Prediction and Enhancement of Power System Transient Stability Using Taylor Series

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***Abstract*—Timely information about behavior of a power system is important for monitoring and controlling the system. Accurate and prompt transient stability prediction is an effective way to reduce the risk of a power system failure and possible blackouts. In this paper, a method for predicting the generators behavior using Taylor Series has been derived that can be used to predict the angular changes during transient oscillations and thus the related critical clearing time. The paper also discusses the application of this approach for preventive control actions. The proposed technique is applied on IEEE 39 bus test system and the advantages, efficiency and error comparisons are presented.**

***Index Terms*—Braking Resistor, Prediction, Transient Stability Enhancement, Transient Oscillations, Preventive Control.**

I. Introduction

One of the main objectives of power systems is to deliver stable, reliable, and high-quality power to customers. The quality of delivered electrical power and safety of electrical facilities are related to the nominal system frequency [1], [2]. System reliability is tested with respect to three criteria, the: (N-1) feasibility, voltage stability, and transient stability [3]. Transient Stability of a power system refers to the study of a power system behavior after the system undergoes a large disturbance. A disturbance creates substantial power imbalance between generated power and network demand. Consequently, oscillations happen in the system, making generators angles to swing, and the system to lose its normal condition. In severe cases these oscillations can lead to a local or global blackout.

Stability of a system depends on the initial operating condition, the nature of the physical disturbance, and the duration of the disturbance even though the study mainly focus on post-disturbance scenarios of the system. It should be noted that post-disturbance stable state may be different from pre-disturbance operating point, depending on the sequence of the disturbances, and the controllers actions [3], [4]. So, the transient stability problem is the study of the stability of the post-disturbance system. Therefore, predicting the behavior of the system helps designing controllers to have better actions that can prevent a system from collapse and possible blackouts. Predicting and controlling the behavior of modern interconnected power systems has a major impact on the economy and national security [5], [6].

Different approaches and studies are reported in the literature for predicting and enhancing transient stability of large power systems. In [7], it is mentioned that various methods, such as hybrid neural network with optimization, wavelet neural network, echo state network are used for predicting the output of a wind generator. A new transient stability prediction method, combining trajectory fitting (TF) and extreme learning machine (ELM) based on two-stage process, is proposed in [8]. In [9], a data-based method for transient stability prediction by using data pre-processing is presented. Ref. [10] uses Taylor Series expansion to find the state space model of the linearized model of a voltage control voltage source inverter (VCVSI).

For enhancing transient stability, different methods, such as fast valving of steam stream in turbines, tripping generators, using braking resistors, and controlled opening of tie lines are mentioned in [11], [12]. In [13], using dynamic programming in a discrete supplementary control for transient stability enhancement in a multi-machine power system is discussed. Ref. [14] proposes an optimal controller for Static Var Compensators (SVCs) to improve transient stability of a power system. In [15], direct feedback linearization (DFL) technique is employed to control excitation system and fast valving actuators to improve transient stability. In [16], an approach based on Hybrid neural network-optimization to take preventive control actions for enhancing transient stability is reported. In [17] a hybrid direct and intelligent method of real-time coordinated wide-area controller for improved power system transient stability has been presented. Ref. [18] uses generation rescheduling to enhance system stability. Ref. [1] presents a new approach for improving transient stability, using the concept of the potential energy terms of energy function. In [19], a hybrid method based on offline analysis method of generator tripping for transient stability enhancement is presented. In [20], the application of a close-loop wide-area decentralized power system stabilizer for transient stability enhancement is investigated.

In this paper, using piecewise linearization and Taylor Series, the behavior of system generators is predicted, which helps finding critical clearing time and angles. Finding them makes it possible to take necessary control actions in order to prevent the system collapse. In this paper, after predicting the critical clearing time, a braking resistor is used to prevent lose of synchronism in the system. The method has been tested on IEEE 9 bus and IEEE 39 bus test systems, and results are provied and compared with numerical methods. The rest of the paper is organized as follows: In section II, the proposed method is discussed. Section III shows an illustrative example of the proposed architecture. Section IV discusses a general prediction methodology for a multiple machine system, and Section V discuss the prediction of generators angle and speed for IEEE 39 bus system. Section VI illustrates and application and section VII concludes the paper.

II. Proposed Method for Predicting Generators' Behavior

Phasor measurement units (PMUs) are devices that provide real-time phasor measurements at those locations of a power

system network where they are placed. Due to advancements in the field of relay technology, digital relays can now act as PMUs, which has significantly reduced the cost of PMUs [21], [22]. In what follows, it is assumed that there are PMUs or digital relays at all generator buses, which is a realistic assumption.

Let the dynamics of generators is modeled using (1) and (2).

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} + D\omega = P_m - P_e \tag{1}$$

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{2}$$

where ω_s is the synchronous speed, which is equal to 1 p.u. Let $\frac{2H}{\omega_s} = M$. So $M = 2H$. Then (1) can be presented as

$$M\frac{d\omega}{dt} + D\omega = P_m - P_e \tag{3}$$

Assume that the behavior of the system between any two consequent time steps is linear. This is a valid assumption since the waveform of any stable power system variables are analytic functions, except at switching moments. Hence, Taylor series can be used to linearize the system dynamics, and δ and ω can be expanded as

$$\delta(t) = \delta(0) + \delta^{'}(0)t + \delta^{''}(0)\frac{t^2}{2!} + ... + \delta^{(n)}(0)\frac{t^n}{n!} + ... \tag{4}$$

$$\omega(t) = \omega(0) + \omega^{'}(0)t + \omega^{''}(0)\frac{t^2}{2!} + ... + \omega^{(n)}(0)\frac{t^n}{n!} + ... \tag{5}$$

Neglecting terms with order higher than two, and considering t_0 as the initial point,

$$\delta(t_0 + \Delta t) = \delta(t_0) + \delta^{'}(t_0)\Delta t + \delta^{''}(t_0)\frac{\Delta t^2}{2!} + O(\Delta t^3) \tag{6}$$

$$\delta(t_0 + \Delta t) = \delta(t_0) + \omega(t_0)\Delta t + \omega^{'}(t_0)\frac{\Delta t^2}{2!} + O(\Delta t^3) \tag{7}$$

$$\omega(t_0 + \Delta t) = \omega(t_0) + \omega^{'}(t_0)\Delta t + \omega^{''}(t_0)\frac{\Delta t^2}{2!} + O(\Delta t^3) \tag{8}$$

where $O(\Delta t^3)$ represents neglected terms. From the swing equation we know

$$M\frac{d\omega}{dt} = P_m - P_e - D\omega = M * a(t) \tag{9}$$

Assuming a linear behaviour for the system between two consequent moments. Then

$$dt = \Delta t = One \;\; Time \;\; Step \tag{10}$$

So:

$$M\frac{\Delta\omega}{\Delta t} = P_m - P_e - D\omega \tag{11}$$

$$M\Delta\omega = (P_m - P_e)\Delta t - D\omega\Delta t \tag{12}$$

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{13}$$

$$\frac{d\delta}{dt} = \frac{\Delta\delta}{\Delta t} = \omega \Rightarrow \Delta\delta = \omega\Delta t \tag{14}$$

$$\Rightarrow M\Delta\omega = (P_m - P_e)\Delta t - D\Delta\delta \tag{15}$$

$$\Delta\omega = (\frac{P_m - P_e}{M})\Delta t - \frac{D}{M}\Delta\delta \tag{16}$$

$$\omega(t_0 + \Delta t) = \omega(t_0) + (\frac{P_m - P_e}{M})\Delta t - \frac{D}{M}\Delta\delta \tag{17}$$

$$\delta(t_0 + \Delta t) = \delta(t_0) + [\omega(t_0)\Delta t + (\frac{P_m - P_e}{M} - \frac{D}{M}\omega(t_0))\frac{\Delta t^2}{2!}] * 2\pi f \tag{18}$$

Using (17) and (18) behaviours of the generators of the system can be predicted. It is worth noting that because a function that shows the variables behaviour is not an analytic function at switching moments, n sample of data is needed to be known to approximate a function with Taylor series of order n.

III. An illustrative Example

Consider the network shown in Fig. 1. It is a Single-Machine Infinit-Bus 50 Hz system. A three-phase symmetrical fault happens at Bus 3 at t=0.1s. According to simulation, Critically Stable Clearing Time (CSCT) is 0.150s and Critically Unstable Clearing Time (CUCT) is 0.151s. The goal is to predict the system behavior. For the machine, $H = 3.5$ and $M = 7$.

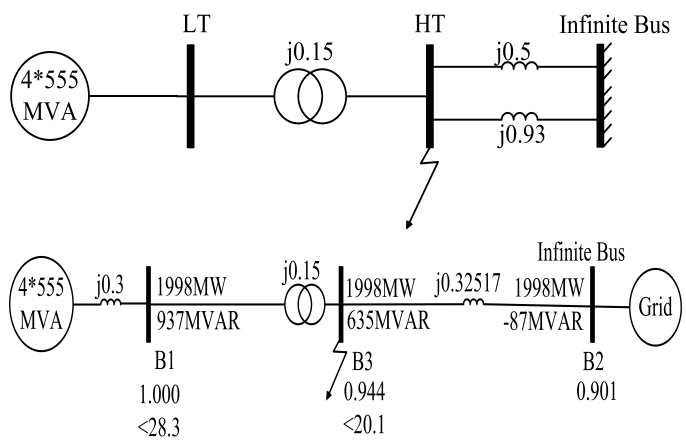

Fig. 1. SMIB Network from Kundur [12]

During the fault the voltage of Bus3 (V_B3) is zero. So, no active power is transferred from the generator to the grid ($P_e = 0$). Assume that the post-fault configuration of the system is same as the pre-fault, or it is known in general. At steady state (until $t = 0.1s$) the system state is as follows

$\delta_{s.s.} = 0.729020rad = 41.77°$, $\omega = 0$.

To predict δ and ω at $t = 0.11$, (17) and (18) can be used. So $7 * \Delta\omega = 0.9 * (0.11 - 0.1) = 0.009$ and thus $\Delta\omega = 0.0013$ and $\omega(t = 0.11) = 0.0013$.

From this $\omega(t = 0.11)_{simulated} = 0.0013$ and $\delta(t = 0.11) = 2\pi f\left\{\frac{0.9-0}{7}\frac{0.01^2}{2!} + 0 * 0.01\right\} + 0.72902 = 0.7310$ and then $\delta(t = 0.11)_{simulated} = 0.7311$

Considering this the prediction of desired paramters at t=0.2s is as follows.

$7 * \Delta\omega = 0.9 * (0.2 - 0.1) = 0.09$

$\Delta\omega = 0.0129$

$\omega(t = 0.2) = 0.0129$

$\omega(t = 0.2)_{simulated} = 0.0129$

TABLE I
Prediction for the network shown in Fig. 1

Time	ω		δ	
	Predicted	Simulated	Predicted	Simulated
0.11	0.0013	0.0013	0.7310	0.7311
0.20	0.0129	0.0129	0.9310	0.9311

$\delta(t=0.2) = 2*\pi*50*\left\{\frac{0.9-0}{7}\frac{0.1^2}{2!}+0*0.1\right\}+0.72902 = 0.9310$

$\delta(t=0.2)_{simulated}$=0.9311

As it can be seen, using pre-fault condition and via knowledge about P_m and P_e at the very moment after fault, the predictions are accurate. Table I, and figs. 2, 3 shows a comparison between the simulated results and predicted results.

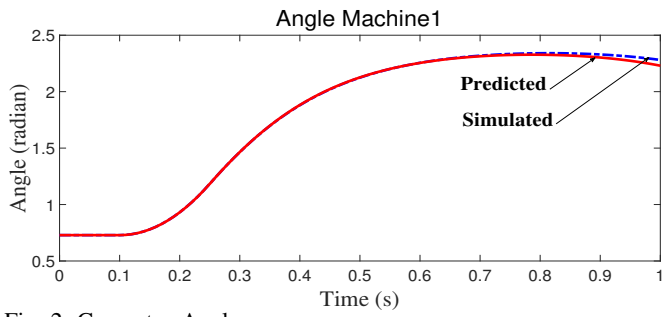

Fig. 2. Generator Angle.

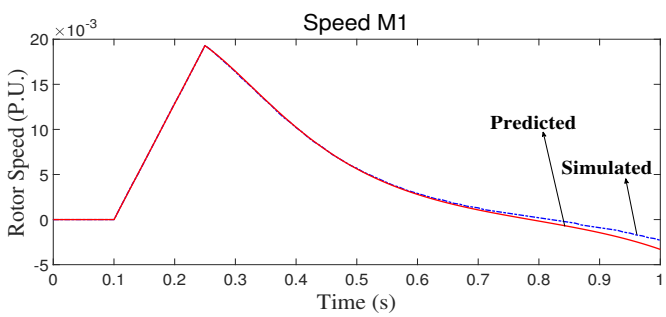

Fig. 3. Generator speed.

IV. General Prediction of the Behaviour of the System in a Multi-Machine System

As could be seen in aforementioned discussions, there is a term P_e in prediction formulas. P_e is the electrical output of the generator that its behaviour is under study. The most accurate prediction happens when the actual output electrical power of generators (P_e) is known. This way, the accelerating power can be found accurately. However, it is not practically possible since the swing equation should be numerically solved to find (P_e). Also, in real-time studies, the actual output of generators cannot be known beforehand to be used for prediction. Therefore, the output of generators for predicting their speed and angle, should be found in another way. Three different approaches can be considered for approximating P_e during the fault:

- Assuming P_e of generators equal to zero.
- Assuming P_e as a constant number. This amount is the amount of P_e one moment after the fault.
- Predicting P_e of generators. Because the behavior of the system is predicted for next time step, Taylor Series can be used. In next session this method is elaborated.

A. Predicting P_e via Taylor series

In order to predict P_e, the behaviour of P_e is considered linear between every two consecutive moments, except at switching times. Hence, Taylor series of P_e can be employed. The expansion of P_e is:

$$P(t) = P(0) + P'(0)t + P''(0)\frac{t^2}{2!} + \cdots \tag{19}$$

$$M\frac{d\omega}{dt} = P_m - P_e - D\omega \tag{20}$$

$$M\frac{d^2\omega}{dt^2} = 0 - \frac{dP_e}{dt} - D\frac{d\omega}{dt} \tag{21}$$

$$\frac{d\omega}{dt} = a(t) \tag{22}$$

$$\frac{dP_e}{dt} = 0 - M\frac{d^2\omega}{dt^2} - D\frac{d\omega}{dt} = -M\frac{da(t)}{dt} - Da(t) \tag{23}$$

Assuming the above equations for one time step and substituting dP_e and dt with ΔP_e and Δt respectively leads to:

$$\frac{\Delta P_e}{\Delta t} = -M\frac{\Delta a}{\Delta t} - Da(t) \tag{24}$$

$$\Delta P_e = P_e(0) - M\Delta a(0) - Da(0)\Delta t \tag{25}$$

So, the first order prediction for P_e will be.

$$P_e(t_0+\Delta t) = P_e(t_0) - M\Delta a(t_0) - Da(t_0)\Delta t \tag{26}$$

This equation has been used for predicting electrical power during the fault. To increase the accuracy, we may have to add a higher order term to the prediction equation.

$$M\frac{d^3\omega}{dt^3} = 0 - \frac{d^2P_e}{dt^2} - D\frac{d^2\omega}{dt^2} \tag{27}$$

Substituting the second term in (21) will result in

$$M\frac{d^2a}{dt^2} = -\frac{d^2P_e}{dt^2} - D\frac{da}{dt} \tag{28}$$

Assuming the above equations for one time step and substituting dP_e and dt with ΔP_e and Δt respectively leads to

$$M\frac{\Delta^2 a}{(\Delta t)^2} = -\frac{\Delta^2 P_e}{(\Delta t)^2} - D\frac{\Delta a}{\Delta t} \tag{29}$$

$$\frac{\Delta^2 P_e}{(\Delta t)^2} = -M\frac{\Delta^2 a}{(\Delta t)^2} - D\frac{\Delta a}{\Delta t} \tag{30}$$

$$P(t) = P(0) + P'(0)t + P''(0)\frac{t^2}{2!} + \cdots \tag{31}$$

$$P_e(t_0+\Delta t) = P_e(t_0) - M\Delta a(t_0) - Da(t_0)\Delta t + \frac{1}{2}(\Delta t)^2\frac{\Delta^2 P_e}{(\Delta t^2)} \tag{32}$$

$$P_e(t_0+\Delta t) = P_e(t_0) - M\Delta a(t_0) - Da(t_0)\Delta t$$
$$+\frac{1}{2}(-M\Delta^2 a(t_0) - D\Delta a(t_0)\Delta t - \frac{D^2}{M}a(t_0)\Delta t^2 + \frac{D^2}{M^2}a(t_0)\Delta t^2) \tag{33}$$

$$P_e(t_0+\Delta t) = P_e(t_0) - M\Delta a(t_0) - Da(t_0)\Delta t$$
$$-\frac{D}{2}\Delta a(t_0)\Delta t + \frac{1}{2}\Delta t^2(\frac{D^2}{M^2}a(t_0) - \frac{D^2}{M}a(t_0)) - \frac{M}{2}(\Delta^2 a(t_0)) \quad (34)$$

Considering $\Delta t = T_S$ as a constant time step, we have

$$\Delta a(t_0) = a(t_0) - a(t_0-\Delta t) = a(t_0) - a(t_0 - TS) \quad (35)$$

$$\Delta^2 a(t_0) = \Delta a(t_0) - \Delta a(t_0-\Delta t) = a(t_0) - 2*a(t_0-\Delta t) + a(t_0-2\Delta t) \quad (36)$$

Hence, (34) can be written in discrete form as follows

$$P_e(i+1) = P_e(i) - M\Delta a(i) - Da(i)\Delta t - \frac{D}{2}\Delta a(i)\Delta t$$
$$+\frac{1}{2}\Delta t^2(\frac{D^2}{M^2}a(i) - \frac{D^2}{M}a(i)) - \frac{M}{2}(\Delta^2 a(i)) \quad (37)$$

Substituting (35) and (36) in (37) leads to (38).

$$P_e(i+1) = P_e(i) - M(a(i)-a(i-1)) - Da(i)*TS - \frac{D}{2}(a(i)-a(i-1))*TS$$
$$+\frac{1}{2}TS^2(\frac{D^2}{M^2}a(i) - \frac{D^2}{M}a(i)) - \frac{M}{2}(a(i) - 2a(i-1) + a(i-2)) \quad (38)$$

Based on (38), we can predict the output electrical power. Using (17), (18), and (38), angles, speeds, and output electrical power of generators can be predicted. It is worth reminding that because 2nd order Taylor series is used, the data for the first two moments after fault or after fault removal is required for predicting the system's variables during the fault and after the fault removal, respectively.

PMUs can be used to improve the accuracy of the prediction for post-fault system. It means that, we may update the initial point of the prediction using PMU data when the post-fault system is being predicted. It should be mentioned that the scope of this work is to predict the behavior of the system during the fault so that using direct methods becomes possible without numerically solving the swing equation for during-the-fault system studies. The prediction also helps to apply predictive controllers and have a more stable system. In addition, considering a sustained fault in a system and predicting the system behaviour can be used for finding the UEP of a system. Finally, with defining an appropriate criteria, prediction can be used for finding the critical clearing time, and for finding the critical machines, which refer to machines that loose synchronism first.

In what follows, the prediction has been used to predict generator behavior in a dynamic IEEE 39 bus test system. The prediction error for desired variable (X), has been calculated and provided using (39) and (40).

$$Error(X_{t_i})(\%) = \frac{X_{t_i}^{actual} - X_{t_i}^{predicted}}{X_{t_i}^{actual}} * 100 \quad (39)$$

$$Mean\ \ Error(x) = \frac{\sum_{i=1}^{n}|Error(X_{t_i})|}{n} \quad (40)$$

where n is the number of moments that the variables are predicted. This can be represetned as in (41).

$$n = \frac{t(faultremoval) - t(faultstart)}{TimeStep} \quad (41)$$

V. Prediction in IEEE 39 Bus test system

To test the proposed method, prediction of generator angles and speed is performed on IEEE 39 bus test system. One-line diagram and the features of the test system are presented in figure 4 and table II. To create system dynamics a symmetrical three phase fault is applied at bus 16 at $t = 0.1$ sec. Fault is removed at $t = 0.285$ sec. The system is critically stable in this scenario, meaning that the critical fault duration is 0.158 seconds. Machine 2 is the reference ($\delta 2 = 0$).

The prediction for system behaviour during the fault is only based on the PMU data for two time steps after fault. However, prediction for post-fault system (after $t = 0.258$ sec) is corrected by updating the initial point in the related formulas every 8 time steps (every 0.08 sec.). The results for machines 4, as the first machines that lose synchrony, are provided in figs. 6 to 11. It can be seen that angle and speed prediction error is within 1%. For machine power prediction, expect during the sudden change in the power at fault time, the error is within a threshold limit of 1%.

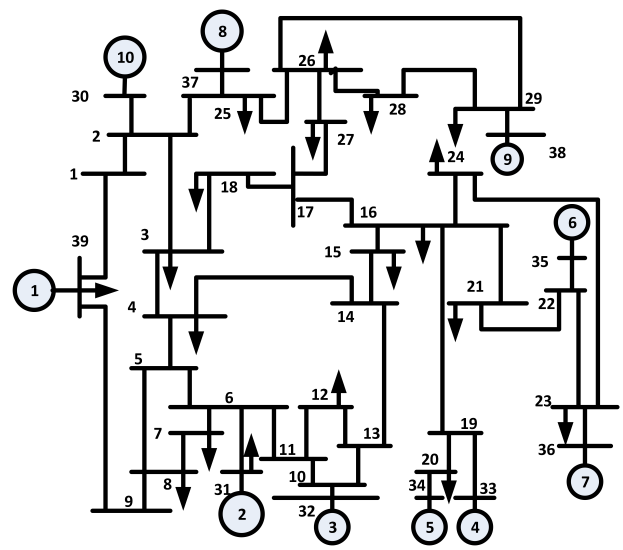

Fig. 4. IEEE 39 Bus Test System

TABLE II
IEEE 39 Bus Features

Buses & Generators	39 Buses 10 Generators	Lines & Loads	46 Lines 19 Loads
Total Active Power Generation (MW)	6147.92	Total Active Load (MW)	6097.100
Total Reactive Power Generation (MVAR)	2487.332	Total Reactive Load (MVAR)	1409.100

VI. Application

To test the efficiency of the proposed method in predicting the system behavior and preventing lose of synchronism, CCT for fault on bus 16 in IEEE 39 bus test system has been predicted. For prediction, a PC has been used with a Core i7-3770-3.4GHz CPU and 8GB of RAM. PASHA and MatLab are used for simulation [5]. Elapsed time for predicting system for 2 seconds was 0.078385 seconds. After prediction, to prevent lose of synchronism, dynamic braking has been used. dynamic

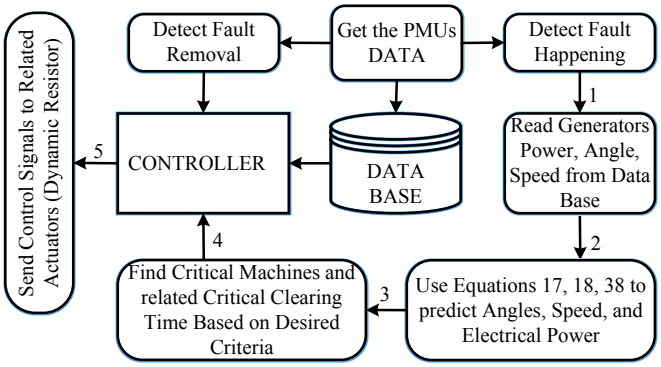

Fig. 5. Schematic of the Prediction Application

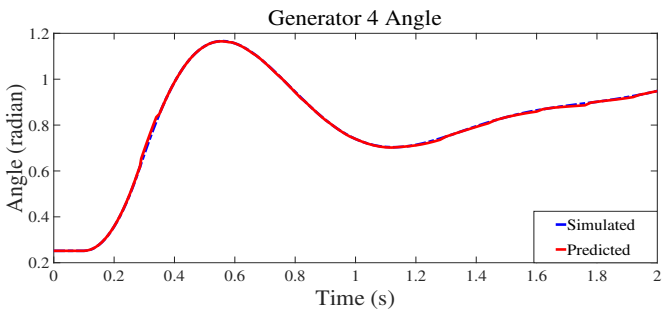

Fig. 6. Machine 4 Rotor Angle

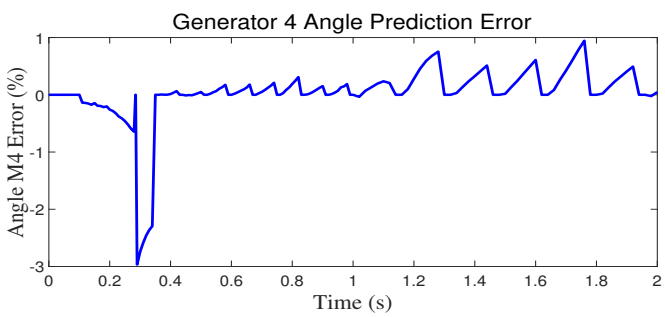

Fig. 7. Error of Machine 4 Rotor Angle Prediction

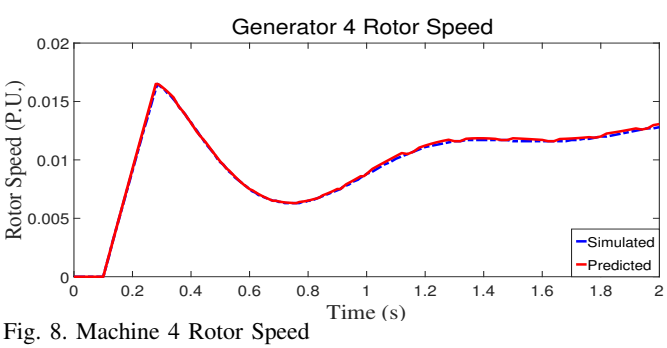

Fig. 8. Machine 4 Rotor Speed

braking uses the concept of applying an artificial electrical load during a transient disturbance to increase the electrical power output of generators and thereby reduce rotor acceleration. One form of dynamic braking involves the switching in of shunt resistors for about 0.5 second following a fault to reduce the accelerating power of nearby generators and remove the kinetic energy gained during the fault [12].

Table III shows the machines that tend to lose synchrony first and their related critical clearing time and angle. Since

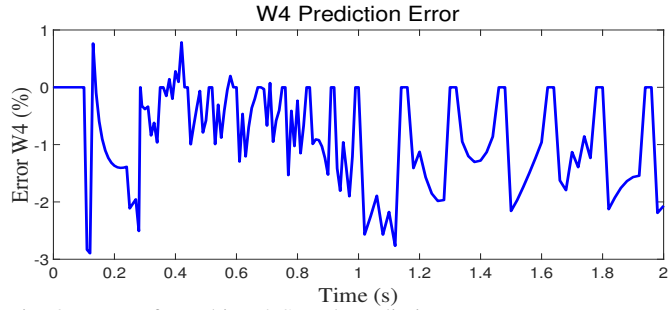

Fig. 9. Error of Machine 4 Speed Prediction

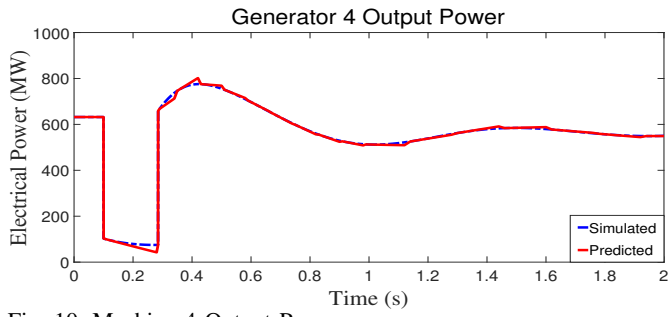

Fig. 10. Machine 4 Output Power

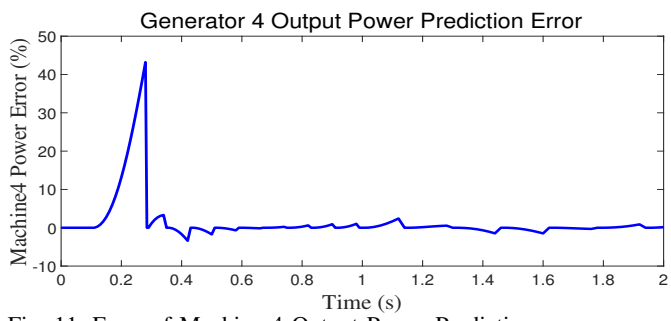

Fig. 11. Error of Machine 4 Output Power Prediction

the first machines that tend to lose synchrony with each other are machine 1 and 4, the braking resistor has been switched in at bus 33 which is connected to machine 4. Fault happens at $t = 0.1$ sec. and prediction results are available at $t = 0.18$ sec. The braking resistor is switched in at $t = 0.2$ sec and is switched out at $t = 0.7$ sec. The fault is not cleared until $t = 0.315$sec. Hence, it shows that although the CCT for the original system is 0.258 seconds, being able to predict the system behaviour and taking a simple preventive action, help save the system even when that fault is not removed for a longer period than CCT.

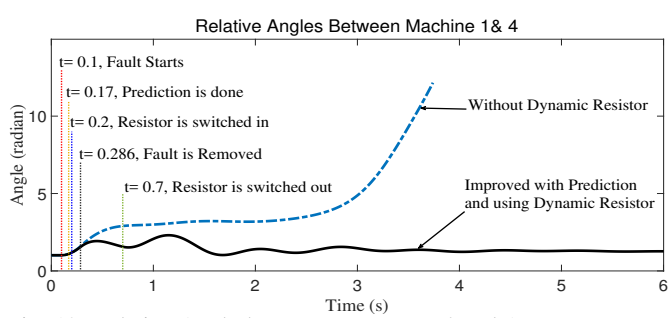

Fig. 12. Relative Angle between generators 4 and 1

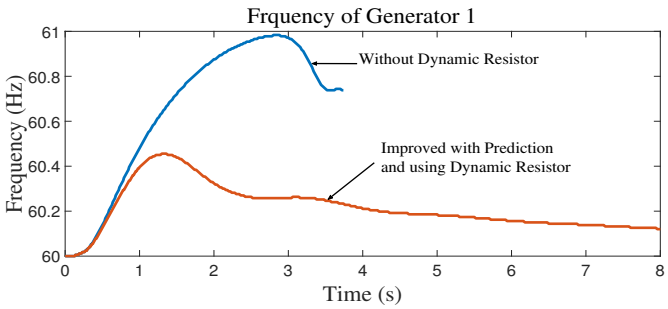

Fig. 13. Frequency of Generator 1

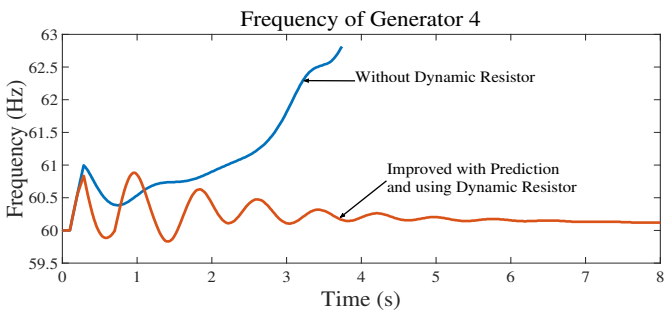

Fig. 14. Frequency of Generator 4

TABLE III
Critical Clearing Time

Machines	Prediction		Machines	Simulation	
	Critical Clearing Angle	Critical Clearing Angle		Critical Clearing Angle	Critical Clearing Angle
1,4	0.2800	-89.1800	1,4	0.2800	-89.8912
1,5	0.2900	-89.5500	1,5	0.2800	-87.1274
1,7	0.3000	-87.1100	1,7	0.2852	-88.1442
1,6	0.3200	-87.6100	1,6	0.3000	-88.5071
4,10	0.3300	87.6600	4,10	0.3100	87.6584
1,9	0.3400	-89.6500	1,9	0.3100	-89.0513
5,10	0.3600	89.2200	5,10	0.3500	89.5624
7,9	0.3700	89.4200	7,9	0.3500	89.2115
6,10	0.4000	89.0600	6,10	0.3900	88.5014
1,3	0.4300	-88.2800	1,3	0.3900	-88.3795
4,8	0.4500	89.5700	4,8	0.4100	85.0587
2,4	0.4500	-88.6400	2,4	0.4200	-86.5300

VII. Conclusions

In this paper a new approach for transient stability prediction and improvement is proposed. The method is based on using Taylor Series for predicting critical clearing time. After prediction, a dynamic resistor is used to prevent lose of synchronism in the system. The technique was applied on IEEE 39 bus system and results showed the accuracy and efficiency of the method.

References

[1] A. Sahami, R. Yousefian, and S. Kamalasadan, "An approach based on potential energy balance for transient stability improvement in modern power grid," in *2018 IEEE Power and Energy Conference at Illinois (PECI)*, Feb 2018, pp. 1–7.

[2] M. Amini and M. Almassalkhi, "Investigating delays in frequency-dependent load control," in *Innovative Smart Grid Technologies-Asia (ISGT-Asia), 2016 IEEE*. IEEE, 2016, pp. 448–453.

[3] A. Gajduk, M. Todorovski, and L. Kocarev, "Stability of power grids: An overview," *The European Physical Journal Special Topics*, vol. 223, no. 12, pp. 2387–2409, Oct 2014. [Online]. Available: https://doi.org/10.1140/epjst/e2014-02212-1

[4] H. Bagherpoor and F. R. Salmasi, "Robust model reference adaptive output feedback tracking for uncertain linear systems with actuator fault based on reinforced dead-zone modification," *ISA Transactions*, vol. 57, pp. 51 – 56, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0019057815000440

[5] A. Sahami and S. M. Kouhsari, "Making a dynamic interaction between two power system analysis software," in *2017 North American Power Symposium (NAPS)*, Sept 2017, pp. 1–6.

[6] M. Gholizadeh, A. Yazdizadeh, and H. Mohammad-Bagherpour, "Fault detection and identification using combination of ekf and neuro-fuzzy network applied to a chemical process (cstr)," *Pattern Analysis and Applications*, Aug 2017. [Online]. Available: https://doi.org/10.1007/s10044-017-0634-7

[7] M. A. Chitsazan, M. S. Fadali, A. K. Nelson, and A. M. Trzynadlowski, "Wind speed forecasting using an echo state network with nonlinear output functions," in *2017 American Control Conference (ACC)*, May 2017, pp. 5306–5311.

[8] Y. Tang, F. Li, Q. Wang, and Y. Xu, "Hybrid method for power system transient stability prediction based on two-stage computing resources," *IET Generation, Transmission Distribution*, vol. 12, no. 8, pp. 1697–1703, 2018.

[9] Y. Zhou, H. Sun, Q. Guo, B. Xu, J. Wu, and L. Hao, "Data driven method for transient stability prediction of power systems considering incomplete measurements," in *2017 IEEE Conference on Energy Internet and Energy System Integration (EI2)*, Nov 2017, pp. 1–6.

[10] A. Banadaki, F. Mohammadi, and A. Feliachi, "State space modeling of inverter based microgrids considering distributed secondary voltage control," in *North American Power Symposium (NAPS)*, 2017.

[11] Y. Zhang, M. E. Raoufat, and K. Tomsovic, *Remedial Action Schemes and Defense Systems*. John Wiley Sons, Ltd, 2016. [Online]. Available: http://dx.doi.org/10.1002/9781118755471.sgd032

[12] *Power System Stability And Control*, ser. EPRI power system engineering series. McGraw-Hill, 1994. [Online]. Available: https://books.google.com/books?id=v3RxH_GkwmsC

[13] D. L. Lubkeman and G. T. Heydt, "The application of dynamic programming in a discrete supplementary control for transient stability enhancement of multimachine power systems," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 9, pp. 2342–2348, Sept 1985.

[14] A. E. Hammad, "Analysis of power system stability enhancement by static var compensators," *IEEE Transactions on Power Systems*, vol. 1, no. 4, pp. 222–227, Nov 1986.

[15] Y. Wang, D. J. Hill, R. H. Middleton, and L. Gao, "Transient stability enhancement and voltage regulation of power systems," *IEEE Transactions on Power Systems*, vol. 8, no. 2, pp. 620–627, May 1993.

[16] V. Miranda, J. N. Fidalgo, J. A. P. Lopes, and L. B. Almeida, "Real time preventive actions for transient stability enhancement with a hybrid neural network-optimization approach," *IEEE Transactions on Power Systems*, vol. 10, no. 2, pp. 1029–1035, May 1995.

[17] R. Yousefian, A. Sahami, and S. Kamalasadan, "Hybrid energy function based real-time optimal wide-area transient stability controller for power system stability," in *2015 IEEE Industry Applications Society Annual Meeting*, Oct 2015, pp. 1–8.

[18] E. D. Tuglie, M. L. Scala, and P. Scarpellini, "Real-time preventive actions for the enhancement of voltage-degraded trajectories," *IEEE Transactions on Power Systems*, vol. 14, no. 2, pp. 561–568, May 1999.

[19] G. G. Karady and J. Gu, "A hybrid method for generator tripping," *IEEE Transactions on Power Systems*, vol. 17, no. 4, pp. 1102–1107, Nov 2002.

[20] R. Hadidi and B. Jeyasurya, "Reinforcement learning based real-time wide-area stabilizing control agents to enhance power system stability," *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 489–497, March 2013.

[21] C. Mishra, J. S. Thorp, V. A. Centeno, and A. Pal, "Stability region estimation under low voltage ride through constraints using sum of squares," in *2017 North American Power Symposium (NAPS)*, Sept 2017, pp. 1–6.

[22] A. Pal, C. Mishra, A. K. S. Vullikanti, and S. S. Ravi, "General optimal substation coverage algorithm for phasor measurement unit placement in practical systems," *IET Generation, Transmission Distribution*, vol. 11, no. 2, pp. 347–353, 2017.