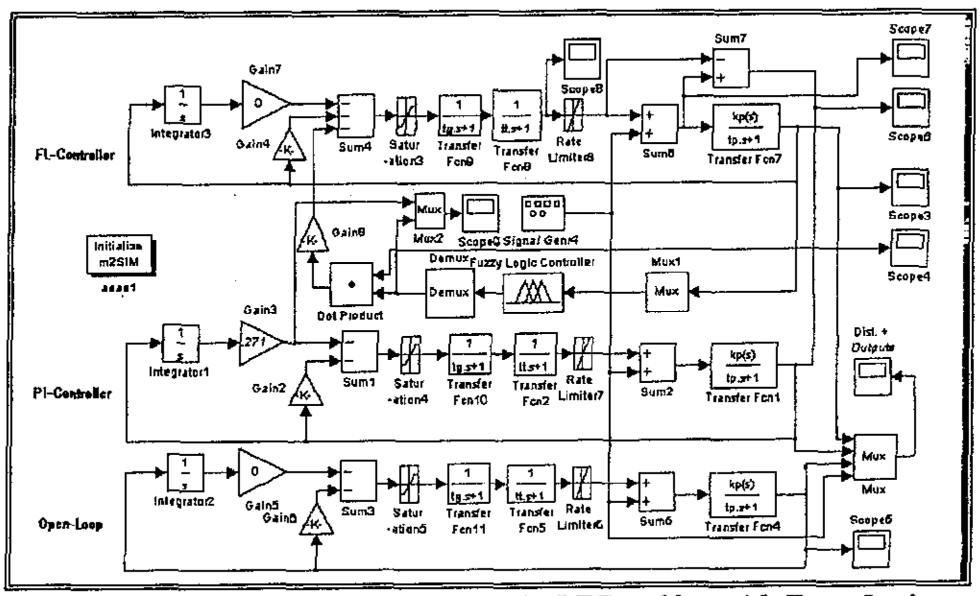

Figure (11) Simulink representation of the LFC problem with Fuzzy Logic-Controller, PI-Controller in addition to the uncontrolled case

An extensive analysis is executed until appropriate membership functions has been selected. Fuzzy rules achieving damping requirements has been also edited in the way previously explained in sections 3.1. and 3.2.. Only two results are given in Figs.(12,13). From which it is evident that the Fuzzy Logic Control strategy can be considered as a robust one. Comparing the results of these two figures prove that a conventional controller can be only applied for systems having certain parameters and not restricted to some practical considerations such as generation rate constraints. One should note that the disturbance used in the controller evaluation is selected as a periodic one. Accordingly, the system will be exposed to more serious disturbance unlike the known step change disturbance which can not reflect the real system disturbances and, hence, the evaluation will be more confidential.

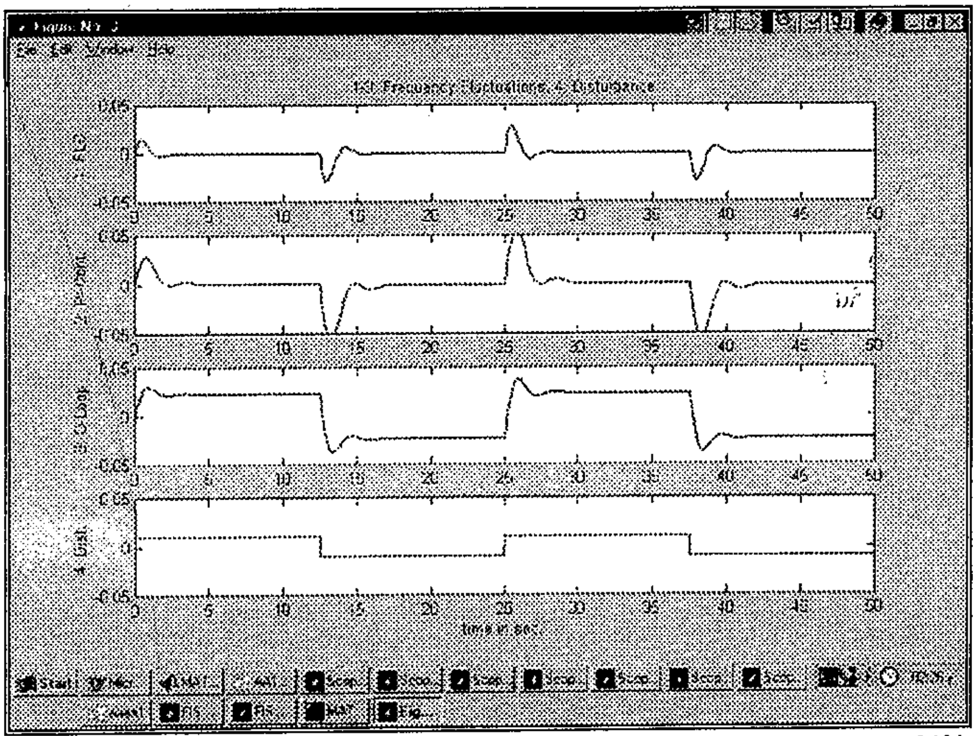

Figure (12) FL- versus PI-Controller response for nominal parameters to -.01% load demand disturbance (Square wave).

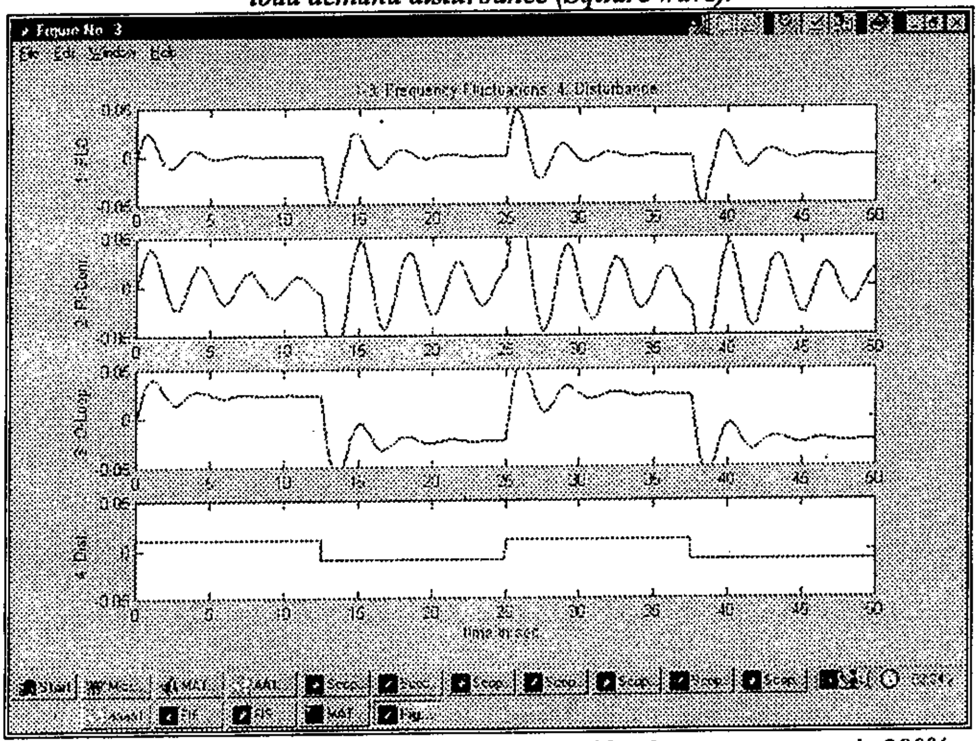

Figure (13) FL- versus PI-Controller response if only one parameter is 200% uncertain to -.01% load demand disturbance (Square wave).

4.CONCLUSIONS

Since many power systems worldwide are still suffering from severe Load-Frequency fluctuations, this paper has presented a novel contribution towards solving such problem. A Variable Structure Fuzzy Controller (VSFC) has been developed to suite the power system model for a wide range of parameter uncertainties. Such control strategy is based on supplementing an input signal to the system via fuzzy logic control which will be multiplied with an error signal from the generated power. The later signal provide the ranges adjustment of the membership functions in accordance to the disturbance type. The performances of the proposed VSFC are compared with a conventional LFC. Results have proved that the proposed VSFC is able to damp the frequency oscillations for a wide range of parameter uncertainties. In addition, the paper has presented an easy tutorial to demonstrate the use of readily available computer software which can be generalized, not only in the analysis and design of Load Frequency Control systems but also may be valid for any other system.

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يعد النموذج الشائع الإستخدام فى التحكم فى تردد القدرة لنظم القوى الكهربية فى صورته الخطية مقربا إلى حد كبير. وخلال العقود الثلاثة الأخيرة تم إعتبار هذا النموذج كأساس يبنى عليه العديد من الحاكمات فى هذا المجال، وهناك العديد من التقارير أثبتت أن بعض نظم القوى الكهربية فى أماكن شتى من العالم يتسم أداؤها بالتذبذب الغير مرغوب فيه فى ترددادتها. وهذه الذبذبات فى التردد قد أحدثت مشكلات فى الإتزان لبعض هذه الشبكات والسبب الرئيسى لهذه المشكلات إستخدام هذا النموذج الخطى المقرب بالإضافة إلى أن بارامترات هذا النظام تقسم بعدم التأكدية مما يؤدى إلى فشل الحاكمات المصممة على أساس ثبات بارامترات النموذج .

ولذلك فإن هذا البحث يقدم حاكم فازى (Fuzzy logic) متغير التركيب ليلائم هذا النموذج خلال مدى واسع من عدم تأكدية بارامتراته ليس فقط عند تعرضه لأخطاء بسيطة بل عند تعرضه لاخطاء جسيمة.

ويقارن البحث أداء الحاكم المقترح بتلك الحاكمات التقليدية وتشير النتائج إلى نجاح الحاكم المقترح فى خمد ذبذبات التردد خلال مدى واسع من عدم التأكدية وعند أخطاء أكثر خطورة مقارنة بإستخدام الحاكمات التقليدية.