



Effects of Time Delays in the Electric Power Grid

Hasan Ali, Dipankar Dasgupta

► To cite this version:

Hasan Ali, Dipankar Dasgupta. Effects of Time Delays in the Electric Power Grid. 6th International Conference on Critical Infrastructure Protection (ICCIP), Mar 2012, Washington, DC, United States. pp.139-154, 10.1007/978-3-642-35764-0_11 . hal-01483810

HAL Id: hal-01483810

<https://inria.hal.science/hal-01483810>

Submitted on 6 Mar 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Chapter 11

EFFECTS OF TIME DELAYS IN THE ELECTRIC POWER GRID

Hasan Ali and Dipankar Dasgupta

Abstract Communication delays in an electric power grid affect the performance of control systems and can cause power losses. This paper analyzes the causes and effects of communication delays. The analysis employs a simulated power network comprising several generators for which braking resistors with intelligent (fuzzy logic) controllers are used for transient stability control. A balanced 3LG (three-phase-to-ground) fault at different points on the transmission lines is considered. Simulation results show that, although a fuzzy-logic-controlled braking resistor can improve transient stability, the communication delay associated with the online calculation of the total kinetic energy deviation, which is the input parameter for fuzzy control, has an influence on the transient stability performance. The paper also examines the delay that a system can tolerate and the cyber attacks that can cause additional delays.

Keywords: Power grid, communication delays, transient stability control

1. Introduction

In a modern electric power grid, numerous parameters are measured and communicated for purposes of control. In fact, the measurement and communications network of a power system is referred to as a “wide-area measurement system” (WAMS) [12]. Due to the increased speed of communications equipment and the introduction of new devices such as phasor measurement units, some power engineers have proposed that existing wide-area measurement systems be used to implement wide-area controls. Such a wide-area control system (WACS) can be used to control a variety of components, including power system stabilizers, HVDC systems and supplementary controllers for flexible AC transmission system (FACTS) devices.

In a wide-area control system, the time required to transmit data from the measurement location to a control center or data concentrator and the time required to ultimately communicate this data to control devices are collectively

referred to as the communication delay or latency [12]. Communication delays can occur at various points in a control system. The introduction of a time delay in a feedback loop has a destabilizing effect and reduces the effectiveness of control system damping. In some cases, system synchronization may be lost [16].

In order to satisfy the performance specifications of wide-area control systems, it is important that delays are taken into account during the controller design. A designed controller should tolerate the specified range of operating conditions and the delay uncertainty [16]. The impact of time delays on controller robustness has largely been ignored in the power systems domain, but the subject has become significant in recent years due to proposals that advocate wide-area power system control.

This paper describes the causes and effects of communication delays in an electric power grid. Also, it examines the amount of delay that a system can tolerate and the cyber attacks that can cause additional delays. The analysis of communication delays is conducted using a simulated power system with generators that employ braking resistors [1] for transient stability control. The switching of braking resistors is implemented using intelligent (fuzzy logic) controllers. The total kinetic energy deviation (TKED) of a generator is used as input to a fuzzy controller for braking resistor switching [2]. Simulations are conducted using the Electro-Magnetic Transients Program (EMTP), a special transient simulation system that can predict the values of variables in an electric power network as functions of time, typically following some disturbance such as the switching of a circuit breaker or a fault [4]. The effectiveness of intelligent braking resistors is demonstrated using a balanced 3LG (three-phase-to-ground) fault at different points on the transmission lines. Various values of communication delays, potentially caused by natural disasters, faults and cyber attacks, are also considered in the transient stability analysis.

2. Communication Delays in the Power Grid

A communication delay in a power grid is defined as the time between the sending of a message from the source device to the receiving of the message at the destination device [14]. It is measured end-to-end between two applications running at the source and destination systems. Because electric power devices do not have communications capabilities, each device is typically attached to an embedded computer system that serves as the communications interface to the network infrastructure.

The electric device and the embedded computer system together form an intelligence electronic device (IED). Figure 1 shows the message processing steps that occur within an IED. In the figure, a message containing device status data is generated and transmitted through four modules in the IED: (i) the analog-to-digital converter transforms the status measurement into digital data; (ii) the CPU processes the measurement data; (iii) the setpoint structure stores the measurement data; and (iv) the network protocol stack formats the

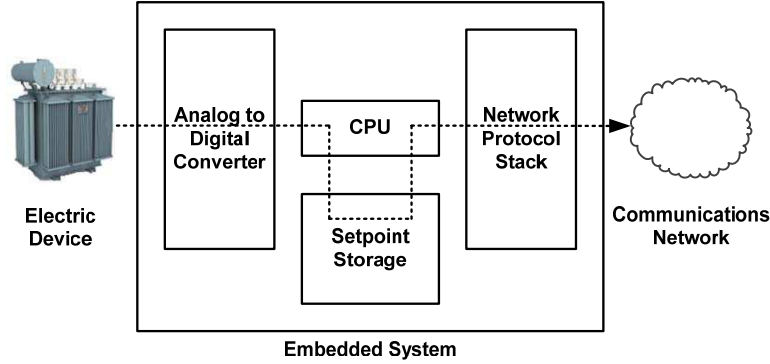


Figure 1. Processing time in an intelligent electronic device.

message and sends it over the network. The time spent by the message within the IED is included in the end-to-end delay.

2.1 Critical Timing Requirements

Timing is critical in power grid communications, more so in the “smart grid.” Indeed, this is the most fundamental difference between communications in the power grid and communications in most other networks. Some types of information exchange between electric devices are useful only within a predefined time window. If the communication delay exceeds the time window, the information does not serve its purpose; in the worst case, the delay could damage equipment in the grid.

An example is power device protection, where a circuit breaker must be opened immediately if the voltage or current in a device exceeds a threshold. Rigorous communication delay requirements have been specified for various types of information exchange in power grids (including smart grids). The mandated timing requirements must be met by power grid communications infrastructures.

2.2 Delay Components

The communications infrastructure in a power grid incorporates many networking technologies and has a hierarchical and hybrid composition. Various types of interconnected networks are used to provide communications in different regions of the grid. The delay experienced by a message includes many components as the message travels within each network and through the interfaces between networks. In general, the delay can be categorized in terms of five components [14]:

- **Data Acquisition Delay:** Status measurements, such as voltage, current and temperature, are acquired periodically from electric devices and converted from their original analog formats to digital representations.

The digital information is processed by the attached embedded system, which functions as a low-profile computer, for transmission through the communications networks. The data acquisition delay is the time between the event occurrence (e.g., voltage change) and the actual digital information capture.

- **Packet Processing Delay:** Data is transmitted through a communications network according to the specified network protocols. Various packet headers and trailers are added, inspected, modified and removed along the packet transmission path. Each step in packet processing adds a delay to the total time spent by a packet in the network.
- **Packet Transmission Delay:** Current link layer mechanisms append a data integrity check field to each data frame to detect possible data errors. Every intermediate node on the packet transmission path verifies data correctness after receiving the complete data frame and before forwarding the packet to the next relay node. Each link incurs a transmission delay due to the sending and receiving of a data frame.
- **Medium Access Delay:** Multiple nodes that share the same transmission medium (e.g., wireless spectrum and wireline cable) compete for medium access in order to transmit their data. A node has to wait for its turn to transmit data. Similarly, a packet at a node has to wait until all the other packets scheduled ahead of it have been cleared from the buffer.
- **Event Response Delay:** Some types of IED status messages require actions to be performed. For example, a measured voltage that exceeds the normal value must trigger a circuit breaker command from the control station. The event response delay is the time taken by the intelligent energy and fault management system that resides at the node responsible for the action to actually perform the action.

2.3 Time Delay Calculations

In a wide-area control system, it is assumed that data is transmitted in the form of packets [12]. The packets are formatted blocks of information that are typically arranged in three sections: header, payload and trailer. The information in the header includes the packet length, origin and destination address, packet type and packet number (if a sequence of packets is sent). The payload carries the measurement or control data. The trailer at the end of the packet carries information that enables the receiving device to identify the end of the packet.

The total time delay includes several delays that occur in communications systems [12]. These delays include: (i) serial delay (delay between successive bits); (ii) between packet serial delay (delay between successive packets); (iii) routing delay (time required for data to be sent through a router and then resent to another location); and (iv) propagation delay (time required to transmit data

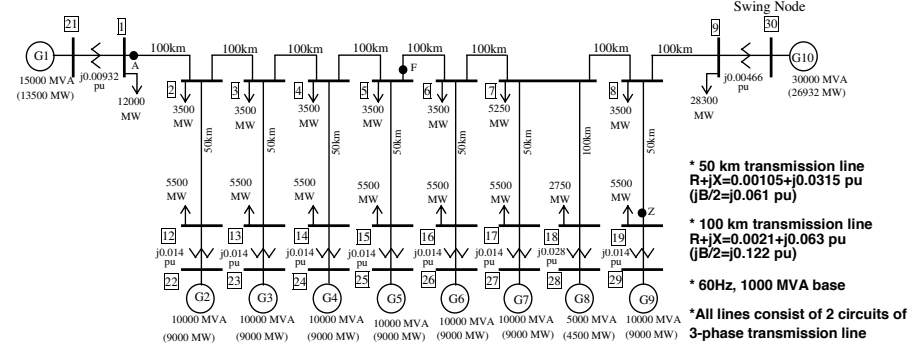


Figure 2. IEEJ West ten-machine model.

over a particular communications medium). The total signal time delay T is given by:

$$T = T_s + T_b + T_p + T_r$$

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

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

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, D_r is the data rate of the network, l is the length of the communications medium, and v is the speed at which the data is sent though the communications medium (e.g., $0.6c$ to c , where c is the speed of light).

3. Analysis of Communication Delays

The IEEJ West ten-machine model [1] shown in Figure 2 is used to analyze the effects of communication delays. This ten-machine tandem model is a prototype of the Japanese 60 Hz system that presents the long-term oscillation characteristics of a tandem system. The model system incorporates ten generators (G1 to G10). Generator G10 is considered to be the “swing generator.” Each line in the figure represents two circuits of a three-phase transmission line. In this work, five braking resistors are installed at the terminal buses of Generators G1, G4-G6 and G10 to stabilize the overall system [2].

Figure 3 shows a braking resistor (BR) with a conductance value of G_{TCSBR} connected via a thyristor switching circuit to one phase of a generator terminal bus. The switching of the braking resistor is accomplished by a fuzzy logic controller. The total kinetic energy deviation (TKED) is used as the input to the fuzzy controller for switching. In our work, TKED is defined as the

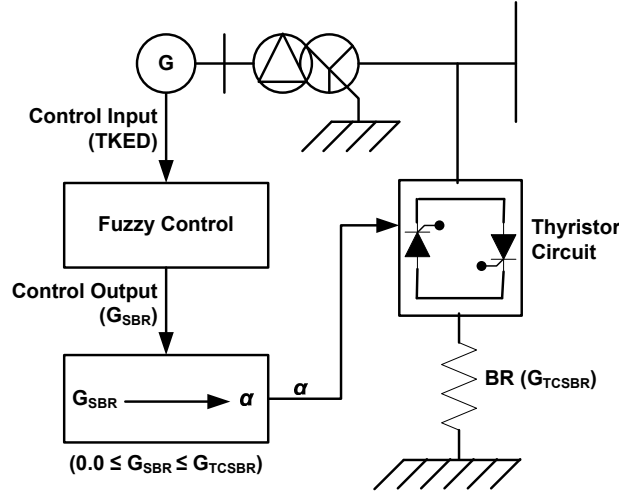


Figure 3. Braking resistor with thyristor switching circuit.

difference between the total kinetic energy (W_{total}) of a generator at a transient state and the total kinetic energy at the steady state. Models of the automatic voltage regulator and governor control system for the IEEJ West ten-machine system were included in our simulation. Interested readers are referred to [1] for details about the generator parameters.

3.1 Closed-Loop Control System

Figure 4 shows a closed-loop control system for braking resistor operation. The communication delay in this system includes the upstream and downstream links. As shown in the figure, the speed equivalent signal of each generator is passed through a filter and an analog-to-digital converter. The resulting digital signals are sent to a central control office, where a global positioning system (GPS) receiver synchronizes the signals using a common timing reference. The synchronized signals are used to compute the TKED, which is sent as input to the fuzzy controller. The signals may be transmitted and received through microwave or optical links.

3.2 Causes of Communication Delays

In the control system in Figure 4, time delays are introduced due to signal transmission via microwave or optical links, analog-to-digital conversion, online TKED computation and time synchronization of GPS signals. These communication delays adversely affect the opening and closing of circuit breakers following a fault in the electric grid. Note that communication delays may also result from attacks on the information infrastructure; these delays are discussed in Section 6.

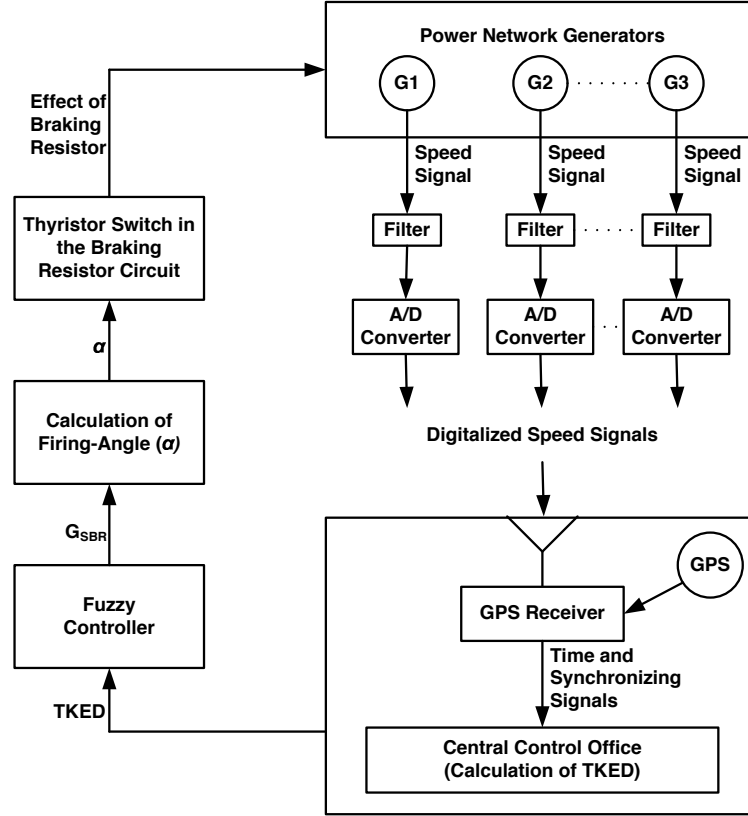


Figure 4. Closed-loop control system with GPS functionality.

3.3 Delay Range

Communication delays typically range from several microseconds to a few hundred milliseconds [3, 13, 15, 17]. In a distributed system such as a protective relay system, the time delay or latency is usually less than 10 ms [16]. Unlike the small time delays encountered in local control, the delays in wide-area power systems can range from tens to several hundred milliseconds or more. In the Bonneville Power Administration system, the latency of fiber optic digital communications is approximately 38 ms for one way, while the latency when using modems via microwave is more than 80 ms [16]. Communications systems that use satellites may have even longer delays.

The delay of a signal feedback in a wide-area power system is usually in the order of 100 ms [16]. If routing delays are included and if a large number of signals are to be routed, then there is the potential to experience long delays and considerable variability (or uncertainty) in these delays. According to some reports (see, e.g., [8, 10]), communication delays of 150 to 200 ms

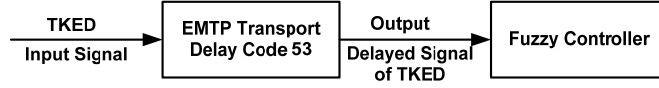


Figure 5. Applying communication delays to a controller.

should be considered when designing some transient stability control systems. In this work, simulations are conducted with communication delays ranging from 20 μsec to 500 msec.

3.4 Implementation of Communication Delays

The simulations were conducted using the Electro-Magnetic Transients Program (EMTP). During the simulations, various values of communication delays were applied to the fuzzy controller input signal through the EMTP Transient Analysis of Control Systems (TACS) Code 53 (i.e., EMTP transport delay code). The procedure is illustrated in the block diagram in Figure 5. According to the EMTP transport delay code 53, at any time t , for a value of total delay t_d (sec), the following equation holds [4]:

$$\text{Output}(t) = \text{Input}(t - t_d)$$

3.5 Delay Realities

The networking infrastructures currently in use were not designed with communication delay performance as a priority and, therefore, they may not always be able to meet the strict delay requirements of power system communications. Preliminary results of experiments on communication delays in substation networks are reported in [7]. The results demonstrate that, in many communications scenarios, the packet delays experienced in typical substation networks exceed the maximum allowed for the most time critical messages. Also, while communication delays within a single Ethernet segment are below 2 ms, the delays increase significantly in wireless and multihop networks.

Communication delays in substations have also been investigated using simulations [11]. The simulation results show that 10/100 Mbps Ethernet networks can provide satisfactory delay performance for communications in a substation. The delay measurements for the simulated network settings are less than 1 ms in most cases, which are consistent with the experimental results on Ethernet networks reported in [7]. Also, it has been observed that communication delays increase with the distance between communicating devices and, therefore, delays in large Ethernet networks may need further investigation.

Single-hop WiFi networks cannot be used to transmit system protection messages, but these networks meet the delay requirements of all other messages (e.g., system monitoring and control, operation and maintenance, text files, images and videos). ZigBee networks and multihop networks with wireless access, however, can only be used to transmit data that is not time sensitive.

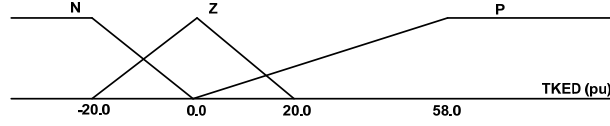


Figure 6. Membership functions for controller input $TKED$.

In particular, these networks cannot be used to transport system protection, monitoring and control messages. The delay performance becomes even worse when networks experience heavy background traffic loads or when complex multihop networks are used. Hence, the design of short-delay networks is a critical problem to support effective energy management functions, especially in the smart grid.

4. Fuzzy Logic Controller Design

Fuzzy logic extends two-valued Boolean logic by permitting truth values in the continuous interval $[0,1]$ where 0 is completely false, 1 is completely true, and the values in between 0 and 1 express degrees of truth. This extension is especially useful for solving problems that involve subjective uncertainty or imprecision.

Fuzzy logic control is a process control paradigm that is based on fuzzy logic. It typically employs a series of IF-THEN rules, whose conditions and actions are expressed as fuzzy variables. This section describes the design of the fuzzy logic controllers used for switching the braking resistors.

4.1 Fuzzification

Each fuzzy logic controller has as input the $TKED$ value of the associated generator and produces an output G_{SBR} , the braking resistor conductance, where $G_{SBR} \in [0, G_{TCSBR}]$. Triangular fuzzy membership functions are chosen for $TKED$ as shown in Figure 6. The membership functions specify the fuzzy linguistic variables *Negative*, *Zero* and *Positive*, which are denoted as N , Z and P , respectively. The precise shapes of the membership functions for $TKED$ are determined by trial and error in order to obtain good performance.

The triangular membership functions μ_A used to determine the fuzzy membership values of input variable values $TKED$ ranging from -20 pu to 58 pu are given by [5]:

$$\mu_A(TKED) = \frac{1}{b} \left[b - 2 \times \left| TKED - a \right| \right] \quad (1)$$

where $\mu_A(TKED)$ is the membership value corresponding to a controller input value $TKED$, b is the width of the membership function and a is the coordinate of the point at which the membership value is one.

Table 1. Fuzzy rule table.

TKED [pu]	G_{SBR} [pu]				
	BR1	BR4	BR5	BR6	BR10
N	0.0	0.0	0.0	0.0	0.0
Z	0.0	0.0	0.0	0.0	0.0
P	15.0	7.0	4.0	4.0	4.0

4.2 Control Rules

The fuzzy control strategy is very simple because it incorporates only three IF-THEN control rules for each controller. Table 1 shows the control rules, where the numerical values of G_{SBR} correspond to the fuzzy controller outputs. Note that the control rules were developed by trial and error based on practical system operations. For example, a braking resistor (BR) can consume active power during acceleration (P : *Positive*) but cannot generate or consume active power during deceleration (N : *Negative*). Also, when the system is at steady state (Z : *Zero*), the braking resistor does not need to consume active power. Thus, the fuzzy rule table only has P (*Positive*) values.

4.3 Fuzzy Inference

Mamdani's inference mechanism [5] is employed by the fuzzy logic controller. According to this mechanism, the degree of satisfaction W_i of a fuzzy rule i is given by:

$$W_i = \mu_A(TKED)$$

where $\mu_A(TKED)$ is the membership value as defined by Equation (1).

4.4 Defuzzification

A defuzzification method is required to determine the crisp (precise) output value of the controller, i.e., the conductance value G_{SBR} of the braking resistor. The center-of-area method [5], a simple and popular defuzzification method, is used in this work. According to this method, the controller output value G_{SBR} is given by:

$$G_{SBR} = \frac{\sum W_i C_i}{\sum W_i}$$

where C_i is the value of G_{SBR} in the fuzzy rule table (Table 1).

4.5 Thyristor Firing Angle Computation

The firing angle α of the thyristor switch is calculated from the output of the fuzzy controller, i.e., from the conductance value of the braking resistor $G_{SBR} \in [0, G_{TCSBR}]$. The conductance value G_{SBR} is related to the power dissipated in the braking resistor.

At any step in the simulation, P_{SBR} , the average power of a system braking resistor (SBR) with a conductance of G_{SBR} , is equal to P_{TCSBR} , the average power of a thyristor controlled system braking resistor (TCSBR) with a conductance of G_{TCSBR} . Thus, the firing angle α can be computed using the equation:

$$P_{TCSBR} = P_{SBR}$$

or

$$\frac{V_g^2 G_{TCSBR}}{\pi} (\pi - \alpha + 0.5 \sin(2\alpha)) = V_g^2 G_{SBR}$$

where V_g is the root-mean-square value of the generator terminal bus voltage.

5. Simulation of Communication Delays

Communication delays can affect the control logic and, consequently, the performance of the overall system. Therefore, it is important to consider communication delays in a study of a power network.

We conducted simulations using balanced (3LG) faults at Points A, F and Z on the transmission lines. In all the test cases, the simulated fault occurred at 0.1 sec, the circuit breakers on the faulty lines were opened at 0.17 sec, and the circuit breakers were closed at 1.003 sec. It was assumed that the circuit breaker cleared the line when the current through it crossed the zero level. The time step and simulation time were chosen to be 0.00005 sec and 20 sec, respectively.

In order to understand the effects of communication delays, we conducted several experiments that ignored communication delays. The transient stability of the system was evaluated using a stability index W_c (lower W_c value indicates better performance). The stability index (sec) is given by:

$$W_c = \int_0^T \left| \frac{d}{dt} W_{total} \right| dt / \text{system base power}$$

where T is the simulation time of 20 sec and W_{total} is the total kinetic energy (Joules) given by:

$$W_{total} = \sum_{i=1}^N W_i$$

Table 2. Values of W_c with communication delays.

Fault Point	Communication Delay	W_c (sec) with BR	W_c (sec) without BR
A	20 μ sec	26.353	238.917
	200 μ sec	29.331	
	2 msec	30.133	
	20 msec	32.786	
	200 msec	39.401	
	500 msec	47.855	
F	20 μ sec	30.527	72.573
	200 μ sec	33.613	
	2 msec	35.565	
	20 msec	36.116	
	200 msec	37.657	
	500 msec	38.282	
Z	20 μ sec	24.267	70.135
	200 μ sec	26.175	
	2 msec	31.063	
	20 msec	33.127	
	200 msec	40.480	
	500 msec	40.536	

in which the kinetic energy of the i -th generator W_i (Joules) is given by:

$$W_i = \frac{1}{2} J_i \omega_{mi}^2$$

Note that N is the total number of generators. Also, the moment of inertia J_i ($\text{kg}\cdot\text{m}^2$) is given by:

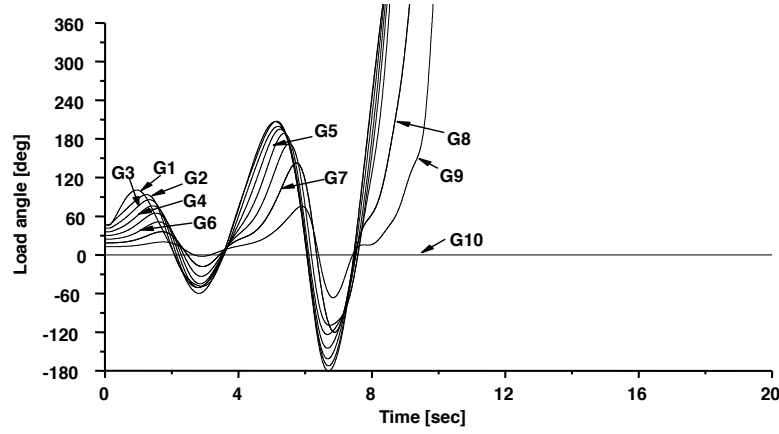
$$J_i = \frac{H \times MVA \text{ rating}}{5.48 \times 10^{-9} N_S^2}$$

where N_S and H are the synchronous angular speed (rpm) and inertia constant, respectively, and

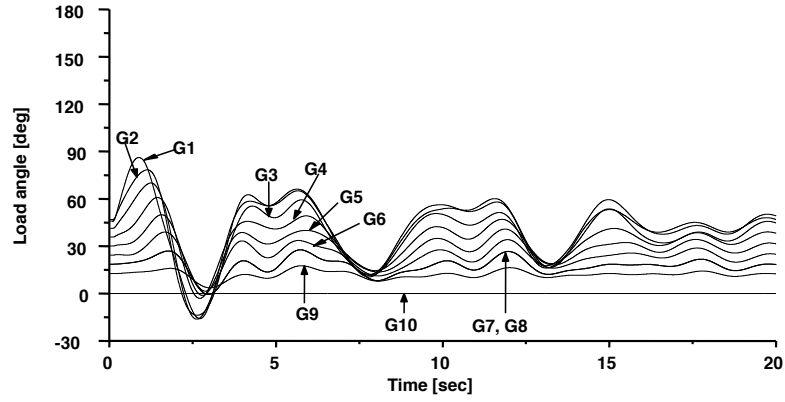
$$\omega_{mi} = \frac{2\pi N_R}{60}$$

is the rotor angular velocity (mechanical rad/sec) and N_R is the rotor speed (rpm).

Extensive simulations were conducted to perform the transient stability analysis. Table 2 shows the W_c values for 3LG faults at Points A, F and Z for various communication delays. The results demonstrate that the fuzzy-controlled braking resistors are effective at improving the transient stability. Also, the W_c values corresponding to different communication delays are different at different points. This indicates that the communication delay associated with the



(a) Without braking resistor.



(b) With fuzzy-logic-controlled braking resistor.

Figure 7. Load angle responses without communication delays.

online calculation of the fuzzy controller input has a small negative impact on the transient stability.

Figures 7(a) and 7(b) show the load angle responses in the case of a 3LG fault at Point A without and with a fuzzy-controlled braking resistor, respectively. Communication delays were not considered in this case. The responses demonstrate that the system is transiently stable when the fuzzy-controlled braking resistor is used.

Figure 8 shows the load angle responses with a fuzzy-controlled braking resistor for a 3LG fault at Point A and a communication delay of 500 msec. The transient stability in this case is worse than that shown in Figure 7(b), where there was no communication delay. This result shows that communication delays do, indeed, affect the transient stability performance.

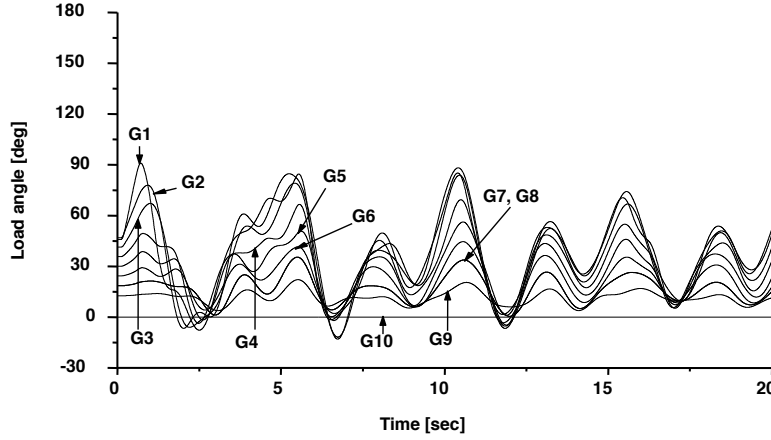


Figure 8. Load angle responses for a communication delay of 500 msec.

It is important to note that each system has a specific delay tolerance for it to function properly. Some systems can tolerate delays of 200 msec while others can function with delays of up to 300 msec. However, in the case of the power system model considered in this work, if the delay exceeds 500 msec, then the system performance deteriorates and the system becomes marginally stable. Therefore, the maximum allowable delay for the system is 500 msec.

6. Attacks Causing Communication Delays

The backbone of a power grid (and especially a smart grid) is the information infrastructure that is used for communications by the various grid components. The power industry uses different types of media (leased lines, wide-area networks, Internet, radio and microwave) to transmit data and signals between control centers and remote locations. The digital signals must be highly synchronized and time-aligned using accurate GPS clocks. However, some of the communications links are highly vulnerable to denial-of-service and man-in-the-middle attacks. Also, an attacker with unauthorized access could inject false signals to disrupt the supervisory control and data acquisition system (SCADA), resulting in power system instability.

An attacker can also use distributed denial-of-service attacks to delay, block or jam the flow of command and control messages in communications networks. Sophisticated malware such as Stuxnet can disrupt communications and synchronization, potentially resulting in massive instabilities in the power grid. These threats will be even more serious in the smart grid where communication delays must be small, and where additional delays are introduced by security measures such as encryption and authentication [6, 9].

7. Conclusions

Electric power grids require an extensive information and communications infrastructure to support the efficient and safe generation, transmission and distribution of electricity. However, the associated communication delays can affect the performance of control systems, causing power losses and possibly equipment damage. The simulation results using the IEEJ West ten-machine model demonstrate that fuzzy-logic-controlled braking resistors are highly effective at improving transient stability. But it is important to note that the delay associated with online calculations of the total kinetic energy deviation (fuzzy controller inputs) can have a negative impact on transient stability performance.

Our future research will investigate the negative effects of delays resulting from faults, failures and cyber attacks. It will also examine defensive strategies involving the use of monitoring, traffic analysis and response tools.

References

- [1] H. Ali, T. Murata and J. Tamura, The effect of temperature rise of fuzzy-logic-controlled braking resistors on transient stability, *IEEE Transactions on Power Systems*, vol. 19(2), pp. 1085–1095, 2004.
- [2] H. Ali, T. Murata and J. Tamura, Effect of coordination of optimal reclosing and fuzzy-controlled braking resistors on transient stability during unsuccessful reclosing, *IEEE Transactions on Power Systems*, vol. 21(3), pp. 1321–1330, 2006.
- [3] B. Chaudhuri, R. Majumder and B. Pal, Wide-area measurement-based stabilizing control of a power system considering signal transmission delays, *IEEE Transactions on Power Systems*, vol. 19(4), pp. 1971–1979, 2004.
- [4] H. Dommel, *EMTP Theory Book*, Microtran Power System Analysis Corporation, Vancouver, Canada, 1992.
- [5] D. Driankov, H. Hellendoorn and M. Reinfrank, *An Introduction to Fuzzy Control*, Springer-Verlag, New York, 1993.
- [6] G. Ericsson, Cyber security and power system communication – Essential parts of a smart grid infrastructure, *IEEE Transactions on Power Delivery*, vol. 25(3), pp. 1501–1507, 2010.
- [7] M. Khanna, Communication challenges for the FREEDM System, M.S. Thesis, Department of Computer Engineering, North Carolina State University, Raleigh, North Carolina, 2009.
- [8] M. Koaizawa, M. Nakane, K. Omata and Y. Kokai, Actual operating experience of on-line transient stability control systems (TSC systems), *Proceedings of the IEEE Power Engineering Society Winter Meeting*, vol. 1, pp. 84–89, 2000.

- [9] National SCADA Test Bed, Study of Security Attributes of Smart Grid Systems – Current Cyber Security Issues, INL/EXT-09-15500, Idaho National Laboratory, Idaho Falls, Idaho, 2009.
- [10] H. Ota, Y. Kitayama, H. Ito, N. Fukushima, K. Omata, K. Morita and Y. Kokai, Development of transient stability control system (TSC system) based on on-line stability calculation, *IEEE Transactions on Power Systems*, vol. 11(3), pp. 1463–1472, 1996.
- [11] T. Sidhu and Y. Yin, Modeling and simulation for performance evaluation of IEC 61850 based substation communication systems, *IEEE Transactions on Power Delivery*, vol. 22(3), pp. 1482–1489, 2007.
- [12] J. Stahlhut, T. Browne, G. Heydt and V. Vittal, Latency viewed as a stochastic process and its impact on wide-area power system control signals, *IEEE Transactions on Power Systems*, vol. 23(1), pp. 84–91, 2008.
- [13] C. Taylor, D. Erickson, K. Martin, R. Wilson and V. Venkatasubramanian, WACS – Wide-area stability and voltage control system: R&D and online demonstration, *Proceedings of the IEEE*, vol. 93(5), pp. 892–906, 2005.
- [14] W. Wang, Y. Xu and M. Khanna, A survey of the communication architectures in the smart grid, *Computer Networks*, vol. 55, pp. 3604–3629, 2011.
- [15] R. Wilson, An investigation of time transfer accuracies over a utility microwave communications channel, *IEEE Transactions on Power Delivery*, vol. 8(3), pp. 993–999, 1993.
- [16] H. Wu, K. Tsakalis and G. Heydt, Evaluation of time delay effects to wide-area power system stabilizer design, *IEEE Transactions on Power Systems*, vol. 19(4), pp. 1935–1941, 2004.
- [17] W. Yao, L. Jiang, Q. Wu, J. Wen and S. Cheng, Delay-dependent stability analysis of a power system with a wide-area damping controller embedded, *IEEE Transactions on Power Systems*, vol. 26(1), pp. 233–240, 2011.