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Minimization of Negative Effects of Time Delay in Smart Grid System

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MINIMIZATION OF NEGATIVE EFFECTS OF TIME DELAY IN SMART GRID SYSTEM

by

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Finally I would like to thank my parents, grandparents and all my friends for always inspiring and supporting me. Without their support I would not be able to come along this far in my life. This thesis is dedicated to them.

ABSTRACT

Yang Zhou. The University of Memphis. August, 2013. Minimization of Negative Effects of Time Delay in Smart Grid System. Major Professor: Thomas Edgar Wyatt.

Previous studies found that using remote signals can stabilize inner oscillation, so the research on wide area control in power fields has been taken seriously. However, communication delay is one of the inevitable problems when using wide area measurement system (WAMS) and it has adverse effects on control systems. This paper aims at explaining current research on communication delay in power systems and providing a new method to minimize negative effects brought by time delay. Simulation takes place on an IEEE nine-bus system using Matlab/Simulink software. Circuit breakers in the system are controlled by the optimal reclosing time (OPRT) method. Different types of faults and different time delays had been considered. The performance of the system considering time delays with and without the proposed predictor has been compared. From the simulation results, it is shown that the proposed predictor performs well in minimizing the negative effects of time delays.

PREFACE

The paper resulting from my Master research is used as the manuscript of this thesis. The paper "Minimization of negative effects of time Delay in smart grid system" was submitted to IEEE 2013 Southeast Conference, and has been used in this thesis.

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LIST OF ABBREVIATIONS

1LG: One-phase ground fault

2LG: Two-phase ground fault

2LL: Two-phase line-to-line fault

3LG: Three-phase ground fault

3LL: Three-phase line-to-line fault

AC: Alternating current

A/D: Analog-to-digital

DC: Direct current

EHV: Extra high voltage

GPS: Global positioning system

OPRT: Optimal reclosing time

PMU: Phasor measurement units

PSS: Power system stabilizer

TKE: Total kinetic energy

TKED: Total kinetic energy deviation

WADC: wide-area damping controller

WAMS: Wide-area measurement systems

W_{index}: Total kinetic energy deviation index

I. Introduction

Time delay arises in a wide range of power system measurements. However, traditional controlling strategies in power system only use the local measuring data. And the time delay of the local measuring data is usually very small (<10ms) compared to the system time constants and can be ignored [1]. Since the 1990s, centralized controllers using wide-area signals have been suggested with the new technology PMUs (phasor measurement units) [2]. PMUs are units that measure dynamic data of power system, such as voltage, current, load angle, output power and frequency. All measurements are synchronized by GPS (global positioning system) satellites. As explained in [1], the system dynamic performance can be enhanced if remote signals are applied to the controller with respect to inter-area oscillations. However, coincidentally time delay is usually obvious in wide area measurement and may have impact on central controller.

The time delay caused by transmission of remote signals is one of the key factors influencing the whole system stability and damping performance [1]. In wide-area power systems the time delay can vary from tens to several hundred milliseconds [3].

In the past, studies have been done in the electrical engineering fields that evaluate time delay impacts on the controlling mechanism and power systems [1], [4-8], while minimizing the effect caused by time delay [9]. A prediction method has been mentioned that proposes an optimal reclosing scheme in extra high voltage (EHV) lines, using the power angle δ, and power angle velocity as input values to optimize the reclosing method.

This paper analyzes the causes and effects of time delays and uses the prediction method [9] to minimize the negative effects of time delay in smart grid applications.

Simulation results show time delays bring oscillation to power system, and proposed prediction method can minimize the negative effects of time delay. The proposed prediction method is the main contribution of this work. The prediction method is simple and efficient and easy to add to the controller without changing the system configuration.

The effectiveness of the proposed method has been tested in the IEEE nine-bus power system model [10]. The optimal reclosing time (OPRT) method [10] has been compared with conventional reclosing; simulation results show that OPRT is better on controlling circuit breaker reclosing, and brings less oscillation to system. OPRT is chosen for finding the reclosing times of circuit breakers for both balanced and unbalanced permanent faults. The W_{index} (total kinetic energy deviation index) with and without predictors are compared in cases of different type of faults and delay times.

A. Motivation

Controllers have been utilized in power systems since they were born, and time delays have been considered in a wide range of practical engineering fields. But time delay is often overlooked in power system control area, because in the past power controllers were mostly local controllers. Recently, with the development of wide-area measurements technique, time delay problems become noticeably and attracted a lot of attention.

In [1], Wu used gain scheduling control to design controllers. Wu considers time delay as the design parameter; the simulation result shows controllers were working well to compensate time-delay's effects. But this method includes complex mathematical calculations and requires matrix expressions for system model. In reality, it is always hard to make a mathematical expression for every system. Zhang's work gives an easy to achieve method, but it didn’t simulate with wide area signals. This paper continues Zhang’s work, taking total kinetic energy of both two generators’ operating signals, and simulating in a much more complicated IEEE nine-bus system. The results reflect this easy method is efficient in compensating time-delay’s affect.

B. Goals

The goals of this study are:

a) Show the cause and effects of communication delay in power system

b) Develop a method to minimize negative effects brought by communication delay in power system

c) Simulate the system with a new method and compare its response with unimproved system.

II.Background

A. Smart Grid Background

In the early years, power systems were local girds [11]. Because at that time, most generators were DC (direct current) generators, and DC voltage cannot be very high due to DC generator’s structure. Low voltage would cause more loss during long-distance transmission, so transmission lines in 20th centuries were short and power systems operated dispersedly. However, interconnected grids are required by industry for economic and reliability reasons. Since the application of AC (alternating current) generators and transformers in industry, power system start to expansion and supplying more power to heavier loads and longer distance. And modern power grids started to take shape.

Now, different type of generators, such as coal-, hydro- and renewable generators, and different capacity generators connected to huge power systems, distribute to national wide area customers. Power grids can be very large both geographically and electrically.

Modern power grids face challenges from different fields, such as power quality, generation efficiency, fault protection, energy saving, etc. The term "smart grid" has been used from 1998 to describe a new (or a smart) grid that can solve approaching problems in nowadays power system. The backbone of the smart grid is the information infrastructure, which is used to communicate with different grid substations. Information infrastructure depends on communication technology to gather information about behaviors of generators and customers in whole grids, and feed back to central controllers to scheduling system and to improve efficiency, reliability, economics and sustainability of generation and distribution of electricity.

Considerable challenges come with smart grid. This paper has discussed one of them — the communication delay in smart grid and the method to minimize its negative influence.

B. Local Control and Wide Area Control

The modern power system is a network connecting not only generators, transformers, transmission lines and distribution systems, but also communication systems and controllers. In order to operate safely, all the generating equipment in system, except some renewable units, must rotate in synchronous frequency and deliver at rated voltage and current, even during faults, disturbance or equipment outages. Controllers and communication systems are undertaking this secure protection.

Controllers are divided into two types by their working area: local controllers and wide area controllers. Local controllers are use inputs within the same substation where the controller outputs are applied. With local controllers there are less communication connections required. For example, power system protection, generator governor control, voltage control and power flow control power system stabilizers are local controllers [12].

Wide area controls collect signals from far away through a communication system and send back information to central controllers. In Figure 1, a “star” network gathers data from substations is a typical structure for control center.

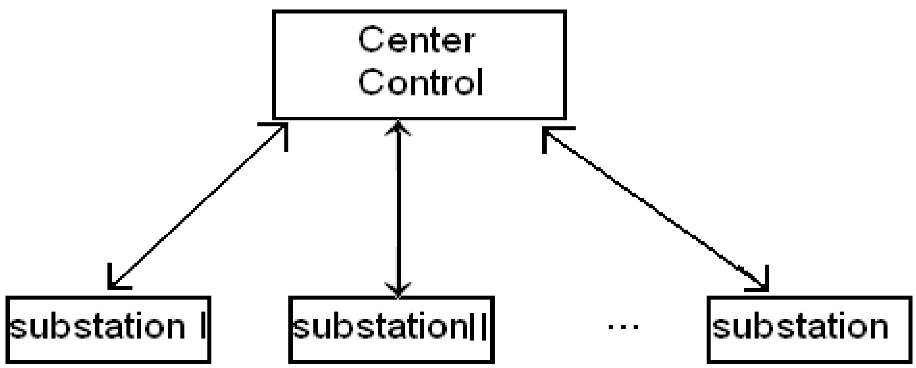


Figure 1: Wide area control

Most of the conventional power system controls are local, because it has faster response. With rapid advancements in wide-area measurement systems (WAMS) technology, the transmission of remote control signals has become rather simpler. Recently, there are studies that suggest remote signals can do better for stabilizing system operation than local signals especially, when systems are operating near their maximum capacity. In [13], Kundur explained stressed operating conditions can increase the possibility of inter-area oscillation between different control areas or even collapse the whole system. In [14], Ali demonstrated that for a large power system, local variable, for example, generator speed deviation as the fuzzy controller input could not stabilize the overall system sufficiently. It is also be found in [15] and [16] that if remote signals from one or more distant locations of the power system can be applied to local controller design, system dynamic performance can be enhanced.

Wide area controllers began being used widely in actual systems with the developing of WAMS. However, communication delay problem began arising simultaneously. Since communication speed is critical for wide area controls, the related branches have become popular research fields, exploring reasons for communication delay [8], effects of communication delay[18][19-20], methods to deal with delay problems[20].

C. The Cause of Communication Delay

In a wide area measurement system, the time required to transmit signals from the measurement location to center controllers, and then to control devices is denoted as communication delays or latency, these factors should be considered in design. Communication delays can come from many aspects. For example, time delays are possibly introduced when signal transmission is through optical fiber or microwave networks, analog-to-digital (A/D) conversion, online calculation of communication signals, and time synchronization of signals by GPS. Also some communication delays are associated with the circuit breakers opening and closing operations following a fault in electric grid. Other factors that cause delays may be from cyber attacks.

From electrical network view, in a WAMS communications network, it is assumed that the data being transmitted are in the form of packets [17]. The packets are arranged in three sections: the header, the payload and the trailer. All the time delays of this type can be categorized into following four types of delays [17]:

a) Serial delays: the delay of having one bit being sent one after another.

b) "Between Packet" serial delays: the time after a packet is sent to when the next packet is sent.

c) Routing delays: the time required for data to be sent through a router , and re-sent to another location.

d) Propagation delays: the time required to transmit data over a particular communications medium.

The total signal time delay can be written as:

$$T = T_s + T_b + T_p + T_r \tag{1}$$

$$T_s = \frac{P_s}{D_r} \tag{2}$$

$$T_p = \frac{l}{v} \tag{3}$$

Where T_s is the serial delay, T_b is the "between packet" delay, T_p is the propagation delay, T_r is the routing delay, P_s is the size of the packet (bits/packet), D_r is the data rate of the network, l is the length of the communication medium, and v is the velocity at which the data are sent through the communication medium. Figure 2 illustrates the delayed signal sent from remote area to center controller.

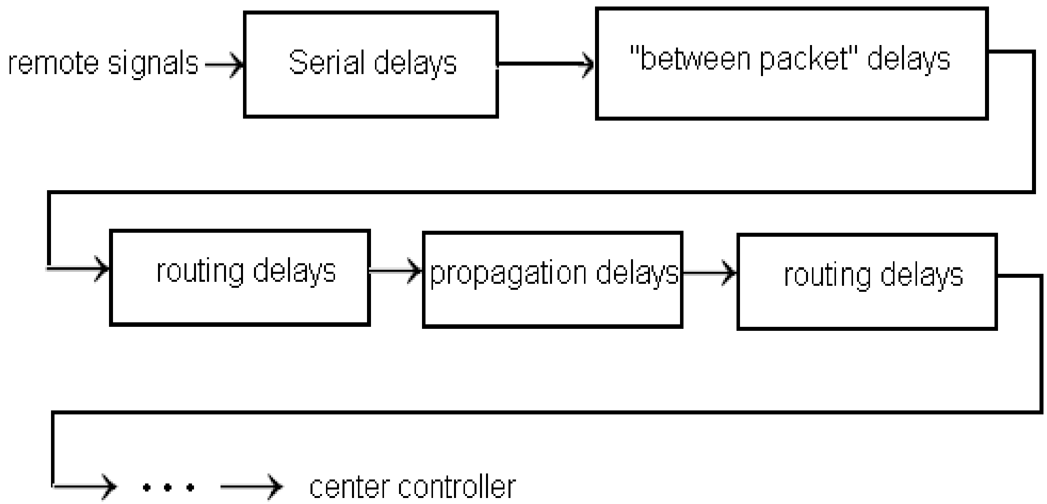


Figure 2: Transmission of Remote Signals

Usually communication delays may range from several microseconds to a few hundreds milliseconds [18]. According to [21] and [22], typically 150 to 200ms delays are considered to design control system. In my work, communication delays of 30ms and 300ms have been considered.

From a cyber attack point of view, the following three typical cyber-attacks can significantly affect communication delays:

a) Packet drop attack: this problem can be caused at various choke points in the communication path (links, firewalls, proxy servers, encryption device, routers, switches, etc.) when a queue within these network points reaches its maximum capacity. While there are some obvious reasons for packet drops, there are also some targeted cyber-attacks which can cause packets to drop before reaching the intended destination (e.g. SCADA or field control units).

b) Distributed Denial of Service (DDoS) attacks: these attacks are mainly used for disrupting, blocking or jamming the flow of information through control and communication networks. Recently, there has been an increase in DDoS attacks (with shorter attack duration, but a bigger packet-per-second attack volume) which not only exploit bandwidth but also attack applications that focus on sending bad traffic using those applications' protocols. This type of attack can significantly disrupt the communication in the smart grid cyber infrastructure.

c) Tampering Communication data/signal: this type of cyber-attack not only delays communication but also contaminates the data in the communication. Such an attack can target specific types of command and control signal. For example, activate or deactivate critical field devices for hostile purpose. This data corruption attack can manifest in many different ways: a malware (like Flame) can make such changes in communication data causing devastating damage to smart grid components including equipment damage, power outage and misreading of smart meter data.

In all these three cases, communication delay value will be at least one second.

Table 3 in section III shows the stability index of system under different delays.

D. Influence of Communication Delays

A lot of work has been done in the past to show the impacts brought about by communication delay [19-21]. In power systems, most communication delays will have negative effects to controllers. They will cause unstable system operation, oscillation or even collapse. Controllers need to be made tolerant to communication delays and methods to minimize negative effects should be investigated.

In [19], an IEEJ West 10-machine model system was used to analyze the effects of the latency by using braking resistor controllers. Total kinetic energy (TKE) was chosen as the evaluation variable and communication delays from $20e^{-6}$ sec to $500e^{-3}$ sec were considered. When a fault happened, the values of TKE are different with relation to different latency values. The TKE increased along with latency. This fact indicates that communication delay has negative effects to controllers and whole system.

In [1], TEST4 with PSS (power system stabilizer) system has been simulated working under latency conditions. Simulation results show that 100ms communication delay can weaken the system performance or even cause instability.

This paper will show the different system stability responses between with and without delays in an IEEE nine-bus system in Chapter 4. From these simulation data and figures, straightforward results can be concluded that communication delay on controllers result in negative effects to power system.

III. PREDICTION METHOD FOR DELAY CONTROL SYSTEM

The impact of the time delay problem had been ignored in power system fields until recent years with development of wide-area system control. The study of control with uncertain delay started from Smith's "posicast control" and "predictor" in 1950s [17]. After Smith's research work the delay control has become an important branch in power control engineering.

In my thesis, the "prediction method" is proposed to offset negative effects brought by time delays. Figure 3 illustrates the signal which has transmission delay corrected by predictor, and then the corrected signals will be sent to the controller.

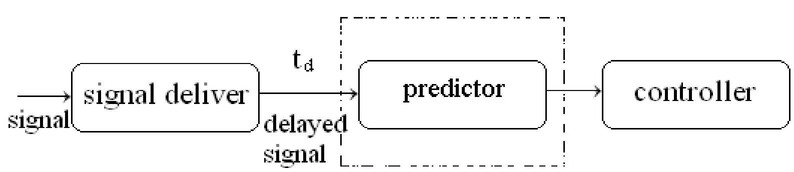


Figure 3: Delay and predictor block

The flow diagram for optimal reclosing including the predicted method is shown in the Figure 4. Since the predictor can modify the delayed signal to the original curve before inputting it into controller, the predictor easily adapts to different kinds of controllers.

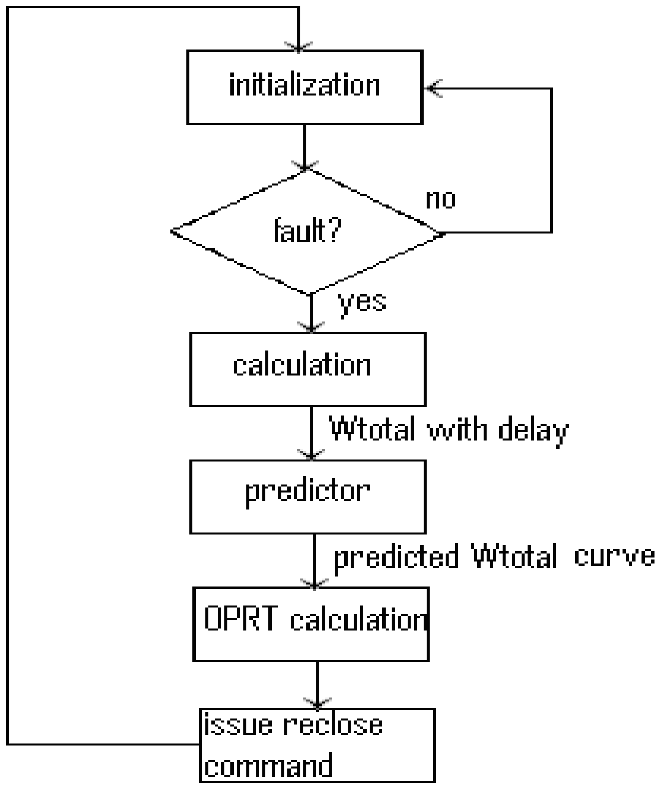


Figure 4: Flow chart diagram of OPTR with predictor

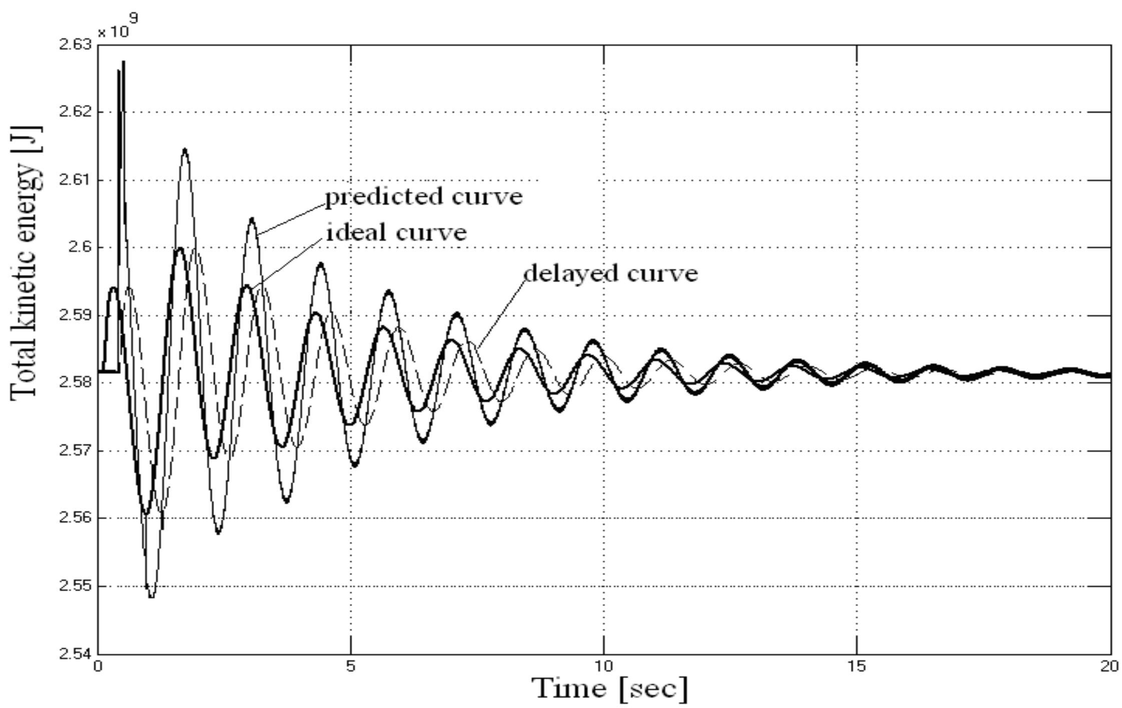
The signals are transmitted from remote locations and proposed by central controllers. There will be a delay between the measured signals and the actual signals. If the time delay is t_d, the predicted signal can be obtained from the measured point, previous measured point and changing rate [9]. For example, consider a signal indicating total kinetic energy (TKE). The predicted method for TKE can be described as:

$$TKE_p = TKE_{previous} + t_d \cdot \Delta\omega \tag{4}$$

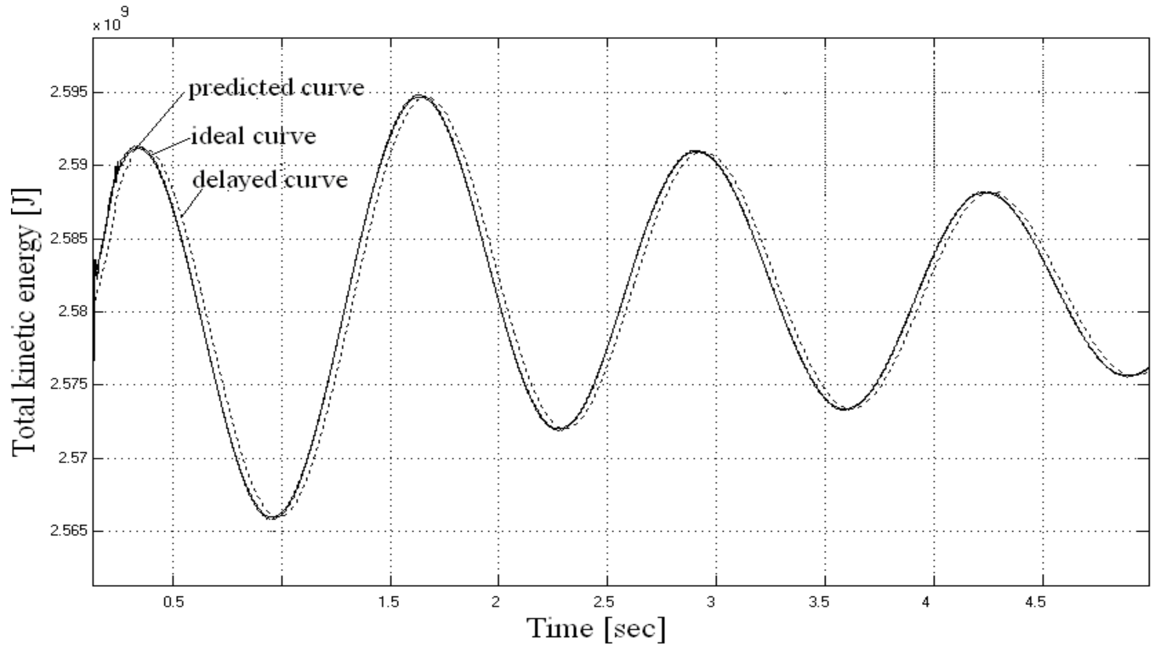
$$\Delta\omega = \frac{TKE_k - TKE_{(k-1)}}{\Delta t} \qquad (5)$$

Where p is the predicted point, k is measured point, and Δw is changing rate of TKE.

Since most signals (such as TKE) are not linear in the real world, the larger the value of t_d, the greater the error in the prediction curve. However, delay time is generally very small and the errors can be ignored. Figure 5 shows the predicted, delayed and ideal response curve for the TKE in case of 3LG fault for 300ms and 30ms delayed system. The changing trend of predicted curve and ideal curve are almost the same. Only the amplitude is different, however the amplitude difference will have little influence on controller. The simulation method and results will be discussed in Chapter 4.



(a) 300ms delay system



(b) 30ms delay system

Figure 5: Response of predicted, delayed and ideal TKE for 3LG permanent fault

IV. Simulated System Background Introduce and Simulated Results

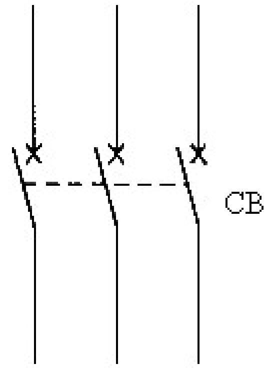
In order to show the influence of time delays on power system and test predicted method, a system model is needed, a simulation environment and a control signal to control some part of the system. In this study I chose IEEE nine-bus system [23] as simulation model and simulated it in Matlab/Simulink. Response of total kinetic energy is chosen to control reclosing time of circuit breakers after faults happened. The concepts of circuit breakers, faults in power system, IEEE nine-bus system, circuit breakers' conventional reclosing and optimal reclosing will be explained from 4.1 to 4.6. Predicted method added to nine-bus system will be explained in section 4.7.

A. Circuit Breakers in Power System

Power systems are normally working under steady-state conditions. However, due to some disturbance or system faults, the voltage or current on the grid may change beyond rating range. When such a situation happens, different kinds of protective schemes will take place.

Circuit breaker is one of the most basic and widely used protective devices. A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. The circuit breaker will open or close the circuit by command. Operation of circuit breakers will affect power system, so how to control circuit breaker properly is an important research branch of power engineering. Figure 6 shows the actual and schematic figure of circuit breaker.

(a) Real power circuit breakers



(b) Schematic figure

Figure 6: Circuit breaker

B. IEEE Nine-Bus System

For the analysis of time delay issues, the nine-bus power system model shown in Figure 7 has been used [23]. The nine-bus system consists of two synchronous generators (G1 and G2), an infinite bus, transformers, double-circuit transmission lines, and loads. In Figure 7, the double circuit transmission line parameters are numerically shown in the forms $R+jX(jB/2)$, where R, X and B represent resistance, reactance and susceptance, respectively, per phase for two lines. The AVR (automatic voltage regulator) and GOV (governor) control models are shown in Figure 8 and Figure 9. The parameters of transfer function in GOV and AVR may be adjusted to meet best system operation. PQ and PV generators' parameters are given in Table 1.

The system bases are 50 Hz and 100 MVA, and the capacities of generators G1 and G2 are 200MVA and 130 MVA, respectively. Faults are considered to take place at F1 (between bus 5 and 7), F2 (between bus 6 and 9), and F3 (between bus 8 and 9).

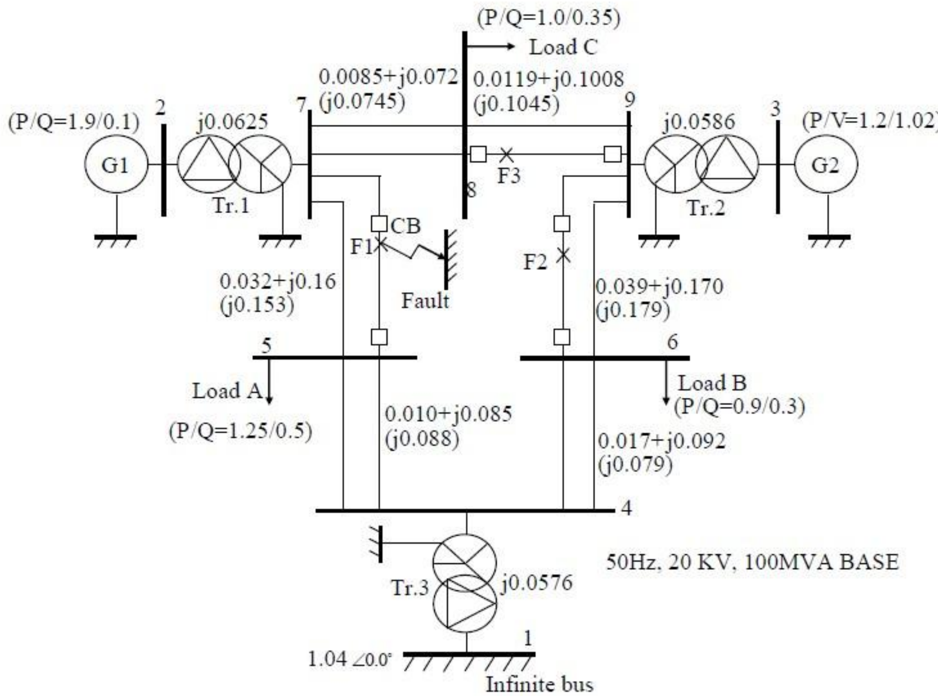


Figure 7: IEEE nine-bus model

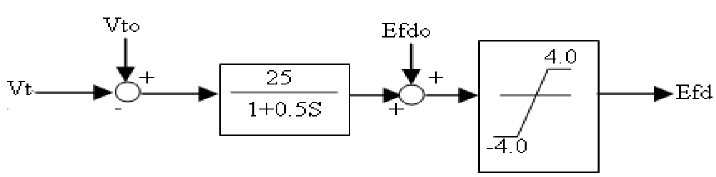


Figure 8: GOV model

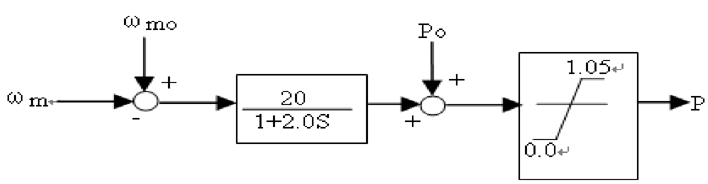
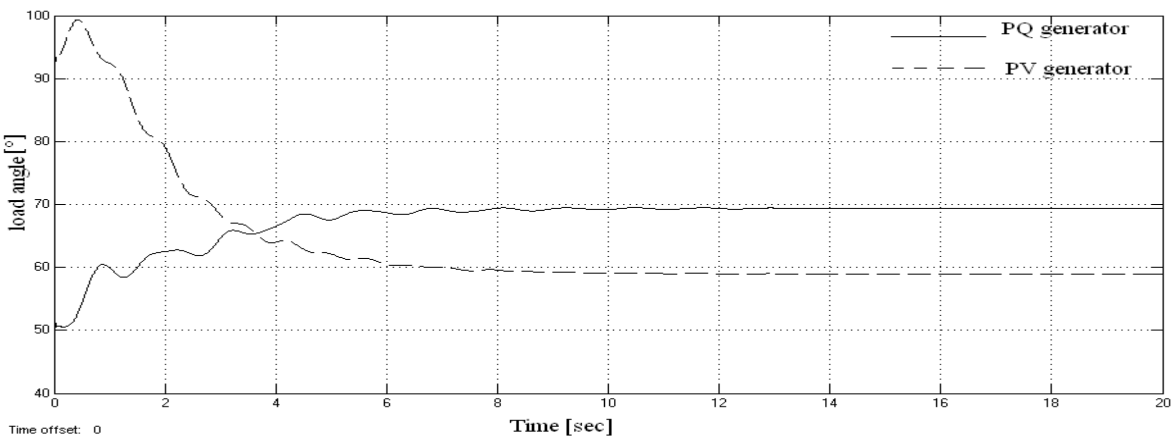


Figure 9: AVR model

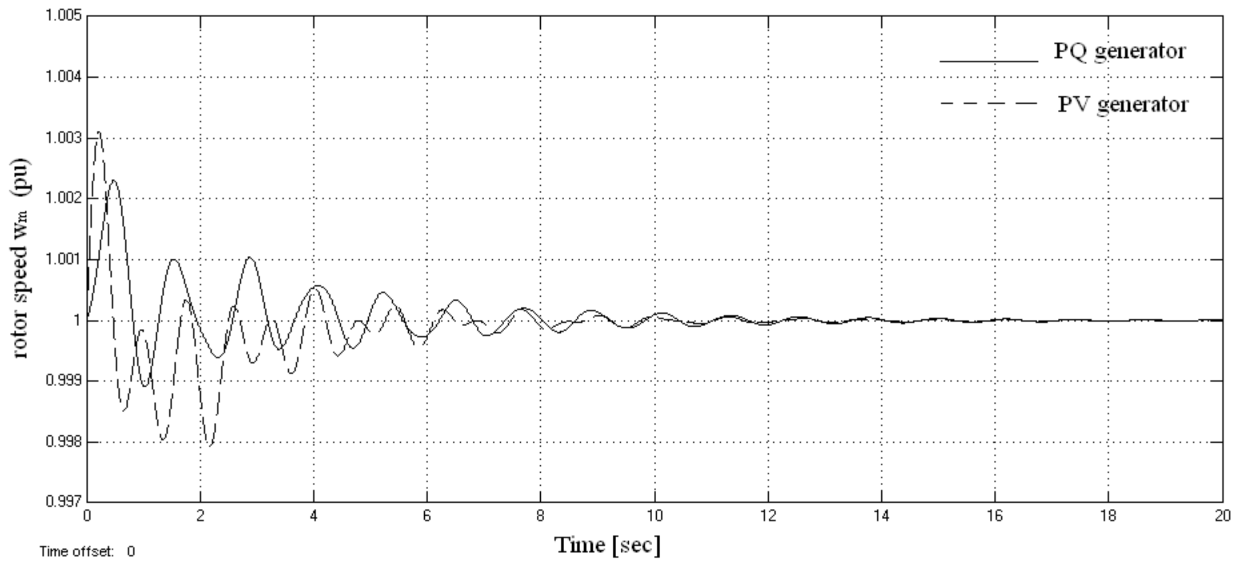
Table 1: Generator parameters

	G1	**G2**
MVA	200	130
ra (pu)	0.003	0.004
xa (pu)	0.102	0.078
Xd (pu)	1.651	1.220
Xq (pu)	1.590	1.160
X′d (pu)	0.232	0.174
X′q (pu)	0.380	0.250
X″d (pu)	0.171	0.134
X″q (pu)	0.171	0.134
T′do (sec)	5.900	8.970
T′qo (sec)	0.535	1.500
T″do (sec)	0.033	0.033
T″qo (sec)	0.078	0.141
H (sec)	9.000	6.000

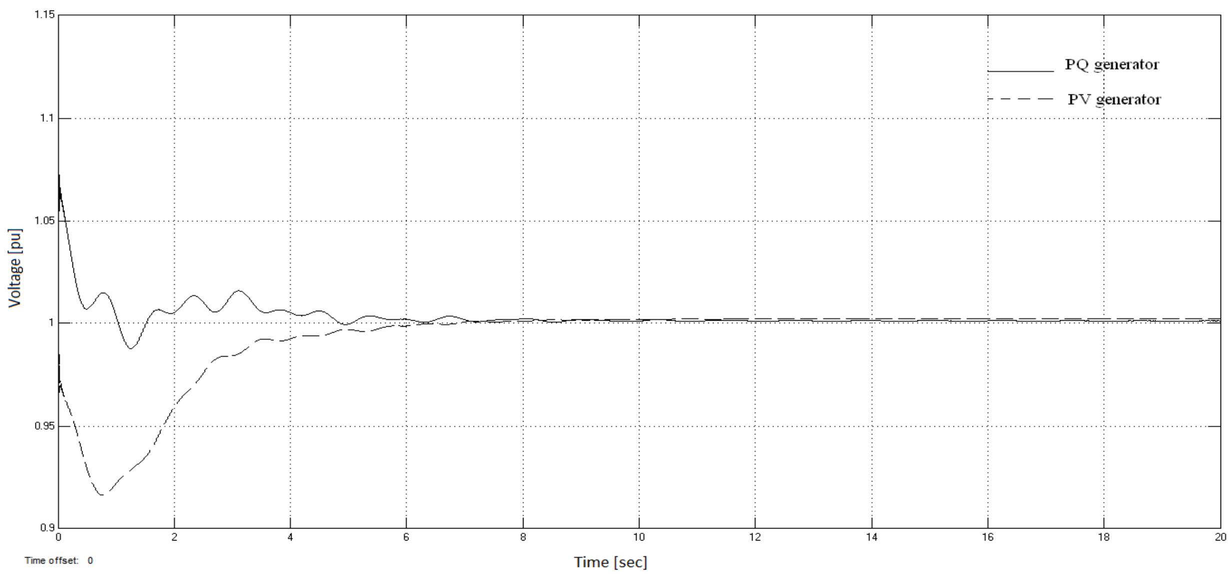
Figure 10 shows the responses of speed, load angle, voltage of PQ and PV generators when under rated operation situation.



(a) Load angle response



(b) Rotor speed response



(c) Voltage response

Figure 10: Generators responses of PV and PQ when working under rated condition

C. Total Kinetic Energy and Total Kinetic Energy Deviation Index

Many signals can be the stability indexes for operating system, for example, output voltage, current, speed, load angle or output power. Here I chose Total kinetic energy (TKE) response as the stability index, because it is easy to get and truly represents system operation status.

Total kinetic energy calculation is based on the generators' speed parameters, and it collects all working generators responses together as the index. A stable system will have a stable Total kinetic energy.

TKE, or W_{total}, can be calculated from the rotor speed of each generator and is given by:

$$W_{total} = \sum_{i=1}^{N} \frac{1}{2} J_i \omega_{mi}^2 (J) \tag{6}$$

Where ω_{mi} is the rotor angular velocity in mechanical *radians/s*, i is the generator number, N is total number of generators, and J_i is the moment of inertia in $kg{\cdot}m^2$ as shown below:

$$J_i = \frac{(H_i \times MVA_{rating\ i})}{5.48 \times 10^{-9} \times N_{s_i}^2} kg \cdot m^2 \tag{7}$$

In (7), H_i is inertia constant of i_{th} generator and

$$N_{si} = \frac{120 \times f}{p} \tag{8}$$

Where f is system electrical frequency, p is the number of poles, and N_{si} is the synchronous speed of the ith generator.

In order to quantify a stable level, I chose the difference between the transient state and steady state TKE based on system base power, which is named total kinetic energy deviation index (W_{index}). The difference is defined as the total kinetic energy deviation, TKED.

$$TKED = W_{total\ transient\ state} - W_{total\ steady\ state} \tag{9}$$

W_{index}, is:

$$W_{index} = \frac{\int_0^T |TKED| dt}{system\ base\ power} \tag{10}$$

Where T is the simulation time and is selected as 20.0s. TKED is the total kinetic energy deviation as calculated in (10). It is apparent that the system performs better for smaller values of W_{index}.

D. Fault Types

A fault in power fields is any abnormal electric current. In a three phase system, a fault may involve more than one phase. Usually there are five types of faults: three-phase ground fault (3LG), three-phase line-to-line fault (3LL), two-phase ground fault (2LG), two-phase line-to-line fault (2LL), and one-phase ground fault (1LG). 3LG fault is a symmetric fault which affects each of the three phases equally. In transmission line faults, roughly 5% are symmetric, but they may cause the most damage to system.

Faults also can be classified by duration time: a transient fault or a permanent fault. A transient fault is a fault that is no longer present if power is disconnected for a short time. A permanent fault does not disappear when power is disconnected.

E. Conventional Reclosing and Optimal Reclosing

a) Conventional Reclosing

From a utility perspective, both transient faults and unbalanced faults are the most common faults. The majority (60% to 80%) of transmission line faults are of a transitory nature [13]. In order to keep the continuity of power supply, circuit breakers need to reclose after a period of time to check if the fault is transient or not. If it is not a transient fault, circuit breakers will reopen and keep the line disconnected. The period between first open and reclose should be neither too small nor too long. Reclosing too fast may judge a transient fault as a permanent fault incorrectly; following this unnecessary reopen will cause system unstable or even a power outage.

For conventional reclosing, the time to reclosing circuit breakers is fixed. That is, the circuit breakers reclose after a prescribed dead time which is set to a constant value. In the works [22]-[25], a conventional reclosing method was used. In [29], simulation data shows that total kinetic energy with conventional reclosing is larger than with optimal reclosing.

b) Optimal Reclosing

Compared to conventional reclosing, which adopts a constant value of reclosing time, optimal reclosing time keeps the system more stable, especially in case of unsuccessful reclosing [30]. Reclosing of circuit breakers at optimal reclosing time (ORCT) can maintain synchronism and enhance transient stability of the system. In this paper, the optimal reclosing time is considered as the point which meets the following conditions:

I. Without the circuit breakers reclosing, the point when the TKE oscillation becomes the minimum.

II. The value obtained from condition I must be greater than T_{cb}, the required reclosing time for circuit breakers to deionize the fault arc. The calculation equation for T_{cb} is from trials and experiments done by previous researchers [19], and shown below:

$$T_{CB} = (10.5 + \frac{KV}{34.5})cycles \tag{11}$$

Where *KV* indicates the line-to-line rms voltage of the system. Here 1 *cycle* =20 ms. If the first minimum point in condition I is less than T_{CB}, the second minimum time of the kinetic energy response should be chosen. In this paper, T_{CB} is calculated as 0.223 sec.

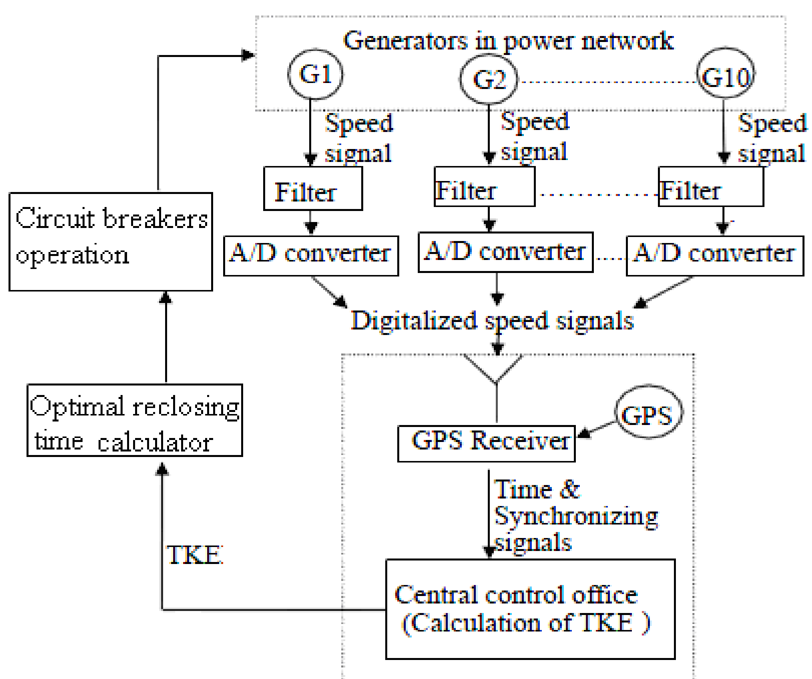
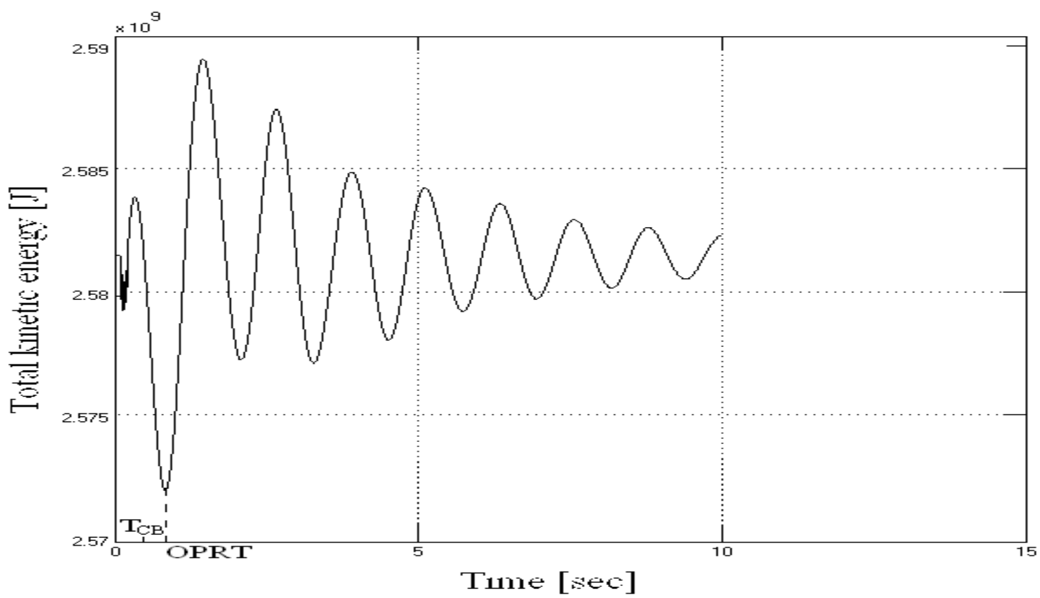


Figure 11: Closed loop circuit breaker control system

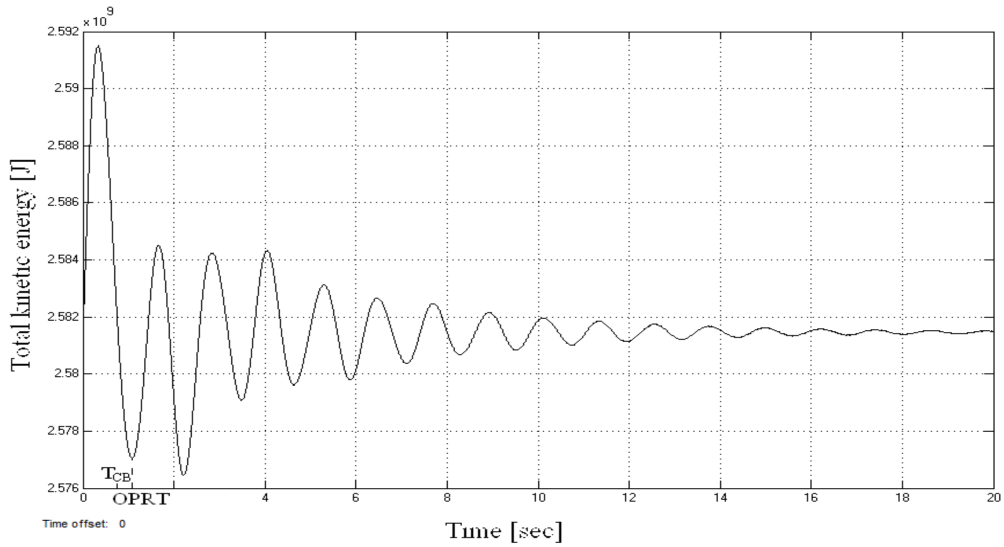
Figure 11 shows how TKE is used as an input signal to control circuit breakers. All generators' kinetic energy signals are gathered by GPS and sent to central controller; after calculation, the optimal reclosing command will be sent back to system.

Figure 12 gives examples of how to get OPRT, where 2LL and 1LG fault occurred at point F3 respectively. In the nine-bus system. Figure 12 shows the total kinetic energy response without reclosing operation after fault happening. The time for the first minimum point is 0.8366 sec, which is greater than T_{CB}.

Using the optimal reclosing technique, the values of optimal reclosing time corresponding to different types of permanent faults at different points are calculated from the simulation graphs of total kinetic energy responses, and are shown in Table 2.



(a)



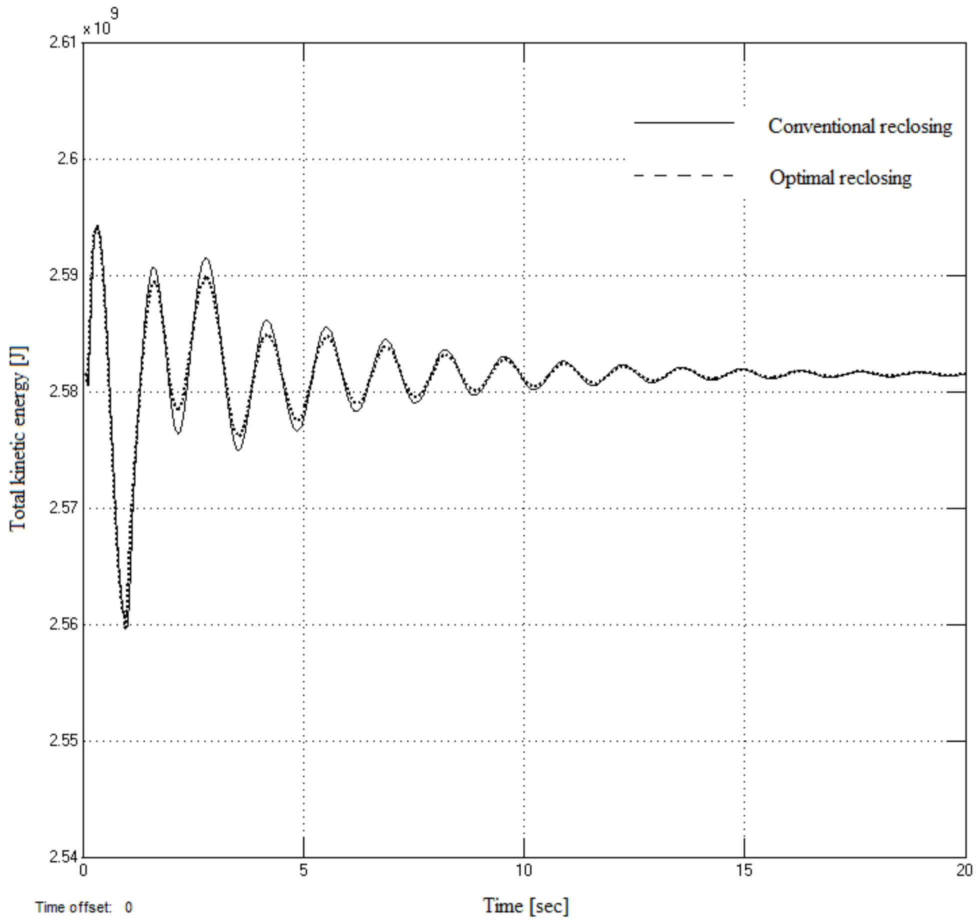
(b)

Figure 12: Response of W_{total} with permanent 2LL (a) and 1LG (b) fault at F3

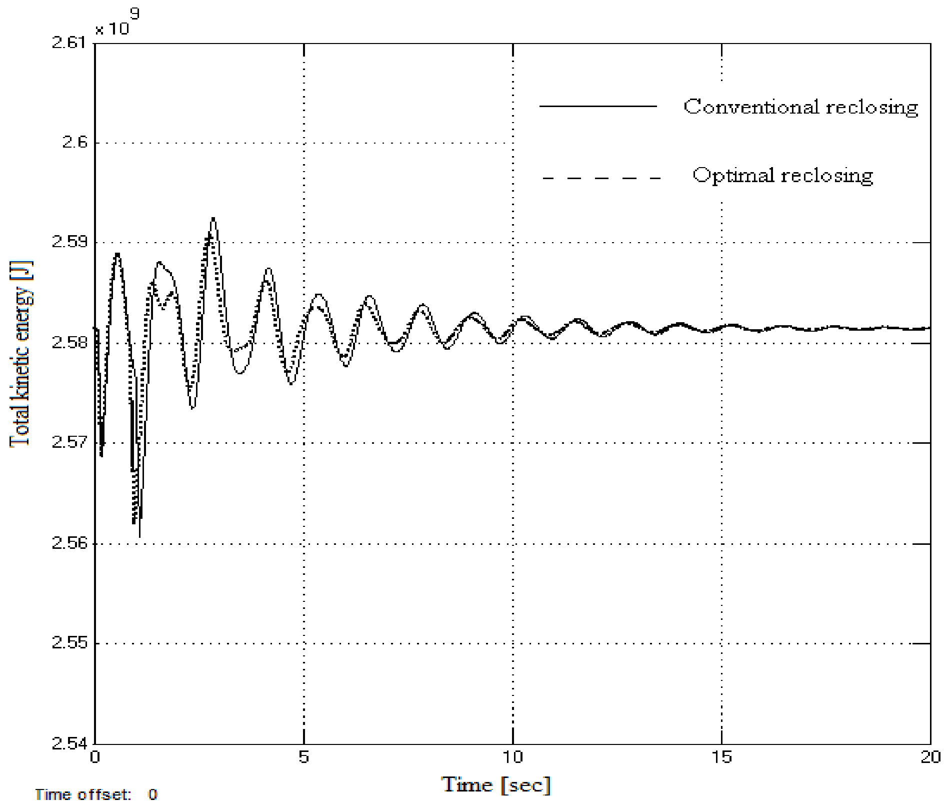
TABLE 2: OPRT for Different Types of Faults at Different Points

Fault type	**Fault point**	**Conventional Reclosing (sec)**	**OPRT (sec)**
3LG	F1	1.0	0.9590
	F2	1.0	0.9572
	F3	1.0	0.8426
3LL	F1	1.0	0.9597
	F2	1.0	0.9558
	F3	1.0	0.8415
2LG	F1	1.0	0.9175
	F2	1.0	0.9135
	F3	1.0	0.8465
2LL	F1	1.0	0.9474
	F2	1.0	0.9380
	F3	1.0	0.8366
1LG	F1	1.0	0.8930
	F2	1.0	0.8860
	F3	1.0	0.8640

Figure 13 shows the different response of TKE when conventional reclosing or optimal reclosing control takes place on a circuit breaker when same type faults happened. In Figure 13, a permanent fault occurred. The y-axis is the TKE response, and the dashed line is the TKE response under optimal reclosing (according to table above, the circuit breaker reclosed at 0.9590 sec for (a)). The solid line is the TKE response under conventional reclosing (the circuit breaker reclosed at 1.0 sec). Figure 13(b) shows that TKE response is better when under optimal reclosing, which means system is more stable.



(a) Fault type: 3LG permanent fault at F1



(b) 1LG permanent fault at F2

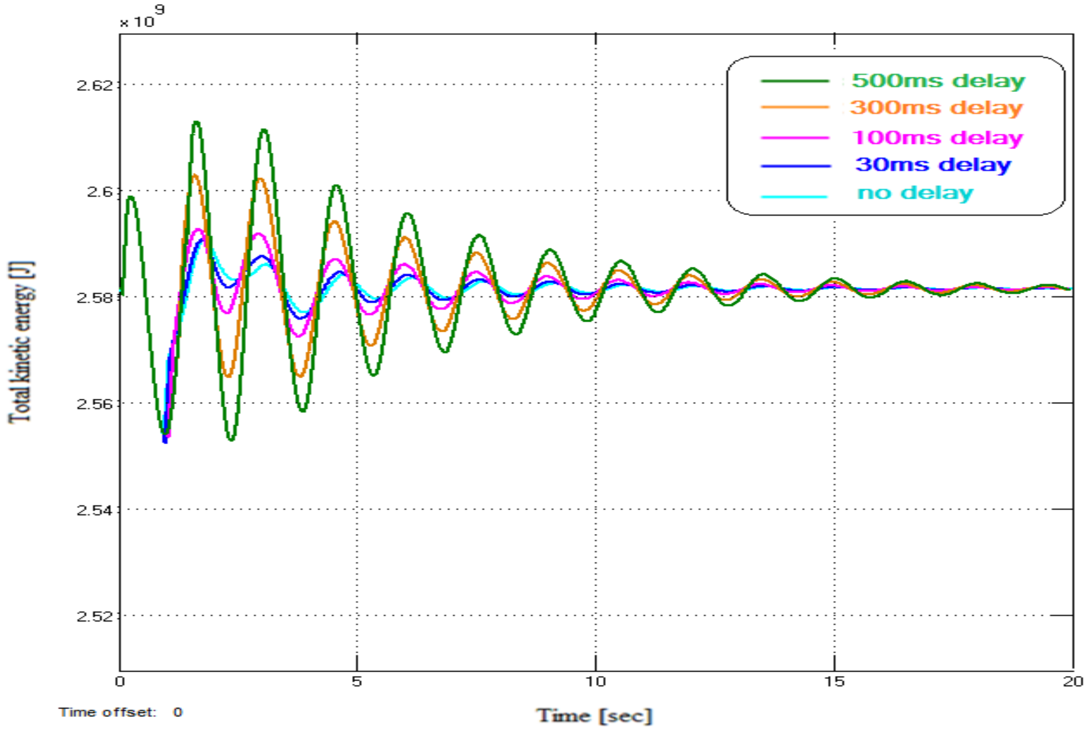
Figure 13: Response for TKE when circuit breaker close at conventional or OPRT point

F. Negative effects of Time Delay in IEEE Nine-Bus System

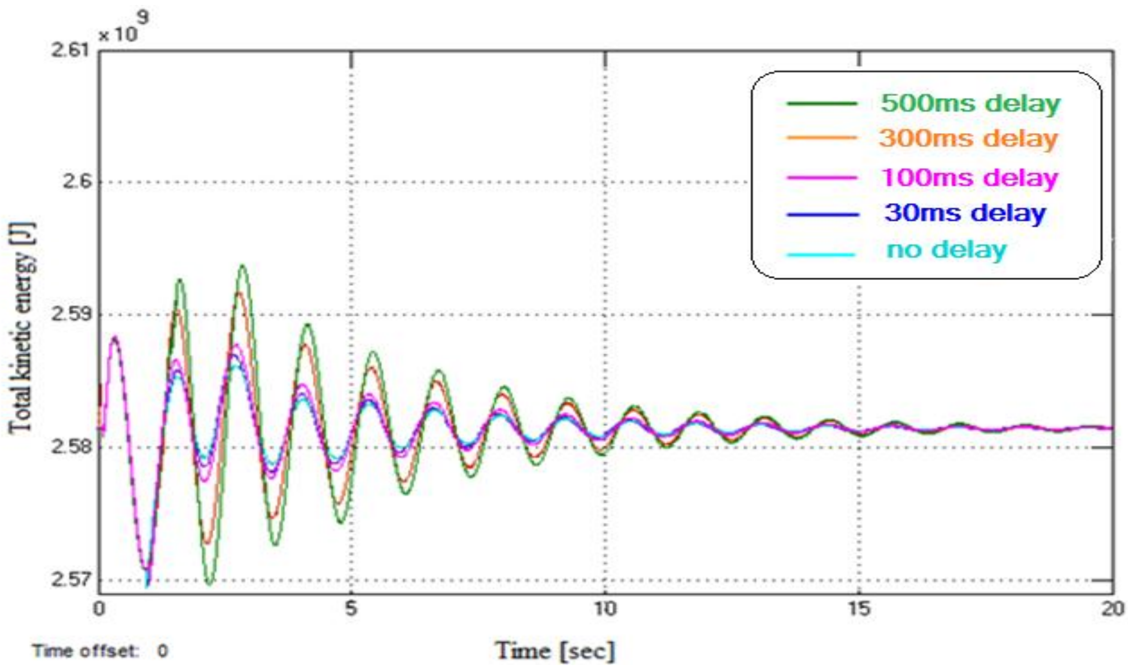
As mentioned in Chapter 2, communication delay will cause a delayed control signal. Although such delay usually is very small, when considered in sensitive signal transmission, it can have significant effects on the system.

Simulations have been done in IEEE nine-bus system, considering electrical network delays. Same faults taken place in 0, 30ms, 100ms, 300ms and 500ms delayed systems. Figure 14 gives a visual description of system responses for different time delays. Large signal delay system has most oscillating TKE response, while zero signal system has the least.

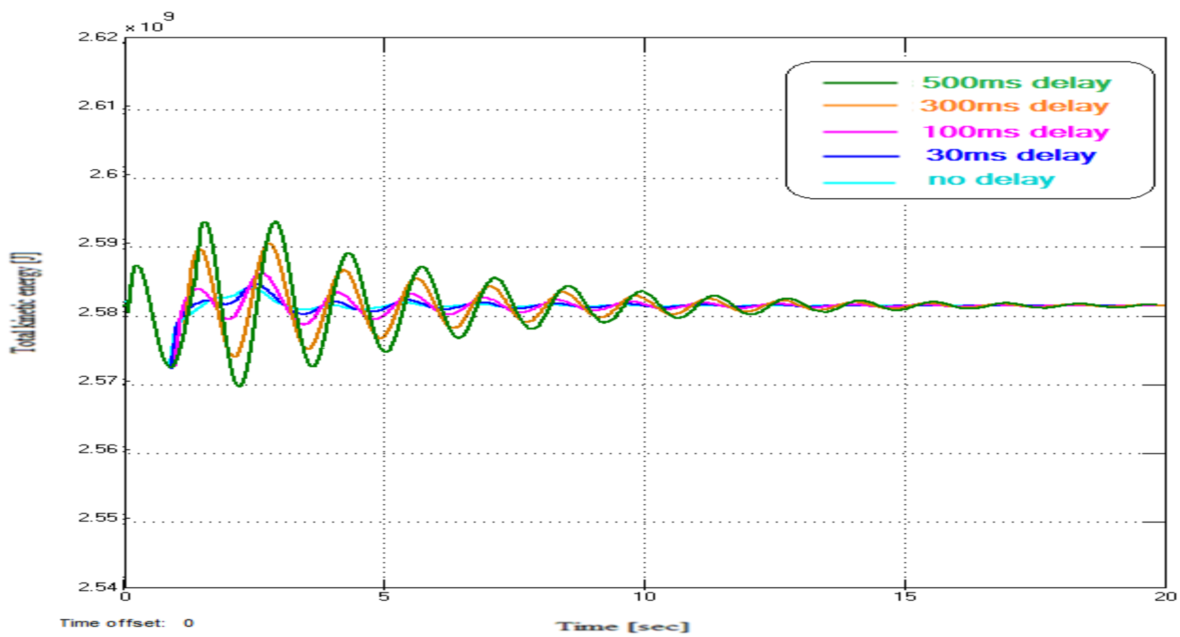
Table 3 compares W_{total} under different delayed systems. Both simulation figures and numeric results show that time delays will bring unstable effects to the system and larger delays will cause larger oscillation.



(a)TKE response for 3LG permanent fault at F1



(b) TKE response for 2LL permanent fault at F1



(c) TKE response for 2LL permanent fault at F1

Figure 14: Response for TKE under different delays for different type faults

Table 3: Some W_{total} under different delayed system

Fault type / W_{total}	**No delay**	**30ms delay**	**100ms delay**	**300ms delay**	**500ms delay**
3LG at F1 permanent	0.3530	0.3966	0.5001	0.5051	0.9493
2LL at F1 permanent	0.1904	0.2116	0.2434	0.3886	0.4670
3LL at F3 permanent	0.3741	0.3800	0.4676	0.5383	0.6867

G. Predicted Method Used in Nine-Bus System

Predictors modify the delayed control signals and try to correct the command to controllers (circuit breakers here) under delayed situations. The delay block is set after calculation of total kinetic energy, and the predictor is set after delay block. Both 30ms and 300ms delays are considered.

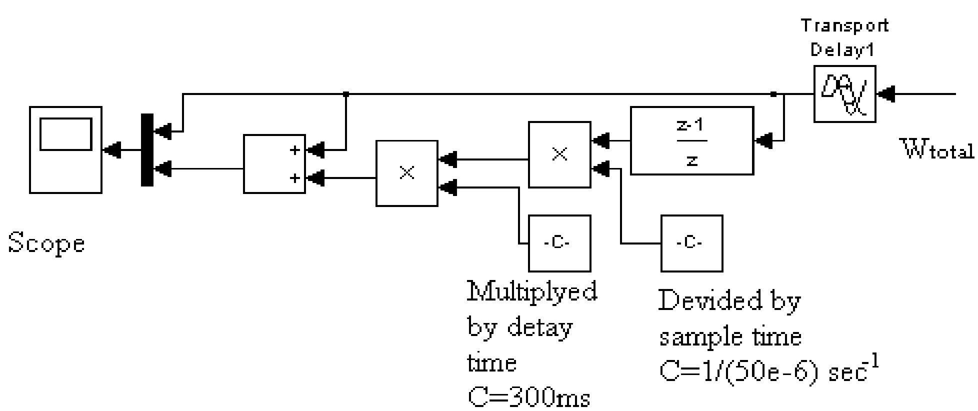


Figure 15: Predicted method simulated in Matlab/Simulink

Figure 15 illustrates the predictor which is simulated in Matlab/Simulink. The input signal is the W_{total}, and the signals in the scope are the delayed version of W_{total} and the predictor signal.

Table 4: Use predictor to calculate optimal reclosing time

		Without delay	**30ms delay without predictor**	**30ms delay with predictor**	**300ms delay without predictor**	**300ms delay with predictor**
Fault Type	**Fault Point**	**Reclosing Time**	**Reclosing Time**	**Reclosing Time**	**Reclosing Time**	**Reclosing Time**
3LG	F1	0.9590	0.9890	0.9620	1.2590	1.0625
	F2	0.9572	0.9872	0.9538	1.2527	1.0627
	F3	0.8426	0.8726	0.8440	1.2426	0.9810
3LL	F1	0.9597	0.9897	0.9540	1.2597	1.0625
	F2	0.9558	0.9858	0.9586	1.0050	1.0627
	F3	0.8415	0.8715	0.8423	1.1415	0.9830
2LG	F1	0.9175	0.9475	0.9150	1.2175	1.0150
	F2	0.9135	0.9435	0.9148	1.2135	1.0040
	F3	0.8465	0.8765	0.8534	1.1465	0.9832
2LL	F1	0.9474	0.9802	0.9550	1.2474	1.0446
	F2	0.9380	0.9680	0.9348	1.2380	1.0246
	F3	0.8366	0.8666	0.8335	1.2366	0.9632
1LG	F1	0.8930	0.9230	0.8960	1.1930	0.9965
	F2	0.8860	0.9160	0.8766	1.2860	0.9860
	F3	0.8640	0.8940	0.8652	1.2640	1.0040

Table 4 shows the results of OPRT calculated after predictor, and compares them with no-delay OPRTs. Conclusions can be made from Table 4 that predictor helps correct the delayed command. For example, consider 3LL fault at F1, system without delay has the OPRT (0.9597sec), while 30ms delayed OPRT is 0.9897sec. OPRT with predictor is 0.9540sec, which is less than the delayed OPRT, but not as good as an ideal system. For a 2LG fault at F3, the ideal OPRT is 0.8465. The OPRT for 300ms delayed system is 1.1465 and with predictor it is 0.9832. The predictor improves the time delay influence.

The simulation results for an improved nine-bus system are shown in Figures 16-20. Figures 16-20 are the total kinetic energy responses for 3LG, and 1LG permanent faults at points F1, F2 and F3 with and without predictor for cases of 300ms and 30ms delays. For 300ms delayed system, it can be seen that from Figures 16-18 that there are significant differences among the ideal, with predictor and without predictor cases. This demonstrates that although the predictor is useful for minimizing oscillations arising from delay, the oscillation is still larger than in the ideal curve. In Figure 19-20, for small delayed system, the curve with the predictor is almost to the same as the ideal curve.

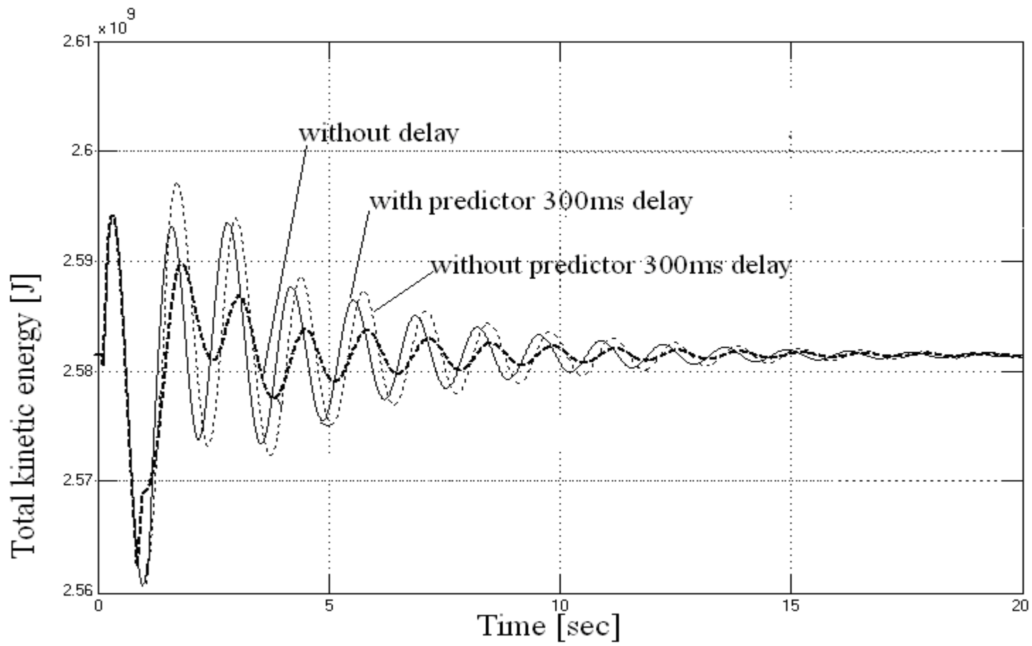


Figure 16: Responses for with and without predictor in case of 3LG permanent fault at F1 in 300ms delayed system

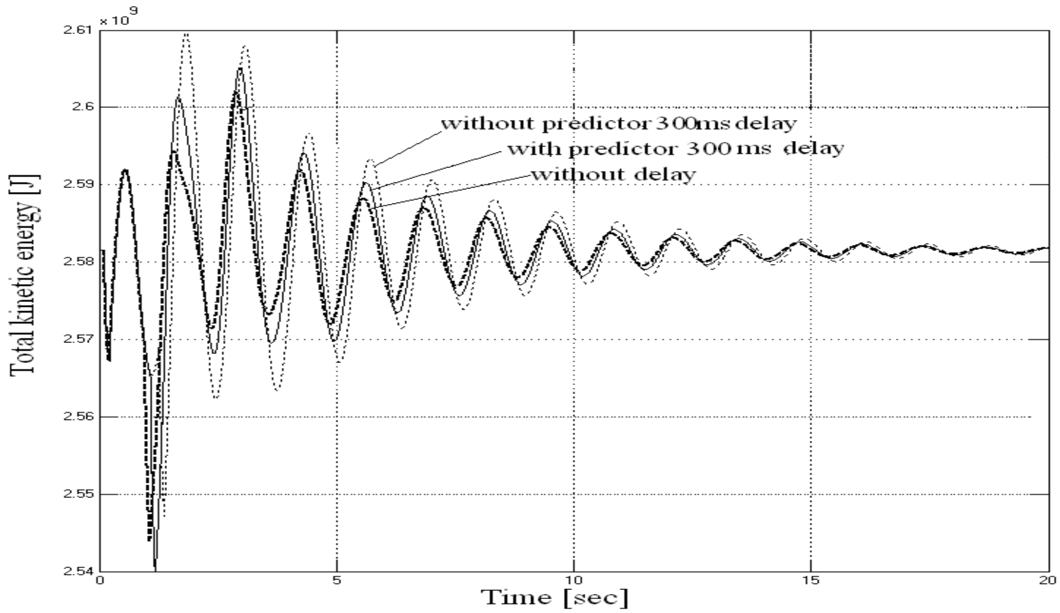


Figure 17: Responses for with and without predictor in case of 3LG permanent fault at F2 in 300ms delayed system

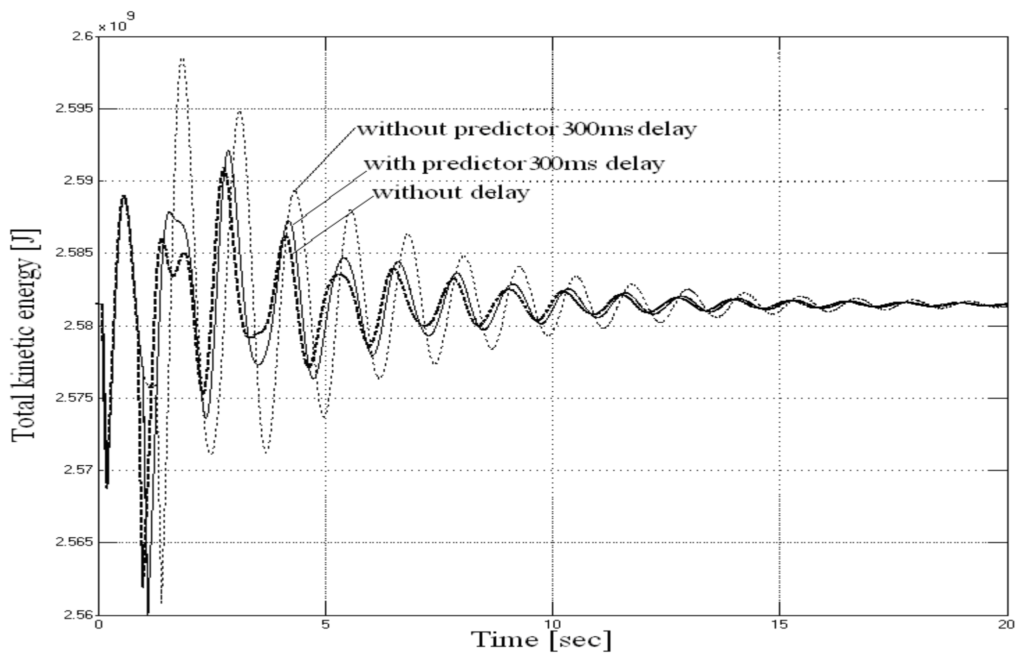


Figure 18: Responses for with and without predictor in case of 1LG permanent fault at F2 in 300ms delayed system

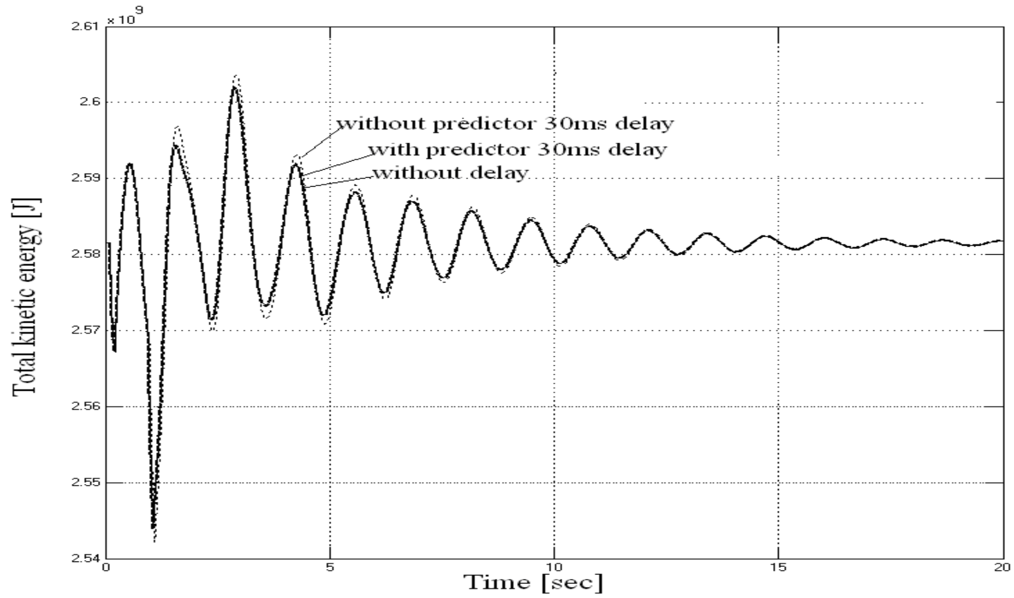


Figure 19: Responses for with and without predictor in case of 3LG permanent fault at F2 in 30ms delayed system

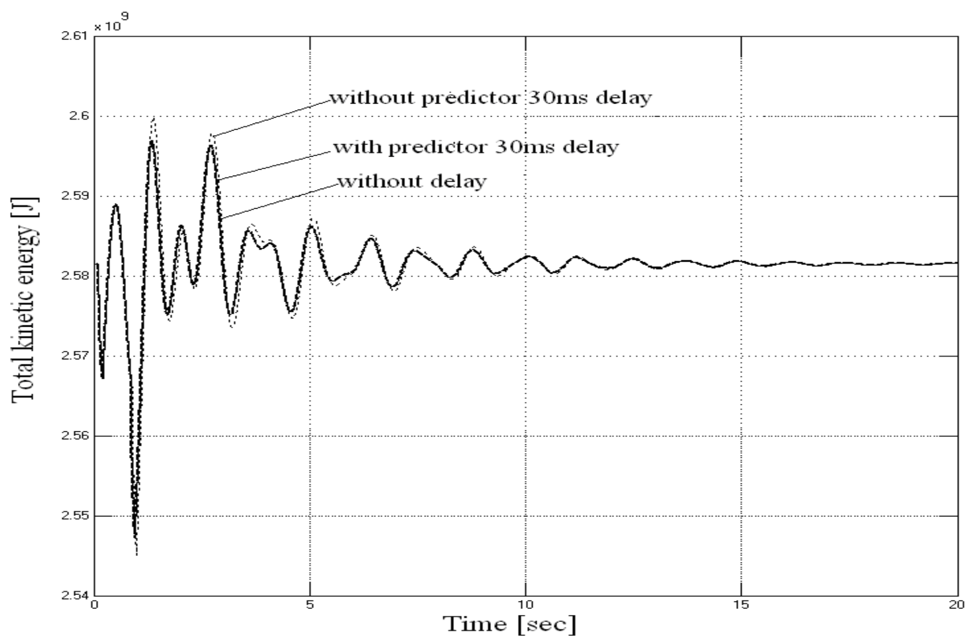


Figure 20: Responses for with and without predictor in case of 3LG permanent fault at F3 in 30ms delay system

Table 5: Comparison of W_{index} in ideal system and 30ms delay system with and without predictor

		Without delay	**30ms delay without predictor**	**30ms delay with predictor**
Fault type	**Fault point**	$\mathbf{W_{index}}$	$\mathbf{W_{index}}$	$\mathbf{W_{index}}$
3LG	F1	0.3253	0.3966	0.3563
	F2	0.6582	0.7291	0.6525
	F3	0.3848	0.4395	0.3837
3LL	F1	0.3467	0.3906	0.3407
	F2	0.6557	0.7265	0.6489
	F3	0.3741	0.4271	0.3796
2LG	F1	0.2195	0.2499	0.2186
	F2	0.5919	0.5405	0.4950
	F3	0.3395	0.3730	0.3442
2LL	F1	0.1904	0.2032	0.1946
	F2	0.3336	0.3597	0.3468
	F3	0.1958	0.2269	0.1950
1LG	F1	0.0964	0.1144	0.1003
	F2	0.2759	0.3023	0.2715
	F3	0.2092	0.2258	0.2140

Table 6: Comparison of W_{index} in ideal system and 300ms delay system with and without predictor

		Without delay	**300ms delay without predictor**	**300ms delay with predictor**
Fault type	**Fault point**	$\mathbf{W_{index}}$	$\mathbf{W_{index}}$	$\mathbf{W_{index}}$
3LG	F1	0.3253	0.6974	0.4455
	F2	0.6582	1.0150	0.8229
	F3	0.3848	0.5102	0.4990
3LL	F1	0.3467	0.6920	0.4403
	F2	0.6557	0.9776	0.8142
	F3	0.3741	0.4213	0.4998
2LG	F1	0.2195	0.4744	0.2760
	F2	0.4917	0.8684	0.5996
	F3	0.3395	0.5690	0.4334
2LL	F1	0.1904	0.3707	0.2283
	F2	0.3336	0.4865	0.3995
	F3	0.1958	0.2963	0.2271
1LG	F1	0.0964	0.2488	0.1275
	F2	0.2759	0.5269	0.3455
	F3	0.2092	0.3954	0.2776

Table 5 compares W_{index} with and without predictor for 30ms delayed system, and Table 6 shows W_{index} with and without predictor for 300ms delayed system. It can be seen from Tables 3 and 4 that:

a) The 3LG fault exhibits the most oscillation while the 1LG fault shows the least. For example, without delay situation, the W_{index} value for 3LG at F1 is 0.3530 and for 1LG it is 0.09645.

b) With the same fault type and fault point, a larger time delays in the system have larger oscillations. For example, for the 2LG fault at F2, W_{index} of 300ms delayed system is 0.8684, and with 30ms delayed system it is 0.5405.

c) The predictor assists in maintaining system stability when comparing the ideal and delayed system. For example, for 300ms delayed system, when 3LL fault occurs at point F1, the W_{index} for ideal, predicted and delayed systems are 0.3467, 0.8142 and 0.9776, respectively. W_{index} for predicted system is less than delayed system. Another example can be shown in the 30ms delayed system. When 1LG fault happens at F3, the W_{index} for ideal, predicted and delayed systems are 0.2092, 0.214 and 0.2258. Again the predicted system is more stable than the delayed system. However, for the small delayed system (30ms delayed) the difference between ideal W_{index} and predicted W_{index} is quite smaller than large delayed system (300ms delayed).

V. Conclusion and Future Work

This thesis deals with the minimization of negative effects of time delays in a smart gird system. The prediction method has been shown to minimize the negative effects of time delays. The OPRT (optimal reclosing time) method is compared to conventional reclosing method to reclose circuit breakers. ORPT was chosen as the best reclosing scheme for system performance. Time delays of 30ms and 300ms as well as balanced and unbalanced permanent faults at different locations have been considered. Different delay times have been considered in IEEE nine-bus system, and the negative effects of time delay in system have been simulated and discussed.

From the simulation results, the following points are noteworthy:

a) Optimal reclosing results in greater stability than conventional reclosing for controlling faults.

b) Communication delays on controllers will make a system unstable, and a larger delay will bring a larger oscillation to system.

c) The proposed predictor performs well in minimizing the negative effects of time delays.

d) The predictor can work more efficiently and accurately when the time delay is smaller.

A. Contribution of the Thesis

Most research work deals with time delay needs to consider a system mathematical model. In this way, the simulation would be very complex and not easy to adapt to another similar system. The predicted method proposed in this paper is easy and efficient to add to controllers with delayed signal problems. Simulation took place on IEEE nine-bus system, and shows good results when adopting predictors.

B. Future Work

The communication delay problem is interesting and can be applied to the real world. Continued research is worthwhile and should be continued. Following are proposed areas for future work:

a) Simulation results show the predicted curve may have oscillations in some scenarios. Future work should be directed to exploring ways to minimize oscillations with the prediction method.

b) Predictors in small delayed system have better results. Combining prediction methods with methods to minimize communication delay should be considered.

c) Smart grids are susceptible to cyber attack. Since a cyber attack can cause much larger delays, they would result a larger disturbances. How cyber attacks can affect smart grid, and how to build cyber security systems to mitigate these threats to systems are my next work.

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