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Efficient Generator Tripping Approach with Minimum Generation Curtailment based on Fuzzy System Rotor Angle Prediction

***Abstract**. In this paper the transient stability of power system is improved by development of an efficient generator tripping approach. Tripping number of generators is one of the most-used technique at when a serious disturbance lurching the steady sate operation of the power system. Traditional generator tripping techniques suffered from over-tripping generators beyond the stability requirements. The instability in the power system is usually followed by some delay to be detected by the system which has been unclear for traditional tripping approaches, resulting in miss-commitment of tripping generators or unnecessary tripping. As a remedy to this, fuzzy system based rotor angle prediction is proposed to study the behavior of the fault before when the instability detected by the system. However, fuzzy system prediction has an impressive performance on nonlinear systems on which the rotor angle attitude is utterly an identical case with nonlinear characteristics. Results obtained by various and practical simulations exhibit that the stability index of the system improved by less number of tripped generators at the proper time. Simulations are conducted by MATLAB and DIgSILENT software on a 9- bus system with 3 generators to demonstrate the promised results.*

***Streszczenie.** Przedstawiono metodę poprawy stanów przejściowych i stabilności system energetycznego przez ulepszenie wyzwalanie generatora. Dla poprawy jakości tego załączania zastosowano układ logiki rozmytej bazujący na przewidywaniu kąta wirnika. (**Skuteczny system wyzwalania generatora z minimalnym ograniczeniem bazujący na układzie z logiką rozmytą z prognozowaniem kąta wirnika**)*

Keywords: Transient stability, Generator Tripping, Fuzzy System, Rotor angle, prediction.
Słowa kluczowe: stabilność system energetycznego, logika rozmyta.

Introduction

Power system stability has been one of the important issues for years. Another sense, holding the current steady-state operation mode of the system is a thorny issue which had drawn long attentions to make the better preventive and corrective actions to such matter. In fact, any abrupt violation from the system prescribed operating zone makes the whole system afflicted by the serious disturbance consequences, resulting in cascading failure to the system. As a severe case, the transient of such disturbance can make this picture even worsen. Therefore, the transient stability of the system has to be strictly maintained to prevent the whole system from falling into asynchronism [1]. Stability of the power system can also be referred to an ability of system, for a given initial operating condition, to return back to operating state equilibrium after being subjected to a physical disturbance. [1].

Different methods such as controlling the generator's excitation, generator tripping [2], fast valving, braking resistor, eliminating time, removal of charge and series capacitors have been reported to improve transient stability [3]. The combinations of said methods can be also made to provide better means for improving transient stability [4, 5].

Tripping one or more generators of one group from those connected to a common busbar, is the simplest technique for rapid changes [6] of torque's balance and it is also an effective technique to manage transient fault [7]. To make a control scheme in tripping process, one has to be able to detect the instability of system earlier, and then unleash any control action. It is known that the best way to follow up the instability of a dynamic system is by monitoring rotor angle oscillations which is greatly reflects the future mode of the system.

Transient instability usually appears as anon-continuous periodic curve that is due to insufficient synchronizing torque. It is manifested as the first swing stability. However, in the large power systems it is also possible that the transient instability occurs in the later swings, mainly relating to lack of sufficient damping torque. The most important form of the large disturbances considered in the transient stability studies includes faults that usually inject a large amount of kinetic energy to the power system [8].

The organization of this paper follows as: at first the issue of transient stability prediction is described. Then the applicability of predicting the rotor angle at generator tripping is expatiated. The proposed methodology to solve the problem is explained afterwards. Paper ends with the results and discussions followed by the conclusions to address the proposed idea.

Problem Description

The problem of transient stability can studied in two categories of evaluation and prediction [9], Transient stability evaluation usually focuses on the critical clearing time (CCT) of the power system in response to a fault. It is defined as the maximum time after occurrence of disturbance, during which if the fault is cleared, the power system can hold the transient stability [9].

There are plenty of methods reported in literature on how to look at the transient stability evaluation issue, such as numerical routines for solving the state space differential equations [10], [11], Direct Methods like energy method [12], [13], [14] catastrophe theory [15], pattern recognition techniques [16], [17], neural networks [18] and combined method of pattern recognition and neural network [19], [20].

In transient stability prediction, the CCT is out of interest. In this aspect, monitoring of the progress of power system transient is targeted when occurrence of a disturbance drew large threat to the operation. The key question in the realm of transient stability prediction is to find that the transient swings are finally become converged or not.

Generally speaking, having prediction on transient status of power system, will equip one to take the better control actions at the suitable time. For instance, as a result of this, some relay operations such as out-of-step blocking and tripping, or other control actions may start on. Moreover, by means of these predictions, the system planners can identify weak points of their power system for future developments [21].

The polynomial function expansion method[22] was proposed on which employed the first several terms in the Taylor series expansion to predict absolute rotor angles for future times. The problem arises when the number of known values is much greater than the required one for prediction. Only *n+1* known values can be used for *nth* order polynomial function. And a high-order polynomial function expansion method becomes unstable in some cases [23].

Two methods of polynomial curve fitting and cubic spline interpolation [23] have also been developed. In this sense, it was shown that the time of calculating the cubic spline interpolation method is more than the polynomial curve fitting method which is important in stability transient online evaluation. In these methods in the last several terms have lots of errors where it may even be diverged in some cases.

The numerical routines or state space techniques for transient stability prediction have found to be inefficient. These methods are computationally demanding, especially for on-line dynamic security assessment. Besides, each execution of these methods usually requires careful preparation of large input data files. The experienced operators usually raise this problem. In these methods when the execution done the rotor angle of the generators appears at the output. These rotor angles are separately evaluated. Plotting these diagrams and comparing them with each other were led to determine the transient stability status, tripped generators and islanded parts (scenario description).

As an alternative, the decision tree building algorithm [24] was developed which usually based on a statistical analysis that recursively splits the training set into regions of increasing purity in terms of class memberships. Each split corresponds to a node of the tree. Starting at the top node, the tree building process checks every split on every variable of the input vector. So, a decision tree for transient stability prediction involves many parameters e.g., rotor angles and complex input/output mapping functions. This technique usually requires tremendous processing and terminal nodes and many training samples. Besides, forecasting accuracy of the decision tree for transient stability prediction is usually limited.

It is seen that a computationally efficient method that can predict the transient stability status without requiring much input data looks worthwhile.

Generator Tripping based on Rotor Angle

Predicting transient stability status of power system aimed at better control actions to maintain stable mode of operation. In order to perform generator tripping effectively, the instability of the system has to be detected beforehand. If the synchronism is lost due to transient instability, after 2 to 3 seconds the instability can be obvious. As a lemma, the generator tripping must be done prior to when instability is triggered.

When a fault occurs, output power of generator is wildly alters while the input power is remained still constant, as a result the synchronism of the system endangered which finally may push the system into instable mode of operation.

The generator tripping has to be managed efficiently, as the production of 1 MW required voluminous amount of money and efforts and involved many technical process to run up. Meanwhile, the tripping has to be initiated at a proper time to prevent over and under tripping. For instance, if the system is strong enough to withstand the fault there would be no machine tripping. Assuming the situation where the generator tripping triggered in unsuitable time. As a consequence, the rotor angle deviation becomes more and more, requiring additional generators to be tripped as a way to recover stability. However, prediction of rotor angle can provide one with better plan on generator tripping. It meant the least number of generators would be blown off. It is known that a generator falls into instability if the change of rotor angle outpaced 180°.

Fig. 1 presents a typical fault which has a fault occurrence time of 0.016 sec,fault clearance time of 0.105 sec. It can be seen that the proper time of generator tripping was found to be at 0.128sec while the instability detected at 0.878 sec which shows a delay from clearance time. It brings one to the point that the generator tripping must be triggered at shorter time after fault clearance and right before instability detected. This is the case if one has applied a predictor on the rotor angles. Further, prediction of instability leads the least amount of generator tripping which is calculated based on rotor angle.

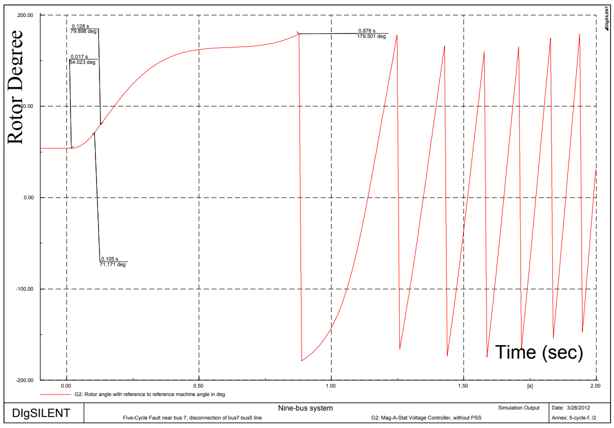

Fig. 1.Timing subsequence of rotor angle

Fuzzy Based Control System Design

Look-up table based fuzzy system

By assuming a pair of input – output (x_o^p, y_o^p) where p = 1,2 , …, N and

(1) $$x_o^p \in U = [\alpha_1, \beta_1] \times \ldots \times [\alpha_n, \beta_n] \subset R^n$$

(2) $$y_o^p \in V = [\alpha_y, \beta_y] \subset R$$

The objective is to design the fuzzy system of f(x) according to input – output pair. Toend objective, following algorithm was employed [25]:

Step 1: Definition of fuzzy set

For each $[\alpha_i, \beta_i]$ where i= 1, 2 , ….. , n. N_i the fuzzy systemis defined as A_i^j where i = 1, 2, … ,N_i as similar for $[\alpha_y, \beta_y]$,N_y the fuzzy systemis defined as B^j where j = 1, 2, … ,N_y.

The fuzzy sets for each $x_i \in [\alpha_i, \beta_i]$ must be a A_i^jat where there should be$\mu_{A_i^j}(x_i) \neq 0$

Step 2: Producing rule

For each input–output pair,$(x_{o1}^p, \ldots, x_{on}^p; y_o^p)$, membership of x_{oi}^p (i=1,2,…,n) in fuzzy sets A_i^j and membership of y_o^p in fuzzy sets B^l are defined accordingly. In other words calculating the $\mu_{A_i^j}(x_{oi}^p)$ and$\mu_{B^l}(y_o^p)$.

Step 3: Specialty of degree to produce rule in previous step. Degree can be defines as:

(3) $$D(\text{rule}) = \prod_{i=1}^{n} \mu_{A_i^{j*}}(x_{oi}^p) \mu_{B^{l*}}(y_o^p)$$

Step 4: Formation of fuzzy rule base.

Step 5: Creating a fuzzy system according to fuzzy rule base.

Fuzzy system prediction

The problem of prediction is when the given values of $x(k), x(k-n), x(k-2n), \dots, x(k-mn)$, where n, m are positive numbers, therefore the expression of $k-mn$ must be positive, and $x(k+n)$ should be predicted. By means of the objective of monograph determination which is obtained from $[x(k), x(k-n), x(k-2n), \dots, x(k-mn)] \in R^n$, to $[x(k+n)] \in R$. This developed fuzzy system monograph is based on input–output data.

Let $x(1), x(2), \dots, x(k)$ are given. The k-n input-output pairs are then constructed as:

$$[x(k-n), \dots, x(k-1), x(k)]$$

.

(4) $$[x(1), \dots, x(n), x(n+1)]$$

These input–output pairs are used to design a fuzzy system f(x) which is called the look-up table technique. Therefore f(x) is used for predicting of $x(k+n)$. Input of f(x) is $[x(k-mn), \dots, x(k)]$ and output is $x(k+n)$.

Fuzzy based rotor angle prediction

In this section,it is intended to predict the nonlinear swing curve of rotor angle which is expressed by:

(5) $$M\frac{d^2\delta}{dt^2} = P_m - P_e = P_a$$

where δ, P_m, P_e, M are rotor angle, mechanical power, electrical power and inertia coefficient respectively.

In order to curb the rotor angle nonlinearity and very rapid changes, the fuzzy system should be designed in a way that more training can now be held. It is also imperative to reduce previous time data on the system output. However, this system will have two separate parts on which one of them perform prediction and the other subsystem used for training. The proposed subsystems exploit the look-up table and prediction is also based on previous data from input–output pairs. Moreover, the fuzzy system is designed by multiple Fuzzy Inference Engine, singleton Fuzzifier and center average Defuzzifier. For each pair, the membership used looks like Fig. 2.

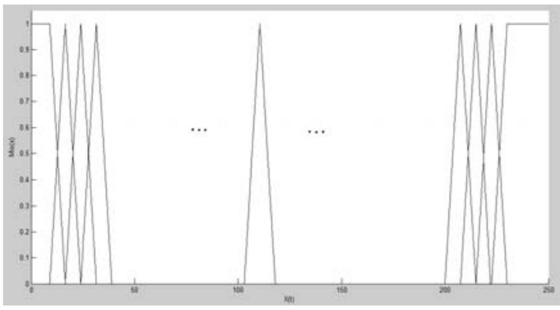

Fig. 2. Membership for each input variable

The fuzzy system must export the order of generator tripping with prediction of rotor angle after fault clearance those caused a serious turbulence and risk of instability. To diagnose these types of fault,lots of methods have been introduced.

As an overall picture, the procedures of training and predicting the fuzzy subsystems can be expressed as following steps:

1. Subsystems 1 and 2 train with times previous data.
2. Subsystem 1 predicts the oscillation of rotor angle in (*T1+k)*for each sample until when it reaches*T1* and subsystem 2 trained from online data.
3. Subsystem 2 predicts the oscillation rotor angle in (*T2+k)* in each sample until when reaches*T1* and subsystem 2 trained from online data.
4. *T1=T1+step_time*, *T2=T2+step_time* (step_time=cte)
5. Returning to the step 2

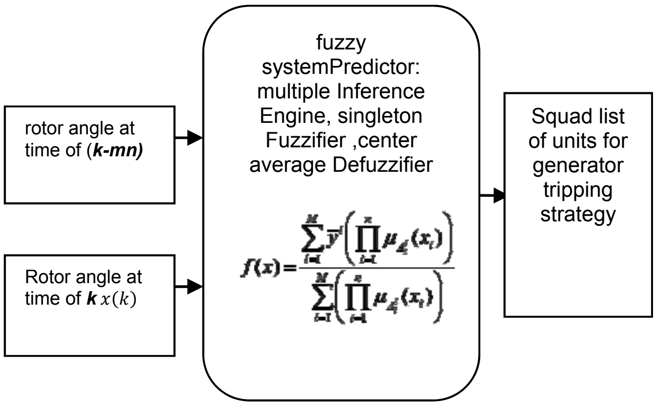

Fig. 3. Fuzzy system

Simulation Results

Analyses were conducted on 9-bus, 3-genrator unit and 6-line system, shown in Fig 4.DIgSILENT and MATLAB software have used to present the proposed algorithm. In this sense, the fuzzy controller available in MATLAB was integrated into DIgSILENT software to cover the proposed approach wholly.

The proposed Fuzzy control structure was drawn in Fig. 3. In this case, the number of membership functions for fuzzy system is found by trial and error which was equal to 6, and in the form of triangle. The fuzzy rules will be fixed and equal to 36 as the number of rules which are defined when the controller was designed. Followings are the simulation results for two type of rotor angle predictor by aid of fuzzy system.

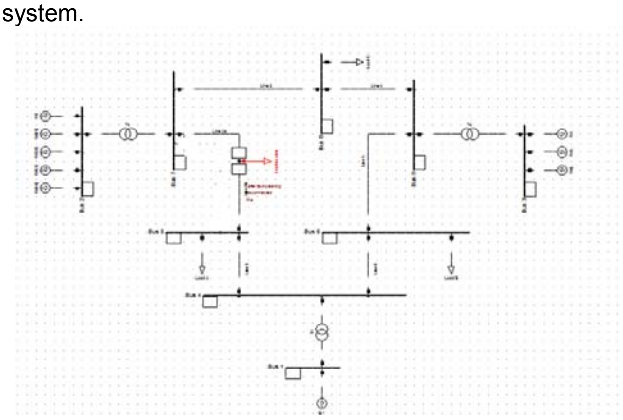

Fig. 4. single-line diagram of studied network

Table 1. Constant values of generators

unit	Number Of machine	H (s)	X'_d (P.U)
1	1	4.775	0.15
2	5	5×0.354	$\frac{1}{5}$×1.15
3	3	3×0.583	$\frac{1}{3}$×0.69

Assumption: machine 1 as a slack unit with voltage of $1.04\angle 0^0$. System's specifications are given in Table 1.

Case I: Fault is 3-phase, occurrence time = 0.01 sec, clearance time = 0.11 sec and 500m away from 7–bus:

The simulation results are shown in Fig.5 and Fig. 6 for both of generators 1, and 2 respectively. The rotor angle prediction has been monitored and pertinent error prediction for both units are calculated upon.

Based on the obtained results, the mean squares error for generator 1 is 7.77 and for generator 2 is equal to 3. 44 degree.

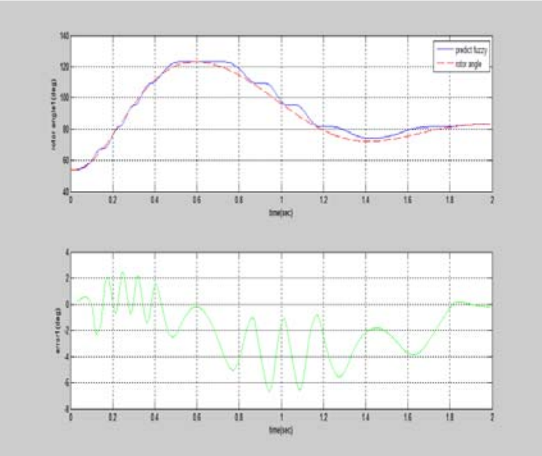

Fig. 5. A) Rotor angle and rotor angle prediction for generator 1 B) prediction error

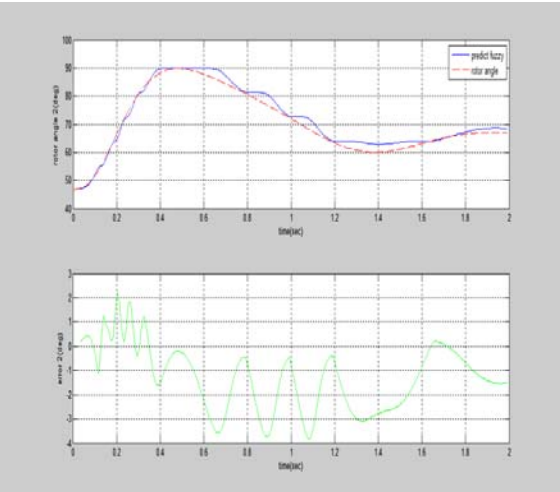

Fig. 6. A) Rotor angle and its prediction for generator 2 B) prediction error

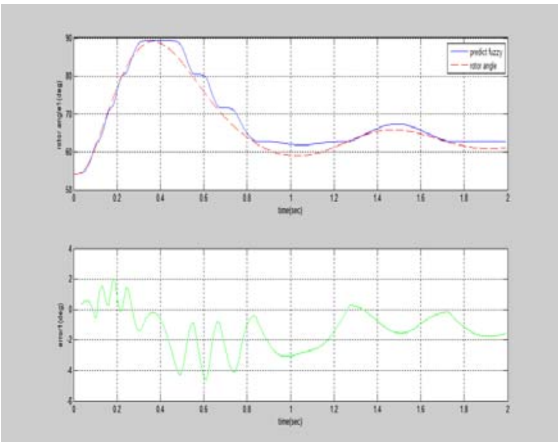

Fig. 7. A) Rotor angle and its prediction for generator 1 B) Error of prediction

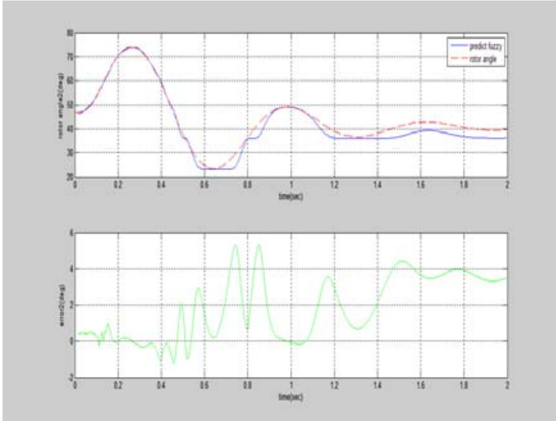

Fig. 8. A) Rotor angle and its prediction for generator 2 B) Error of prediction

Case II: Fault is 3-phase, occurrence time= 0.01 sec, clearing time = 0.1 sec, 500m away from 78 –line:

The results are demonstrated in bellow Fig. 7 and Fig. 8.

The mean squares error for generator 1 is 3.46 and for generator 2 is equal to 6.35 degree.

It is important to say that the best time to perform the proposed fuzzy based generator tripping control is when the instability has become completely clear. In this point, efficient number of tripped generator can be attained without any interruption.

As an example, let a 3-phase fault with occurrence time of 0.01 sec, clearance time of 0.15 sec happened at 200 m from 7–bus, using rotor angle fuzzy prediction, Fig. 9 shows that the system will be instable unless generator tripping comes to the picture.

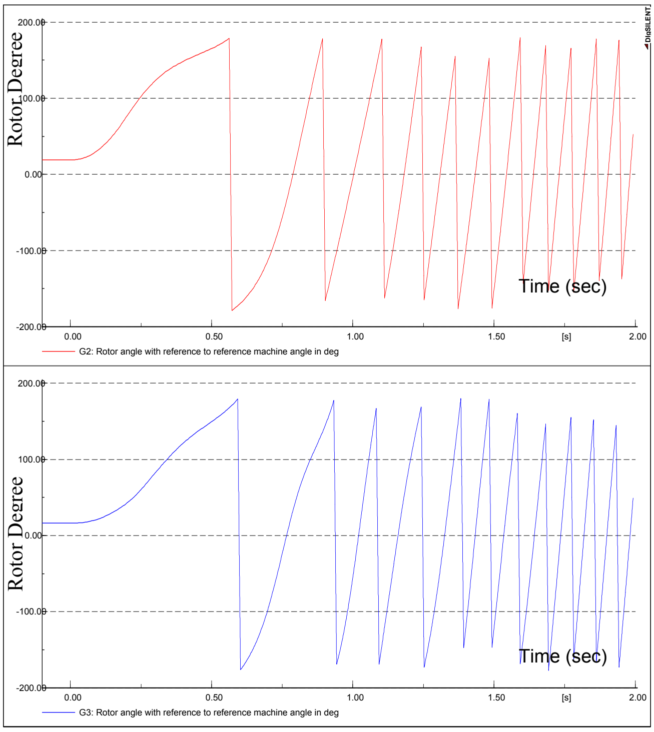

Fig. 9. Rotor angle after occurring fault

a) Without fuzzy predictor:

If one neglects the fuzzy prediction, as mentioned earlier, the instability of the system has to be detected first. In this case, instability detected at 0.563 sec therefore at this time generator tripping is triggered. Fig.

10 shows that though tripping one generator at this time would be inadequate and system still lies on instable mode.

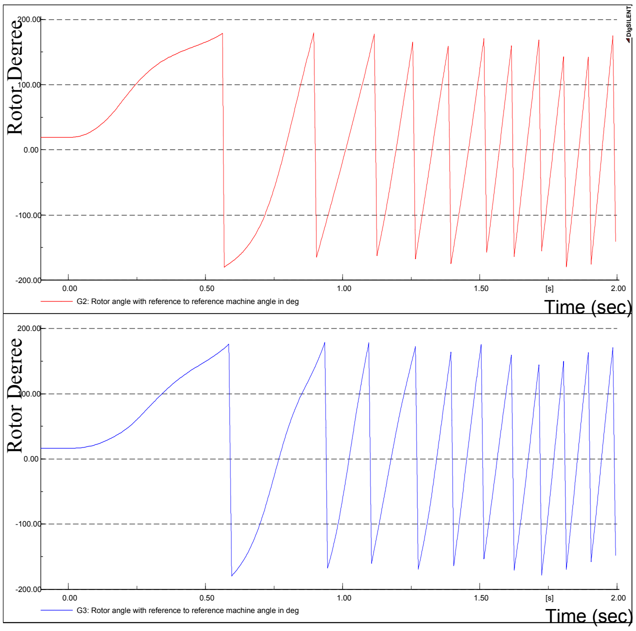

Fig. 10. Rotor angle after tripping the generator 2 without fuzzy predictor

To improve stability, at the time of 0.563 sec, more generators required to be tripped. With tripping 4 generators system will be healed up. Fig. 11demonstrates how tripping 4 generators without use of fuzzy predictor can still hold up the stability of the system.

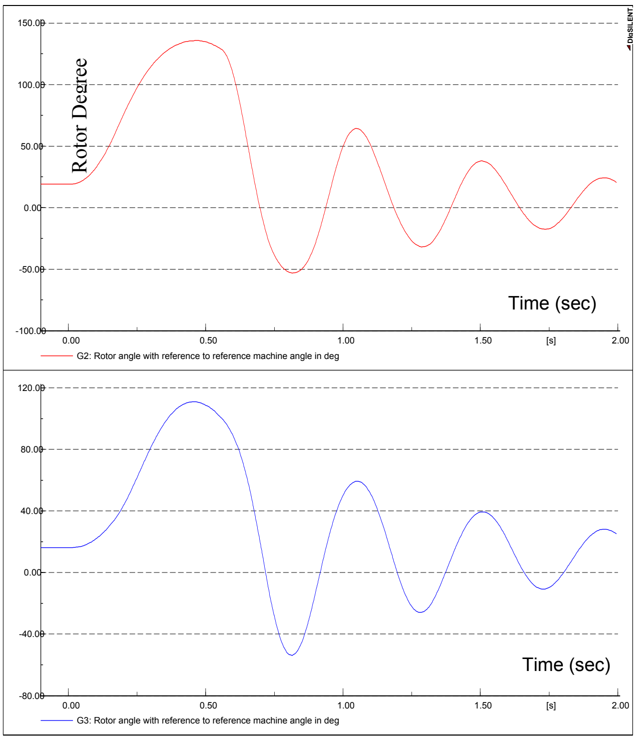

Fig. 11. Rotor angle after tripping 4 generators from plant 2 without fuzzy predictor

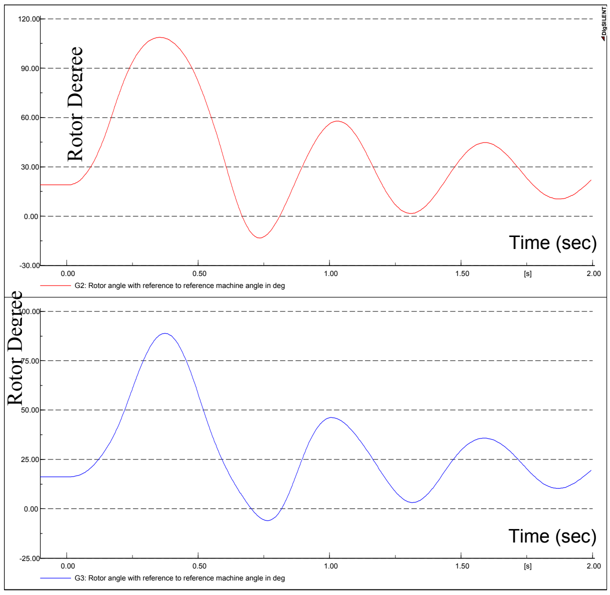

Fig. 12. Rotor angle after tripping one generator from plant 2 with fuzzy predictor

b) With predictor fuzzy system:

If fuzzy predictor used integrated with generator tripping, it may result in preventing instability with minimum plan of generator tripping at the proper time. If the synchronism is lost within transient instability, instability will be popped up few cycles following a severe fault. In this sense, the generator tripping must be done before outbreak of generator instability. In this example, instability detected at 0.563 sec whereas for many instants the system was instable. To avoid total instability previously prescribed additional generators to be tripped. Using fuzzy predictor led one to anticipate the instability several cycles before power system became instable. As a result, with less tripped generators, the system returns back to the initial stable point.

In this simulation, fuzzy system predicts rotor angles which found to be instable at 0.563 sec. tripping at 0.16 (a moment after fault detected) replaced by 0.563 sec. Consequently, one generator was tripped to prevent instability. Fig. 12 shows how fuzzy predictor made the generator tripping quite efficient with only one generator and the system withstands against the given fault in such a robust manner.

Conclusion

In this paper, a fuzzy system used to improve the traditional way of performing generator tripping, aimed at enhancing the transient stability of the power system. Generator tripping has been widely used but over-tripping of the generators has also been reported by many cases. As an alternative, a fuzzy logic based generator tripping was proposed. It enabled the system to predict the instabilities before when it really appeared to the system. This issue has long suffered the conventional tripping approaches. The proposed fuzzy based rotor angle prediction has boosted the conventional tripping approach with robust control actions and minimum number of tripped generators at the right time. The improvement in transient stability as well as obtained results demonstrate the effectiveness of the proposed technique which can offer plenty of opportunities for system planner to make use of this efficient approach.

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