Design of Robust Fuzzy Logic Power System Stabilizer

S. A. Taher, and A. Shemshadi

Abstract—Power system stabilizers (PSS) must be capable of providing appropriate stabilization signals over a broad range of operating conditions and disturbance. Traditional PSS rely on robust linear design method in an attempt to cover a wider range of operating condition. Expert or rule-based controllers have also been proposed. Recently fuzzy logic (FL) as a novel robust control design method has shown promising results. The emphasis in fuzzy control design center is around uncertainties in the system parameters & operating conditions. In this paper a novel Robust Fuzzy Logic Power System Stabilizer (RFLPSS) design is proposed The RFLPSS basically utilizes only one measurable $\Delta\omega$ signal as input (generator shaft speed).

The speed signal is discretized resulting in three inputs to the RFLPSS. There are six rules for the fuzzification and two rules for defuzzification. To provide robustness, additional signal namely, speed are used as inputs to RFLPSS enabling appropriate gain adjustments for the three RFLPSS inputs. Simulation studies show the superior performance of the RFLPSS compared with an optimally designed conventional PSS and discrete mode FLPSS.

Keywords—Controller design, Fuzzy Logic, PID, Power System Stabilizer, Robust control.

I. INTRODUCTION

ONE of the most important stability problems arising from large scale electric power system interconnections is the low-frequency oscillations of interconnected systems [1].

The frequency is of the order of a fraction of 1Hz to a few Hz. The oscillations may be sustained for minutes and grow to cause system separation if no adequate damping at the system oscillating frequency is available [1]. The oscillation is caused because insufficient damping torque in synchronous generator unit. It is well known that the overall Stability of power systems can be enhanced by applying supplementary control signals to the generator excitation control loops. The supplementary control signal is normally generated through analog circuits, commonly known as power system stabilizer (PSS) [2].

The conventional Power System Stabilizer (CPSS), a fixed parameters lead-lag compensator, is widely used by power system utilities [3]. The gain settings of these stabilizers are determined based on the linearized model of the power system around a nominal operating point to provide optimal performance at this point. Generally, the power systems are highly nonlinear and the operating conditions can vary over a wide range. Therefore, CPSS performance is degraded whenever the operating point changes from one to another because of fixed parameters of the stabilizer. The application of a power system stabilizer (PSS) for improving the stability of power systems has received much attention [3,4,5]. Fuzzy control appears to be the most suitable one, due to its robustness and lower computation burden [6]. The fuzzy logic controllers could easily be constructed using a simple microcomputer. The supplementary stabilizing signal is determined using fuzzy membership. This paper presents a Robust Fuzzy Logic Power System stabilizer (RFLPSS) for the real time nonlinear control of generator excitation. Control signal is given to sum point of AVR unit & will provide sufficient damping torque for synchronous generator unit with extra enhanced in rise time & settling time & maximum overshoot and finally robustness that makes it much suitable for interconnected nonlinear synchronous generators.

II. SYSTEM MODELING

The basic system consists from one nonlinear synchronous generator (appendix) connected by two parallel transmission lines to an infinite bus (Fig. 1). The output signal of proposed & other compared PSS(s) is given to summing point of AVR (Automatic Voltage Regulator) and finally obtained signal is given to exiting system (with IEEE type DClA exciter [7]) of synchronous generator and by regulation current of the exciter we can achieve to necessary damping torque, so oscillations will damp in settling time.
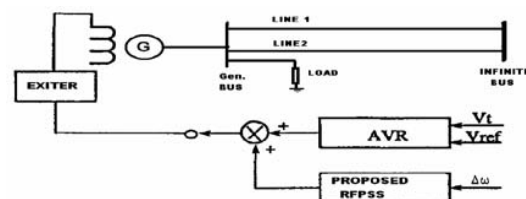

Fig. 1 Model of synchronous generator connected to infinite bus

For studying robustness and rise time (tr) and settling time (ts) and maximum overshoot (Mp) we will give Three-phase to ground fault on generator bus and transmission line outage and sudden gen. bus loading as followed in Fig. 2.
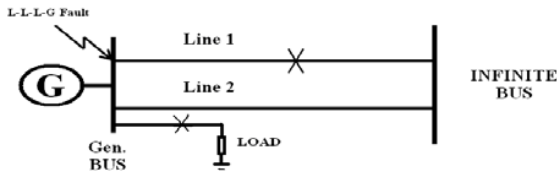

Fig. 2 Fault occurred on the bus of generator, line outage (line 1) and sudden load entrance

III. FUZZY LOGIC CONTROLLER

Fuzzy control systems are rule-based systems in which a set of so-called fuzzy rules represent a control decision mechanism to adjust the effects of certain system stimulus.

The aim of fuzzy control systems is normally to replace a skilled human operator with a fuzzy rule-based system [9]. The fuzzy logic controller provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Fig.3 illustrates the basic configuration of a fuzzy logic controller which consists of a fuzzification interface, a knowledge base (consists of data base & rule base), a decision making logic, and a defuzzification interface block applies control signal.
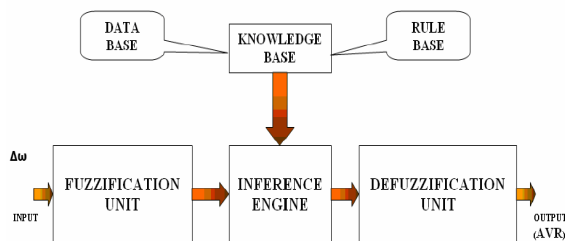

Fig. 3 Model of fuzzy controller and its blocks

IV. DESIGN OF PROPOSED RFLPSS

In this research we have developed a fuzzy controller using delay units to make a needed electrical torque in phase with the speed deviation, phase lead blocks circuits are used to compensate for the lag. In the work reported here, the Robust Fuzzy Power System Stabilizer (RFLPSS) utilizes the speed deviation, $\Delta\omega$ of the synchronous generator as the input. Three separate signals are generated from $\Delta\omega$ using time delay blocks, which are then fed as inputs to the FPSS. First and second input signals act as error and error deviation in classic fuzzy controllers design method, third input is an auxiliary signal that provides ability of more accuracy in control signal production and main reason for increase the robustness. Saturation units are added after every input signal to limit incoming signals in the range of input membership functions.

V. THE RFLPSS INPUTS

The first input U1 to the FLC comes directly from $\Delta\omega$, i.e.

$U1=\Delta\omega(t)$
$U2=\Delta\omega(t)-\Delta\omega(t-\Delta t)$
$U3=\Delta\omega(t-\Delta t)-\Delta\omega(t-2\Delta t)$

The second and third inputs U2 and U3 of the RFLPSS are derived by the application of a 'delay and sum circuits' with a delay of time (as shown above) which is tuned based on frequency of power network (here Δt=0.09 Sec.) as the third level difference of $\Delta\omega$. The RFLPSS takes all three inputs separately and amplifies them respectively via the gains G1, G2 and G3 to provide acceptable system behavior. For the current application, the gain settings resulting in a satisfactory speed response are chosen. Since the speed deviation under steady operation is zero, the nominal values of the inputs to RFLPSS are set equal to zero. The inputs to RFLPSS which are crisp numerical values are scaled between the range [-1,1] because each input membership functions is designed to accept inputs within this range. An identical range is adopted for the output membership functions. Choosing a positive and negative range to the input (as well as output) membership functions allows the RFLPSS to inject either positive or negative stabilizing signals into the excitation system. Thus, accelerating or decelerating torque, as necessary, can be applied to the rotor of the generator. The main RFLPSS design procedure mentioned earlier, via, fuzzification, rules definition, inference mechanism and defuzzification will now be discussed.

VI. FUZZIFICATION

Fuzzification is mapping from the crisp domain into the fuzzy domain. Fuzzification also means the assigning of linguistic value, defined by relative small number of membership functions to variable.

VII. INPUT MEMBERSHIP FUNCTIONS

As explained earlier, three separate inputs are created from the speed deviation and fed in the RFLPSS. The next step is to determine the number and shape of the membership functions. For this particular design, numerous membership functions were tried and the functions under consideration proved most promising. For the inputs, a total of six membership functions are used for the fuzzification. For example, the Pin1 is the positive input membership function

of the first input while Nin2 is the negative input membership function of the second input. Here, the input (antecedent) membership functions are arctangent functions describing the gaussian curve membership functions, namely, Pin (positive) and Nin (negative), one for each of the three inputs is chosen.
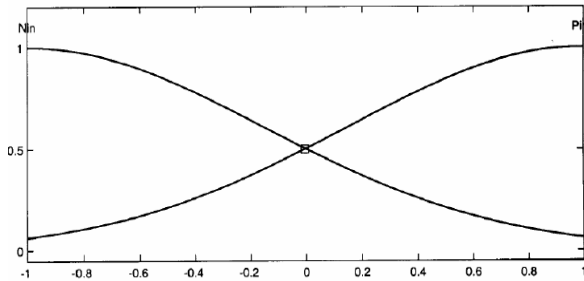

Fig. 4 Input membership functions

The input membership functions Pin and Nin are shown in Fig. 4. The membership functions for each of the three inputs are considered identical. This shape of the membership function produces an effect similar to a PID controller and compensates any large differences coming from the 1st level difference, 2nd level difference or 3rd level difference. For example, if any of RFLPSS input is large, then the RFPSS would output a large compensating signal of appropriate polarity due to the chosen shape of the membership functions. Thus, the tendency of the generator rotor would be to neither accelerate nor decelerate (i.e. maintain constant value).

VIII. Output Membership Function

For the outputs, two membership functions, namely, Pout and Nout are used for the deffuzification process where the subscript indicates the output membership function. The functions consist of two opposite sloped lines as shown in Fig. 5.
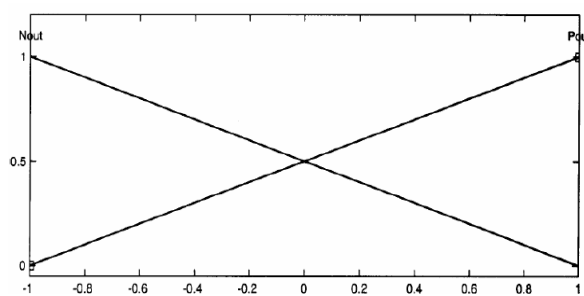

Fig. 5 output membership functions

The reason for choosing a linear relationship is because the output membership function is usually a linear representation of the input membership functions. In the design, this was accomplished using the trapezoidal membership functions. Once the membership functions are formulated, these can be used to develop the rule base.

IX. Rule Base

The designed rule base of the RFLPSS consists of the following rules:

1.If (U1 is Pin1) then (outFLC is Pout) (1)
2.If (U1 is Nin1) then (outFLC is Nout) (1)
3.If (U2 is Pin2) then (outFLC is Pout) (1)
4.If (U2 is Nin2) then (outFLC is Nout) (1)
5.If (U3 is Pin3) then (outFLC is Pout) (1)
6.If (U3 is Nin3) then (outFLC is Nout) (1)

Or in table form we have Table I.

TABLE I
RULE BASE

INPUTS	U1		U2		U3	
	P	N	P	N	P	N
OUTPUT	P	N	P	N	P	N

The inference from the rule base is altered if changing the weight of any rule is changed. In this design, each rule has been given equal importance and provided with a weight of 1. The complete RFLPSS model can be represented as shown in Fig. 5. To illustrate the working of the rule, consider for example, the 1st rule:
If (U1 is Pin1) then (out RFLSS is Pout) (1)
When U1 (i.e. $\Delta\omega$) has a value which corresponds to a certain membership degree on the Pin1 function (e.g. if U1=0.4 then Pin1»0.8). As a result, the output membership function Pout gives a corresponding fuzzy output. Similarly, other rules will also provide their fuzzy output contributions to the overall output.
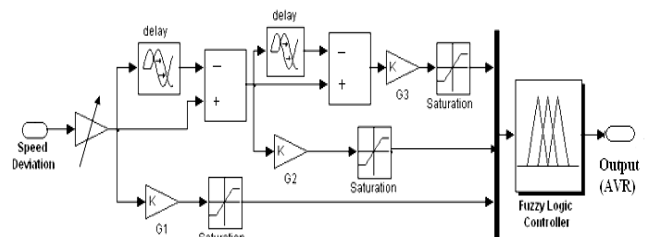

Fig. 6 block diagram of RFLPSS

X. Inference Mechanism & Defuzzification

As seen, the input membership functions Pini (i=1,2,3) and Nini (i=1,2,3) individually fuzzifies the three crisp input acting on it. The fuzzified variables then appear as inputs

to Pout and Nout membership functions.

The individual contribution coming from each rule depends on the membership functions and the type of operators used in the inference mechanism such as shape of membership functions, IF-THEN rules, implication method, aggregation method etc. In the current design, the max function is used for both implications of the inputs as well as aggregation of the individual fuzzy outputs the overall fuzzy output is then defuzzified to obtain a crisp output. The centroid method (Mamdani type (center of gravity of all outputs of the rules)) is used in this paper for defuzzification. Fig. 7 shows the overall relationship between the inputs, rules, membership functions and the outputs illustrating the process of input fuzzification and output defuzzification.

Fig. 7 Inference and defuzzification (Mamdani type)

As followed above if for example if U1=0.8 & U2=0.2 & U3=0 then output will be center of gravity of first 6 right hand surfaces which is equal with 0.135.

XI. ADAPTATION OF THE GAINS FOR ROBUSTNESS

It was observed that once appropriate gain setting of G1, G2 and G3 are chosen, the controller behaves satisfactorily in the entire region of operation without significant deterioration in performance. However, to further improve the performance and the robustness of the controller, an adaptation feature for the gain settings G1, G2 and G3 has also been incorporated. A-priori simulations are carried out to provide the values of G1, G2 and G3 for different operating conditions. Based on the operating conditions defined by Po, Qo, a set of IF - THEN statements then selects the appropriate values for G1, G2 and G3 for a particular operating condition.

XII. SIMULATION RESULTS

The system is simulated in simulik (MATLAB 7.2) and a well tuned PID (CPSS) and a discrete mode FPSS (as a robust conventional FPSS) explained in [8] are used for comparing results. System's responses for four different conditions are obtained using non-linear simulation: 1-Small disturbances (step response for increment in Pm), 2-Large disturbance (consists of line outage, L-L-L-G fault and variation in generator loading suddenly). At the first obtained results for Pm-δ (step response) are given in Fig. 7-a to Fig. 7-d that show very good and smooth response for ts, tr & Mp parameters (exact results are given in the tables beside every diagram) comparing with other controllers for given transmission line length ranges, but more important case is that RFLPSS is stable for long length lines but CPSS for l>800km & discrete mode FPSS for l>1100km are unstable this truth which is shown in Fig. 8-(a.b.c.d) is one important reason for high robustness of RFLPSS. If a line outage (line 1) occurs in T=30 sec. and for Δt=30 as shown in Fig. 9-a it is seen again the ability of the RFPSS for stabling system & of course it's better tr, Mp & specially ts .for long length lines unstability occurs for PID and discrete mode FPSS that is shown in Fig. 9-b. In the other part for constant line length (800km)three phase to ground fault is given on the generator bus ,results are given in Fig. 10-(a,b,c,d). these diagrams illustrate high robustness of proposed RFLPSS that cause stability remaining for longer line fault that comparing controllers unstable for these faults. as shown in Fig. 10-(b,c,d), additionally with suitable response quality. And finally if the generator bus is loaded by a three phase load as shown in Fig. 2 and considering four load level range (100,200,300,400MW), it is seen that RFLPSS still is robust & stable for all cases shown in Fig. 10-(a,b,c,d) with excellent response for ts & tr & Mp but PID and discrete mode FPSS have poor response quality or unstable at all. Then obtained results show high performance and robustness of proposed RFPSS.

XIII. CONCLUSION

Implementation of a Robust Fuzzy Logic controller as a power system stabilizer is described in this paper. The stabilizing signal generated by the controller is computed using a standard fuzzy membership function. The proposed RFLPSS has an advantage of high performance for ts, tr & Mp which are most important factors in control & high robustness. Extra robustness that is achieved by this controller comparing with PID (CPSS) and conventional Fuzzy PSS, makes it useful for power stations which work under small and large signal disturbances (namely input mechanical torque or probability of line outage).this controller is so very suitable for the real time control of generators because of its simple control rules and its shorter computation time because of it's few and simple fuzzy rules.

APPENDIX

Generator parameters:
1000 MW – 13800 (v) – 60 Hz – 32 pole
Silent pole - Hydraulic turbine prime mover
X_d, X'_d, X''_d = 1.305, 0.296, 0.252 (pu)
X_q, X'_q, X''_q = 0.474, 0.243, 0.18 (pu)
T'_d, T''_d, T''_{qo} = 1.01, 0.053, 0.1 (Sec.)
Stator resistance = 2.544e-3 (pu), H= 9

Governer parameters:

Ta=0.07 - Ka=10/3 - Rp=0.05 - Kp= 1.163

Ki= 0.105 - Kd=0.0 -Td=0.01

Transmission line :

R=0.01755 ohm/km L=0.8737e-3 (H)/km

C=13.33e-9 F/km

REFERENCES

[1] Juan Shi, Herron L. H. and Kalam A."*Application of Fuzzy Logic Controllerfor Power System Stabilization*", VictoriaUniversity of Technology - Australia, *IEEE TENCON '2002 ,Beijin.*.

[2] Laesen E. V. and Swann D. A. "*Applying power system stabilizers: Part I, 11 and III*",IEEE Trans., Vol.PAS-100, No. 6, 2003, pp.3017-3041.

[3] LARSEN E.V. and SWANN D.A. "*ApplyingPower System Stabi1isers*",JEEE *Trans.,PAS-100, 1981, pp. 301 7-3046.*

[4] ANDERSON P.M.and FOUAD A.A. "*Power System Control and Stability*", Iowa State University Press, Ames, Iowa, 1999.

[5] DEMELL0 F. P. and CONCORDIA C. "*Concepts of synchronous Machine Stability as Affected by Excitation Control*", *IEEE TRans., PAS-88,2001, pp. 31 6-32.*

[6] Hiyama T. " *Application of Rule - based Stabilizing Controller to Electrical Power System*", IEE Proc. C, Vol. 136, NO. 3, 1989, pp. 175-181.

[7] IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE Standard 421.5-1992.

[8] Chetty M. and Trajkoski N. "*A DISCRETE MODE FUZZY POWER SYSTEM STABILI ZER*", Department of Electrical and Computer Systems Engineering Monash University. Australia.

[9] Toliyat H. A. , Sadeh J. And Ghazi R. "*Design of Augmented Fuzzy Logic Power System Stabilizers to Enhance Power Systems Stability*", *IEEE Transactions on Energy Conversion, Vol. 11, No. 1, March 1996.*
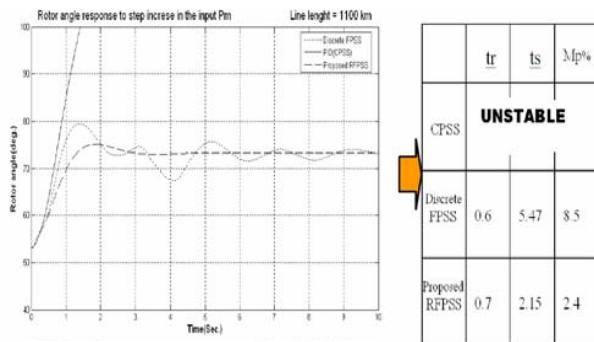
Fig. 8-a L=400 km

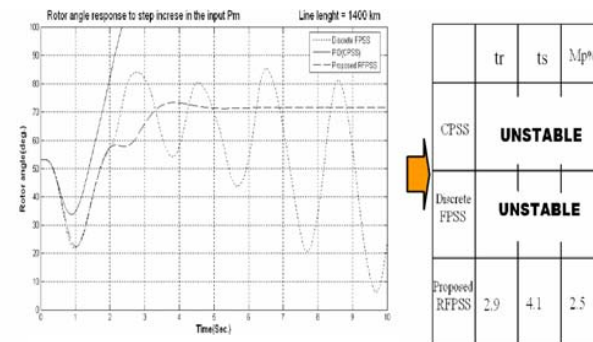
Fig. 8-b L=800 km

Fig. 8-c L=1100 km

Fig. 8-d L=1400 km

Fig. 8 rotor angle response to step increase in the input Pm for various line length
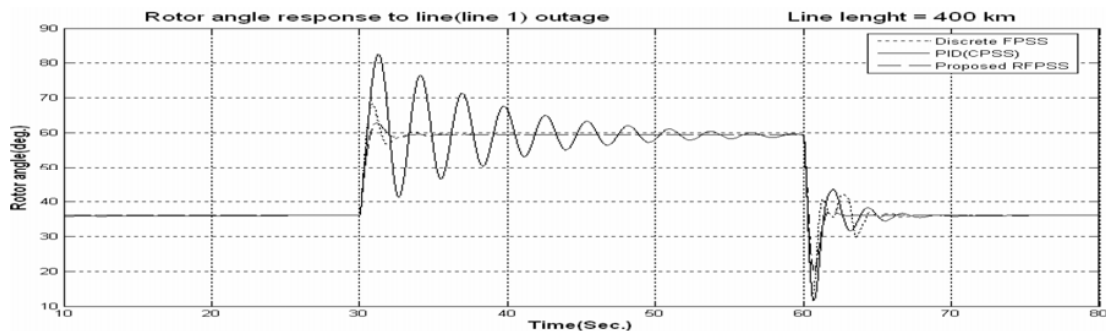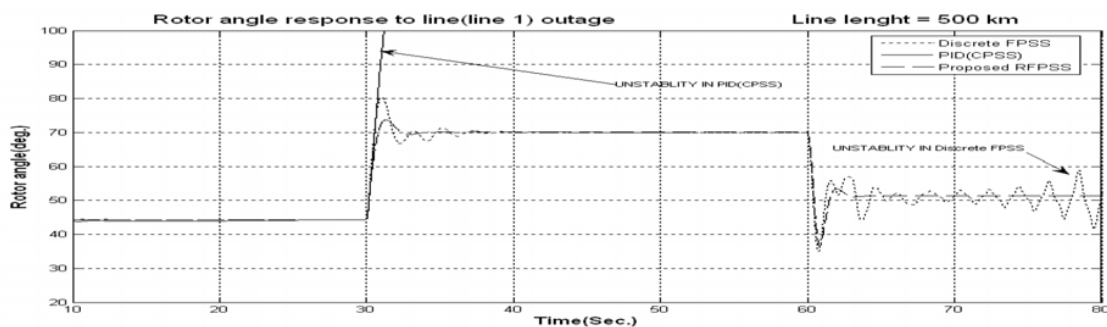
Fig. 9-a L=400 Km

Fig. 9-b L=500 Km

Fig. 9 Rotor angle response to transmission line outage for various line length
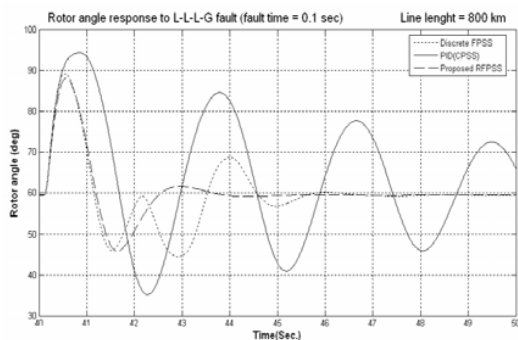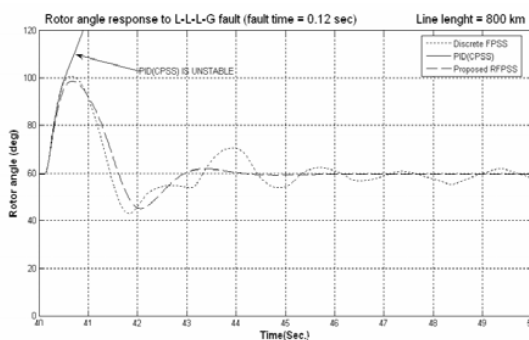

Fig. 10 (a) Fault duration = 0.10 sec.
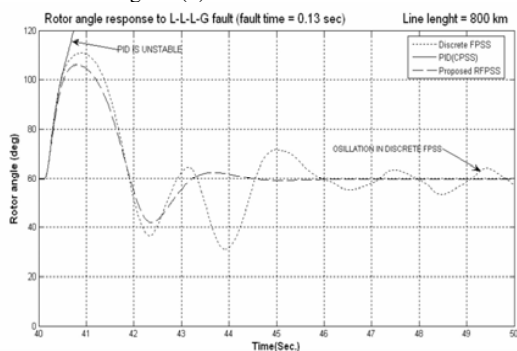

Fig. 10-b Fault duration = 0.12 sec.

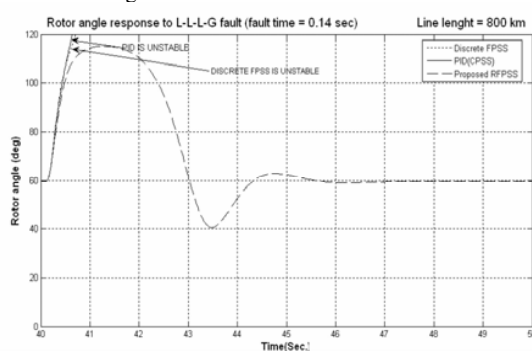Fig. 10 (c) Fault duration = 0.13 sec.

Fig. 10 (d) Fault duration = 0.14 sec.

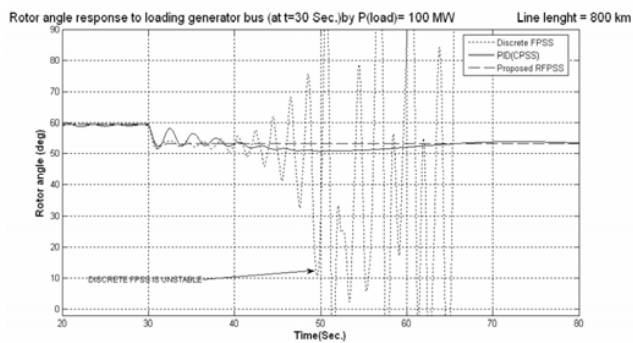Fig. 10 Rotor angle response to L-L-L-G fault for various fault times & constant line length=800km
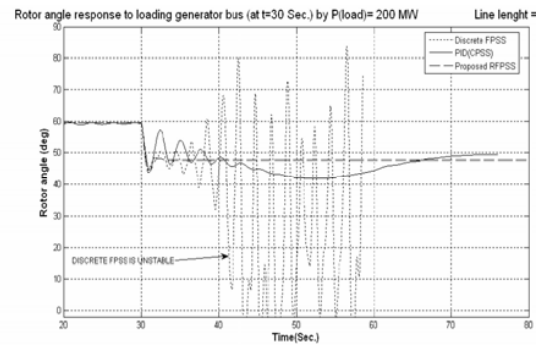
Fig. 11(a) P(Load) = 100 MW
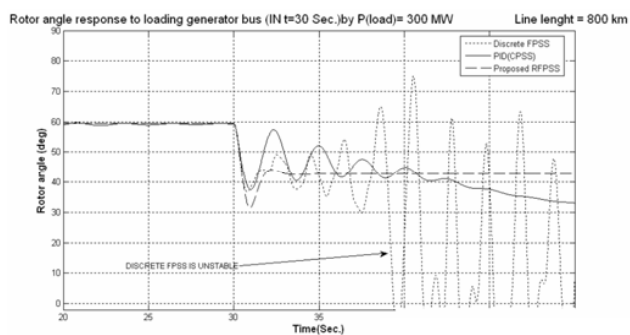

Fig. 11 (b) P(Load) = 200 MW
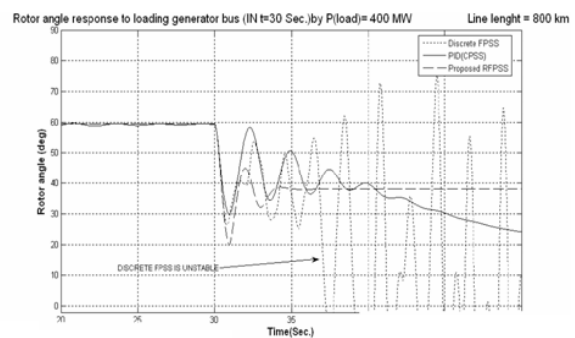

Fig. 11-c P(Load) = 300 MW

Fig. 11-d P(Load) = 400 MW

Fig. 11 Rotor angle response to loading generator bus for various load level & constant line length=800km