Transient Voltage Stability Enhancement Using Fuzzy Logic Controller Techniques *

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Abstract: This paper discusses the transient voltage stability of a synchronous generator at its bus in a power system with a detailed transient modeling for the generator after being subjected to a three phase fault, and designing a Takagi-Sugeno first order fuzzy logic controller with center of area defuzzification algorithm as a fuzzy logic controller based exciter to stabilize the terminal voltage and to damp its oscillations so as to keep the generator under balanced working conditions. The proposed exciter can be easily modified by changing the steady state field voltage value to be applied to any other synchronous generator. This paper also used the integral of square error as an indicator of the terminal voltage stability and monitored all of the generator variables specially the rotor angle to see whether the generator will maintain synchronism or not after the occurrence of the fault.

Keywords:

Voltage stability, Fuzzy controller, Exciter, Integral of square error.

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List of symbols:

dV_{err}	Change in error voltage.
E_f	The field excitation voltage on the stator side.
E'_q, E'_d	The stator voltages behind the transient reactances.
$[f_{abc}]$	Any three phase (AC) quantities.
$[f_{qd0}]$	The equivalent two phase (DC) quantities.
H	Inertia constant.
i_q, i_d	The stator windings currents.
λ	Flux linkage.
mmf	Magneto-motive force.
r_s	The stator winding resistance.
r_e, x_e	The external line resistance and reactance respectively.
T_{acc}	The rotor accelerating torque.
T_{em}	The electro-mechanical torque developed.
T_{mech}	The input mechanical torque.
T'_{qo}, T'_{do}	Transient time constants, which represent the change in the field currents in response to a change in the excitation voltage.
$[T_{qd0}(\theta)]$	The Park's transformation matrix with respect to angle(θ).
V_{err}	Error voltage.
V^r_{qi}, V^r_{di}	Infinite bus voltages referred to the rotor synchronously rotating frame.
V^s_{qi}, V^s_{di}	Infinite bus voltages referred to the stator synchronously rotating frame.
ω_b	The base electrical angular frequency.
x_q, x_d	The synchronous steady state reactences.
x'_q, x'_d	The synchronous transient reactences.
δ	Rotor angle.

1. Introduction:

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance from a given initial operating condition. According to the time frame of interest there are two main types of voltage instability that the power system may suffer during its operation which are long term voltage instability and transient or short term voltage instability [1].

The long term voltage instability is caused by the inability of the power system to meet the demand for reactive power which will lead to voltage collapse in one or more buses. The transient voltage instability occurs after the system being subjected to a disturbance followed by either slow or inappropriate control action from the controlling device. This will lead to oscillations in the voltage and therefore oscillation in the active, reactive power and the rotor angle and as a subsequence loose of synchronism. In other words improving the transient voltage stability will also improve the rotor angle stability [2] [3].

The controller which will be discussed in this paper is the field windings exciter of a synchronous generator. It directly controls the voltage magnitude and the reactive power injected to the system by the generator which is the primary source of reactive power in the system and to great extent responsible for maintaining a good voltage profile across the power system [4].

2. Synchronous machine transient modeling:

The case study system is shown in Fig. 1 below which consists of one synchronous generator connected to an infinite bus by a short transmission line with r_e and x_e.

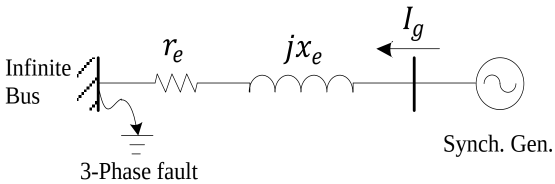

Fig. 1 Synchronous generator connected to infinite bus.

The Park's transformation or qdo transformation will be used to model the synchronous generator for two main reasons; firstly, to isolate the voltage control from the torque control, and secondly, for sake of simplicity and reduction of calculations because it converts the three phase AC quantities into two phase DC equivalent quantities. The Park's transformation consists of two imaginary axes. The one to the North Pole is the direct or$d-axis$. The quadrature or $q-axis$ is defined in the direction 90 electrical degrees ahead of the direct axis. The field mmf will be along the $d-axis$, and the stator internal voltage, $d\lambda_{af}/dt$ will be along the $q-axis$. It should be mentioned that the damping winding is not effective during the transient time interval therefore it won't be mentioned and also the changes in the stator qd flux linkages will be neglected [5]. Also the transient of x_q reactance will be ignored in equations 5.B, D_z eq., 6 and 8.B because its time constant is relatively small **compared** to$x_d$transient time constant.As an example for the simulated machine($T'_{do}=7.9\,sec.$) while ($T'_{qo}=0.41\,sec.$); in which these times represent the effective time for each reactance [6]. The Park's transformation matrix and its inverse are shown below:

$$[\boldsymbol{T_{qd0}(\theta)}] = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta-\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (\mathbf{1.A})$$

$$[\boldsymbol{T_{qd0}(\theta)}]^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta-\frac{2\pi}{3}\right) & \sin\left(\theta-\frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta+\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) & 1 \end{bmatrix} \quad (\mathbf{1.B})$$

And they can be used to change the quantities from three phases to two phase representation and vice versa by using the following equations:

$$[\boldsymbol{f_{qd0}}] = [\boldsymbol{T_{qd0}(\theta)}] * [\boldsymbol{f_{abc}}] \quad \textbf{(2.A)}$$

$$[\boldsymbol{f_{abc}}] = [\boldsymbol{T_{qd0}(\theta)}]^{-1} * [\boldsymbol{f_{qd0}}] \quad \textbf{(2.B)}$$

Using the above equation (2) the infinite bus voltages will be referred to qdo axes of the stator synchronously rotating frame. Then they will be transformed from the synchronously rotating frame of the stator to the one of the rotor by using the following equation (3):

$$\begin{bmatrix} \boldsymbol{V^r_{qi}} \\ \boldsymbol{V^r_{di}} \end{bmatrix} = \begin{bmatrix} \cos\boldsymbol{\delta} & -\sin\boldsymbol{\delta} \\ \sin\boldsymbol{\delta} & \cos\boldsymbol{\delta} \end{bmatrix} \begin{bmatrix} \boldsymbol{V^s_{qi}} \\ \boldsymbol{V^s_{di}} \end{bmatrix} \quad \textbf{(3)}$$

The synchronously rotating frame on the rotor will be the reference frame and all the variables will be transformed to it and calculated according to this assumption, and all the rotor quantities will be referred to the stator side by using the appropriate turn's ratio [5]. By definition, the frequency of the infinite bus is constant at the synchronous value. With only one machine, it will be convenient for

calculation purposes to select the phasor of the infinite bus voltage as the reference phasor and also the $q-axis$ of the synchronously rotating reference frame. With this choice of synchronously rotating reference frame, V_{di}^{r} in the above equation will be identically zero.
The voltage behind the transient reactance (speed voltage) will be:

$$\frac{dE_q'}{dt} = \frac{1}{T_{do}'}\left[E_f - (x_d - x_d')i_d - E_q'\right] \quad (4.A)$$

$$\frac{dE_d'}{dt} = \frac{1}{T_{qo}'}\left[(x_q - x_q')i_q - E_d'\right] \quad (4.B)$$

Thus the stator windings currents will be:

$$i_q = \frac{1}{D_z}\left[-(r_s + r_e)(V_{qi}^r - E_q') - (x_d' + x_e)(V_{di}^r - E_d')\right] \quad 5.A)$$

$$i_d = \frac{1}{D_z}\left[(x_q + x_e)(V_{qi}^r - E_q') + (r_s + r_e)(V_{di}^r - E_d')\right] \quad 5.B)$$

$Where$
$$D_z = (r_s + r_e)(r_s + r_e) + (x_q + x_e)(x_d' + x_e)$$

The electro-mechanical torque developed equation is:

$$T_{em} = E_q' i_q + E_d' i_d + i_d i_q (x_q - x_d') \quad (6)$$

While the rotor accelerating torque equation will be:

$$T_{acc} = T_{mech} + T_{em} - Slip * Damp.Factor \quad (7)$$

$Where$
$$Slip = \frac{1}{2H}\int T_{acc}\,dt$$

Then the $qd-axes$components of the terminal voltage will be:

$$V_{qt} = E_q' - r_s i_q - x_d' i_d \quad (8.A)$$

$$V_{dt} = E_d' - r_s i_d + x_q i_q \quad (8.B)$$

Finally the terminal voltage, current, active and reactive power, and delta equations are:

$$|V_t| = \sqrt{V_{qt}^2 + V_{dt}^2} \quad (9)$$

$$|I| = \sqrt{i_q^2 + i_d^2} \quad (10)$$

$$P = V_{qt} i_q + V_{dt} i_d \quad (11)$$

$$Q = V_{qt} i_d - V_{dt} i_q \quad (12)$$

$$\delta = \omega_b \int Slip\,dt \quad (13)$$

3. Fuzzy Based proposed exciter:

The real problem which will face any researcher in this specific topic is the high non-linearity of the synchronous generator dynamics [7]. Some studies concerning Fuzzy logic controller (FLC) applications in excitation controller design using fuzzy set theory have been developed before [7], [8], [9], [10].

3.1. Fuzzy logic controller structure:

In conventional control, the amount of control is determined in relation to a number of data inputs using a set of equations to express the entire control process. Expressing human experience in the form of a mathematical formula is a very difficult task, if not an impossible one. Fuzzy logic provides a simple tool to interpret this experience into reality. FLCs are rule-based controllers. The structure of the FLC resembles that of a knowledge-based controller except that the FLC utilizes the principles of fuzzy set theory in its data representation and its logic [11]. The basic configuration of the

FLC can be simply represented in four parts, as shown in Fig. 2 below:

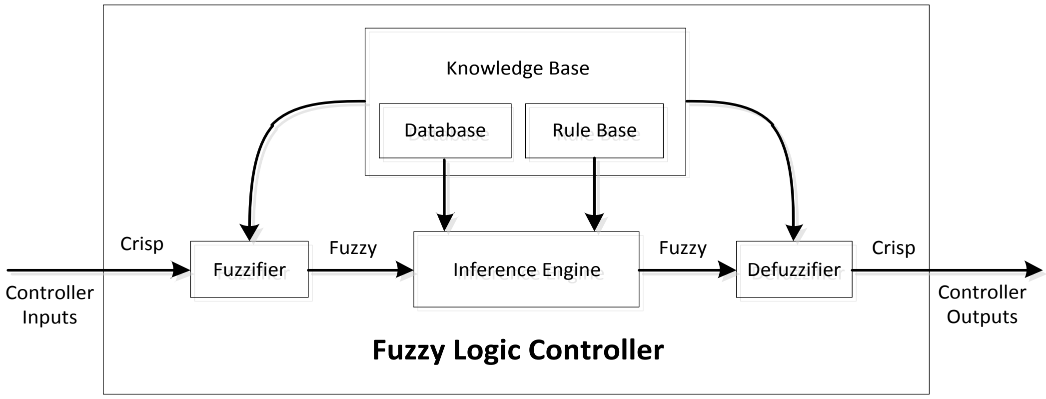

Fig. 2 Schematic diagram of the FLC [11]

Fuzzification module: the functions of which are, first, to read, measure, and scale the control variable (e.g. voltage, current) and, second, to transform the measured numerical values to the corresponding linguistic (fuzzy) variables with appropriate membership values.
Knowledge base: which includes the definitions of the fuzzy membership functions defined for each control variable and the necessary rules that specify the control goals using linguistic variables.
Inference mechanism: which is the kernel of the FLC. It should be capable of simulating human decision making and influencing the control actions based on fuzzy logic.
Defuzzification module: which converts the inferred decision from the linguistic variables back to numerical values.

3.2. Fuzzy Based proposed exciter design:

There are mainly two types of FLC; Takagi-Sugeno FLC and Mamdani FLC. The Mamdani FLC is used mainly for diagnosing, planning and for offline or slow speed systems because it involves the computation of a two dimensional shape by summing of the output memberships, which is a time consuming calculation. while the Takagi-Sugeno FLC ignores the output fuzziness and considers each output membership as a constant (singleton) resulting in a faster response of the system which makes the Takagi-Sugeno FLC superior to the Mamdani in the fast systems applications. Many researches showed that the structure of the Takagi-Sugeno FLC is more robust in the presence of noisy input data. Furthermore, when the sensitivity of both Takagi-Sugeno and Mamdani systems are tested it would be observed that the Takagi-Sugeno FLC is more sensitive in areas where there is significant imprecision in the input representation, i.e. when the fuzzy sets overlap, and this point is very helpful in designing an FLC with relatively wide range of the input signal [12].
In order to keep the controller acting for the current and the upcoming instance the controller shall not ignore any gradient of the input variables and therefore the

controller shall use Center of area (COA) defuzzification algorithm; it is the most used method although its computational complexity is relatively high [13]. The input and the output variable memberships are shown in Fig. 3.

The fuzzy rules used in this controller are Takagi-Sugeno first order rules and they are given in Table 1.

Table 1 The proposed FLC Rule Base

dV_{err} / V_{err}	PBDV	PMDV	PSDV	ZEDV	NSDV	NMDV	NBDV
PBV	PBU	PBU	PBU	PBU	PMU	PSU	ZEU
PMV	PBU	PBU	PMU	PMU	PSU	ZEU	NSU
PSV	PBU	PMU	PMU	PSU	ZEU	NSU	NMU
ZEV	PMU	PMU	PSU	ZEU	NSU	NMU	NMU
NSV	PMU	PSU	ZEU	NSU	NMU	NMU	NBU
NMV	PSU	ZEU	NSU	NMU	NMU	NBU	NBU
NB	ZE	NS	NM	NB	NB	NB	NB

The rules use only the fuzzy (And) operator between the input variable memberships which are (Error Voltage) and (Change in Error Voltage) (shown in the clear cells) to form the incident and the output memberships (shown in the shaded cells) as the consequence [11]. The control surface of the proposed FLC based exciter is shown in Fig.4.

For each instant the proposed FLC based exciter will act according to the flowchart shown in Fig. 5.

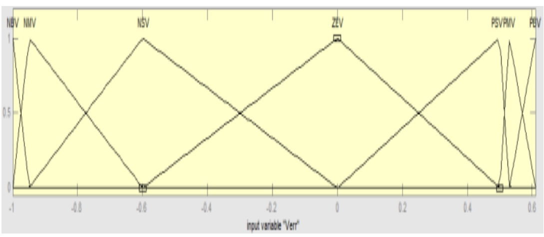

Fig. 3.a Error voltage (V_{err}) memberships (trigonometric)

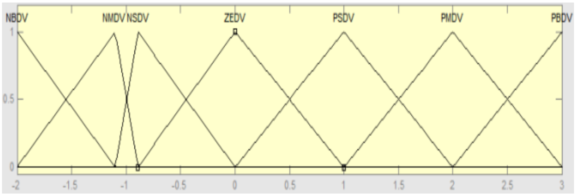

Fig. 3.b Change in error voltage (dV_{err}) memberships (trigonometric).

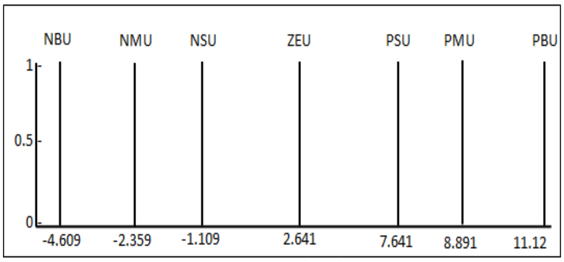

Fig. 3.c Field voltage $\left(E_f\right)$ memberships (singleton).

Fig. 3 The input and the output variable memberships of the controller. Where: NB-Negative Big, NM-Negative Medium, NS-Negative Small, ZE-Zero, PS-Positive Small, PM-Positive Medium, and PB-Positive Big.

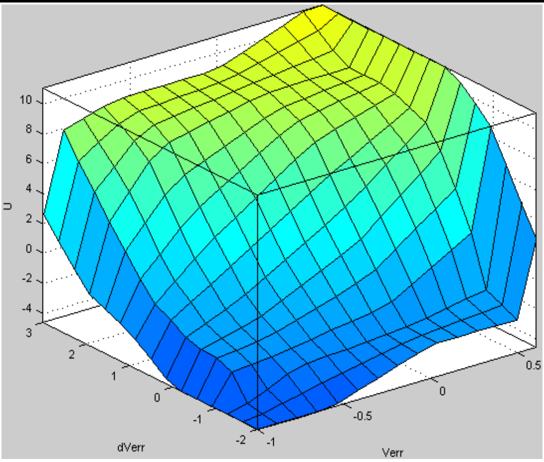

Fig. 4 The control surface of the proposed FLC based exciter

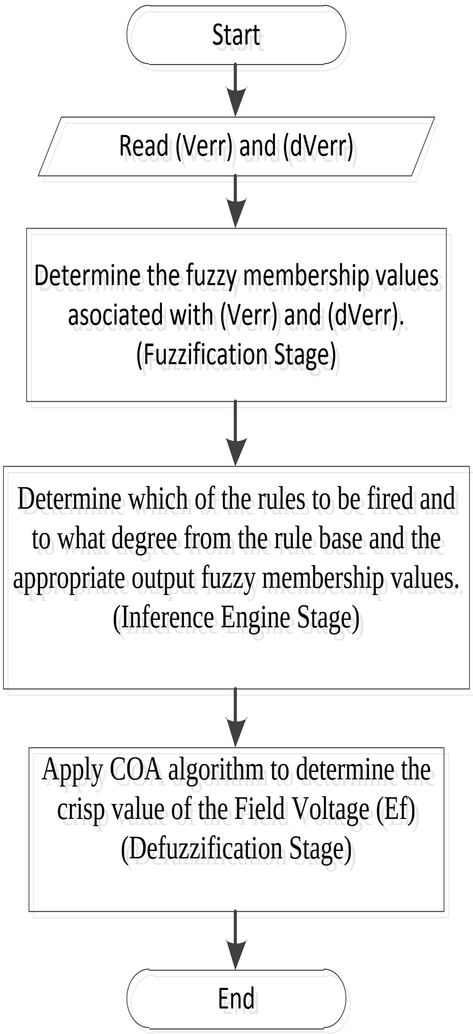

Fig. 5 The Proposed FLC based exciter flowchart.

4. Simulation and results:

The system shown in Fig. 1 will be simulated by solving the equations in section 2 using MATLAB/Simulink. The disturbance subjected to the system is a three phase solid fault on the infinite bus which will reduce the infinite bus voltage to zero, the first run will be with the field windings of the generator being fed from a conventional DC1A excitation system model [14] while the second one will be fed from the proposed fuzzy based exciter. The system will be re-subjected to the fault after 10 seconds in order to check the robustness of the exciter. The simulation also shows the Integral of Square Error (ISE) of the terminal voltage as an index of its stability. Simulink Signal Scopes were used to display and store the variable values, but in order to get clear graphs, the data stored in the (Scopes) were plotted using the (plot) command in the (MATLAB) command window.

4.1. The first run results:

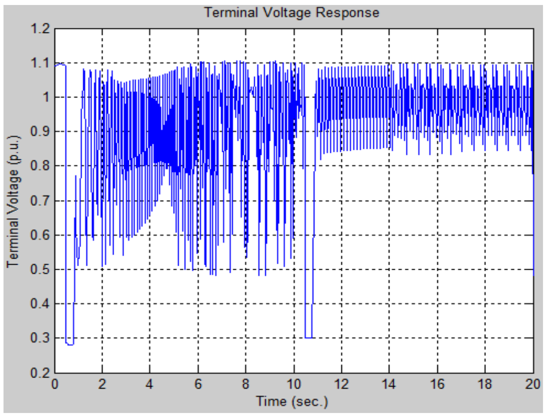

Fig. 6 The terminal voltage response of the generator.

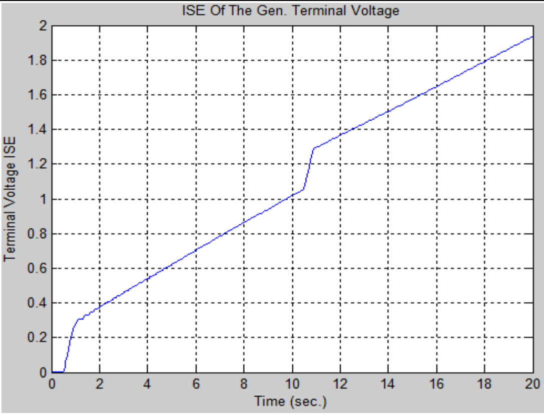

Fig. 7 The ISE of the terminal voltage response.

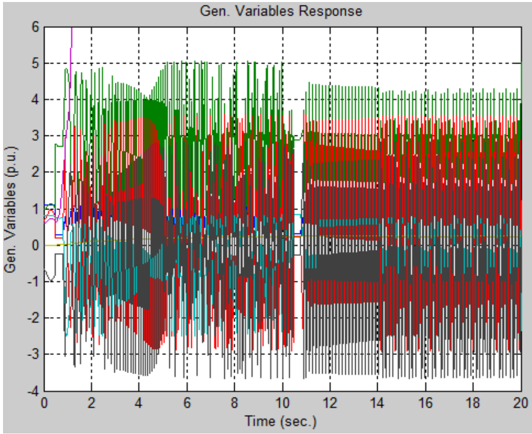

Fig. 8.a All of the generator variables.

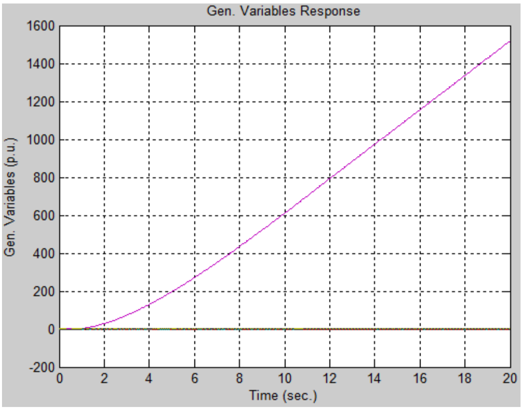

Fig. 8.b The rotor angle of the generator.

Fig. 8 The response of all the generator variables after being subjected to the fault.

4.2. The second run results:

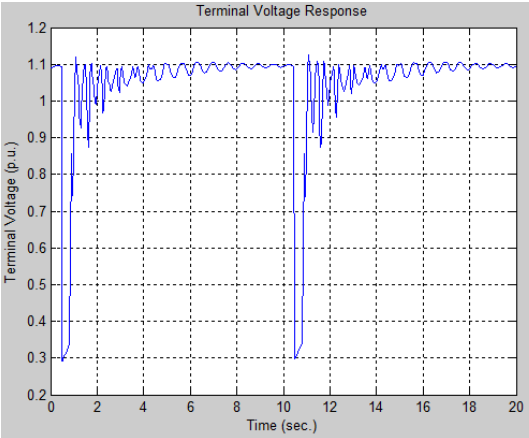

Fig. 9 The terminal voltage response of the generator.

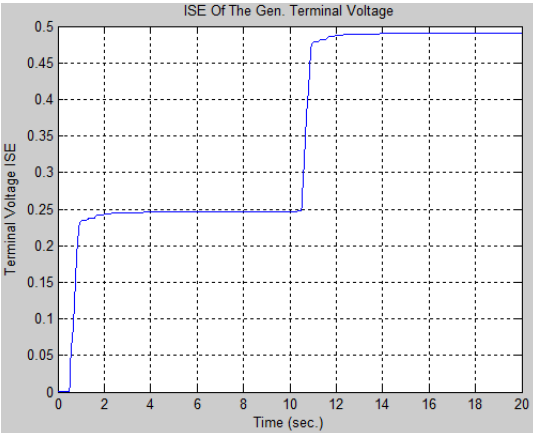

Fig. 10 The ISE of the terminal voltage response.

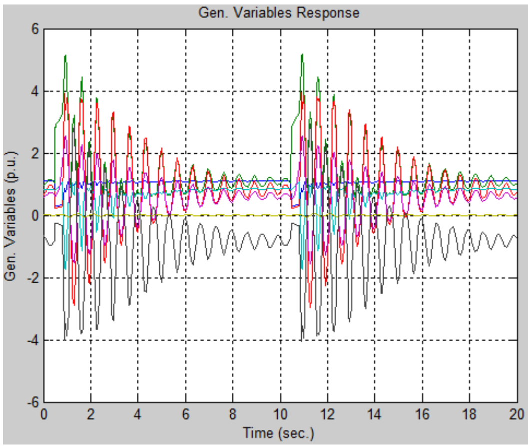

Fig. 11 The response of all generator variables after being subjected to the fault.

5. Discussion

The first run shows clearly that the conventional DC1A exciter couldn't handle the fault which leads to large scale oscillations in the terminal voltage (Fig. 6) which leads to the terminal voltage having a progressive ISE (Fig. 7). (Fig. 8.a) shows that all of the generator variables active power, reactive power and the electro-mechanical torque are oscillating without damping, while (Fig. 8.b) shows that the rotor angle goes out of order indicating that the machine had lost synchronism from the first occurrence of the fault.

The second run with the proposed exciter shows fast damping for the oscillations of the terminal voltage (Fig. 9) and stable ISE after each occurrence of the fault (Fig. 10), and (Fig. 11) shows that all of the generator variables have been damped and stabilized due to the action of the proposed FLC based exciter.

6. Conclusion

The conventional exciter in which its control action is very dependent on the generator response because of the built-in feedbackcontrol loops is unable to change the control action significantly from one distinct value to another with relatively large difference between them fast enough, i.e. has a slow controlling action and thereforeit is incapable of handling many kinds of disturbances without additional assistance from stabilizing and protecting elements.While the fuzzy controller deals with current values of the input variables, in other words, it adapts itself to the current instant which makes it faster than the conventional control feedback strategies used in the conventional excitation systems in handling sever disturbances with fast and large scale fluctuations without relying on any other stabilizing or protecting elements.

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Appendix:

Simulink blocks for the simulated system:

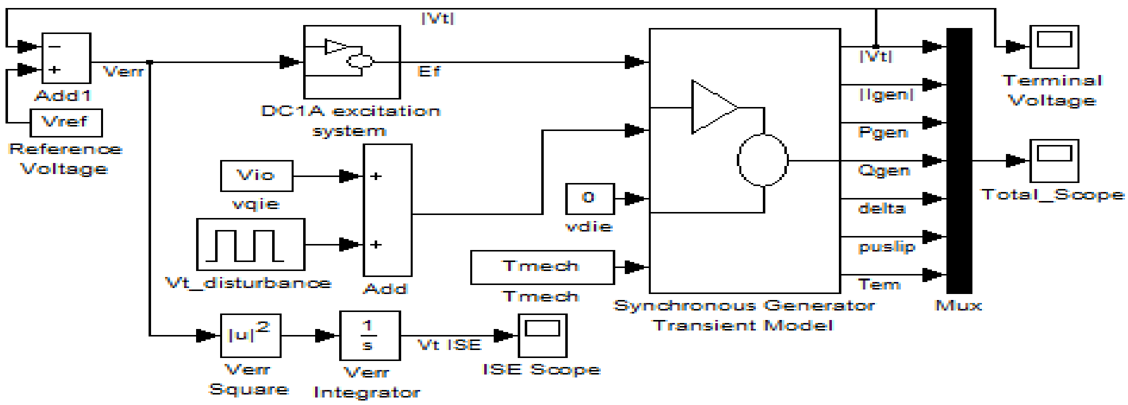

Fig. A.1 The total system with the DC1A excitation system.

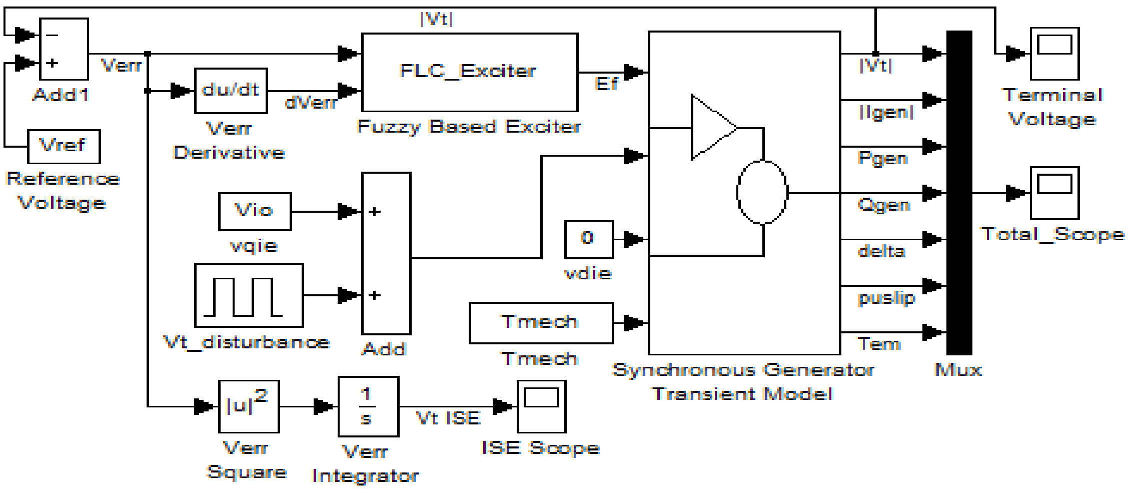

Fig. A.2 The total system with the proposed FLC based exciter.

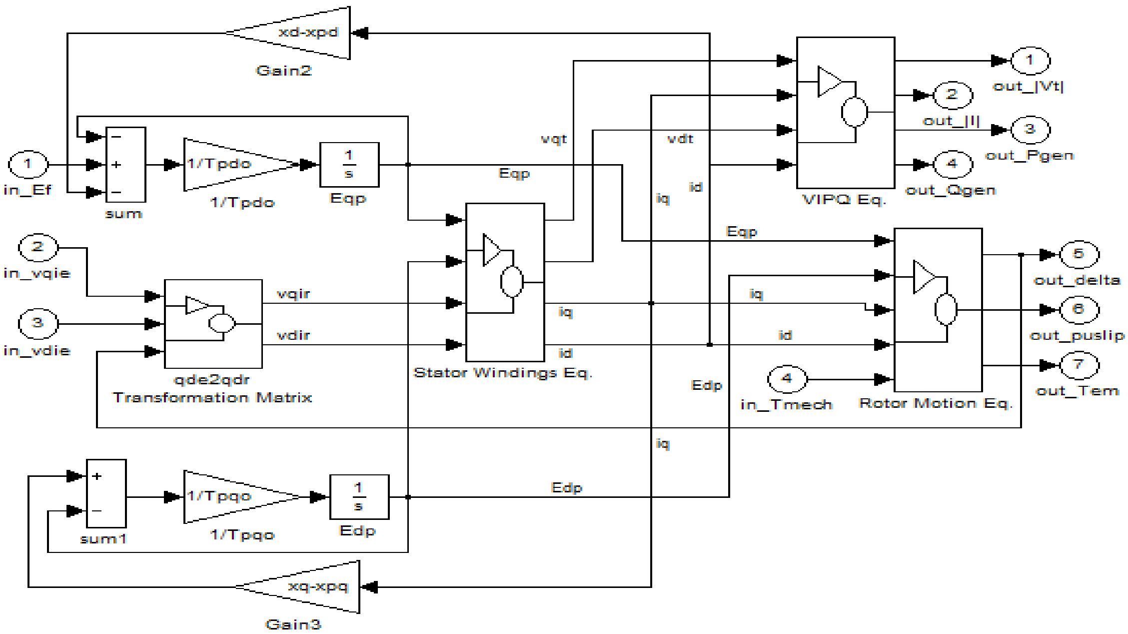

Fig. A3 Inside the (Synchronous Generator Transient Model) subsystem

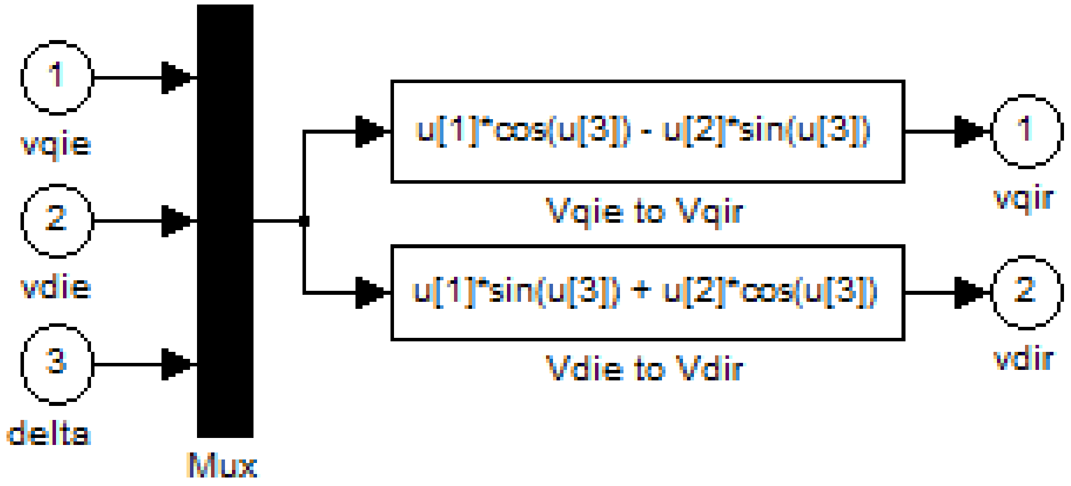

Fig. A4 Inside the (qde2qdr Transformation Matrix) subsystem

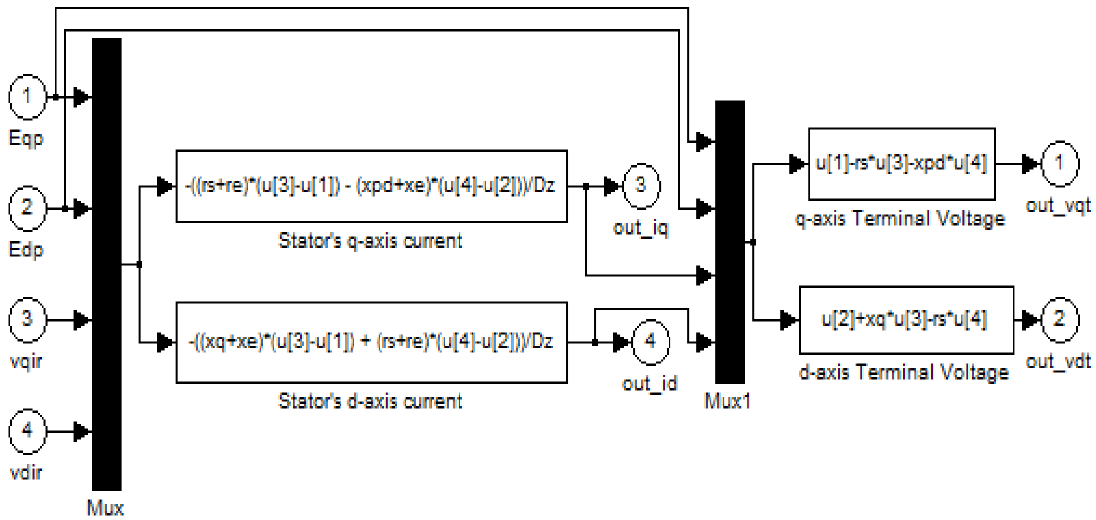

Fig. A5 Inside the (Stator Windings Eq.) subsystem

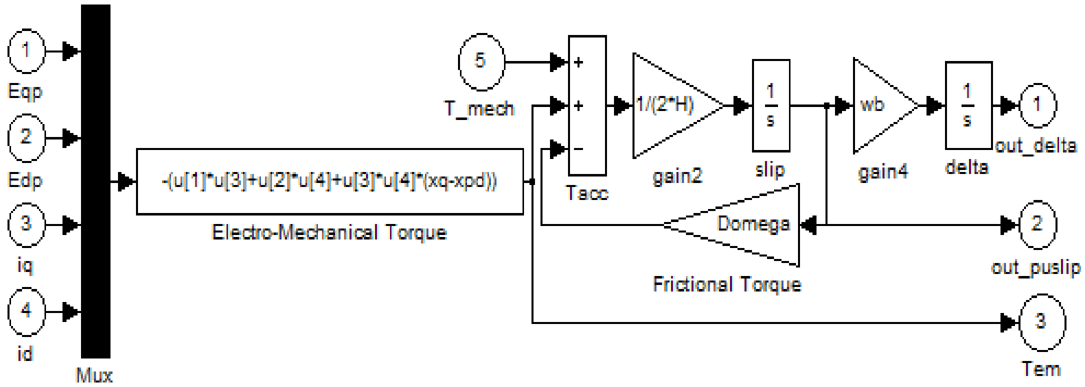

Fig. A6 Inside the (Rotor Motion Eq.) subsystem

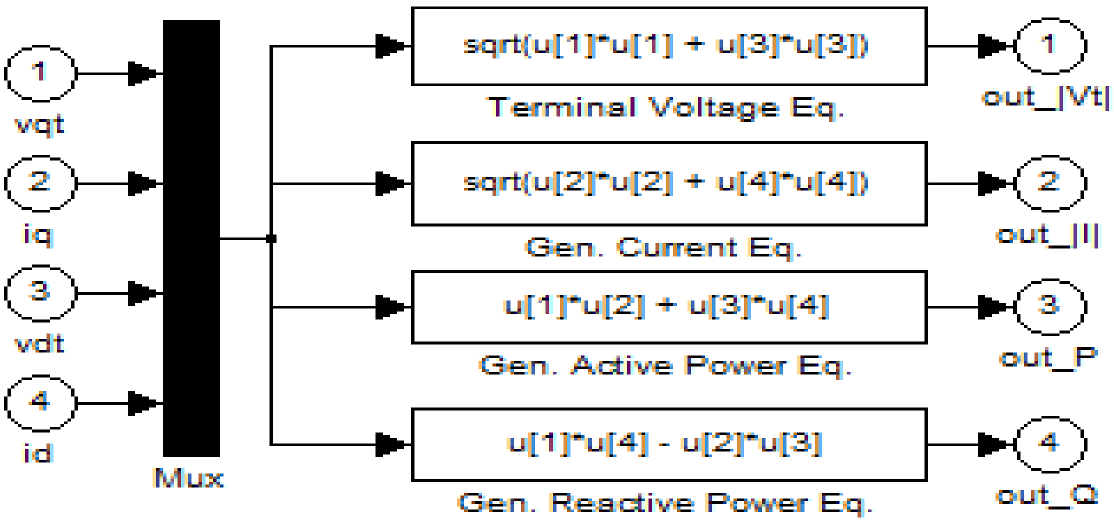

Fig. A7 Inside the (VIPQ Eq.) subsystem