Nuclear Engineering and Technology 50 (2018) 860–868

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Development of earthquake instrumentation for shutdown and restart criteria of the nuclear power plant using multivariable decision-making process

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A R T I C L E I N F O

Article history:
Received 29 December 2017
Received in revised form
20 March 2018
Accepted 3 April 2018
Available online 10 April 2018

Keywords:
Fatigue
Operating Basis Earthquake
Peak Ground Acceleration
Safe Shutdown Earthquake
Structure, System, and Components

A B S T R A C T

This article presents a new design of earthquake instrumentation that is suitable for quick decision-making after the seismic event at the nuclear power plant (NPP). The main objective of this work is to ensure more availability of the NPP by expediting walk-down period when the seismic wave is incident. In general, the decision-making to restart the NPP after the seismic event requires more than 1 month if an earthquake exceeds operating basis earthquake level. It affects to the plant availability significantly. Unnecessary shutdown can be skipped through quick assessments of operating basis earthquake, safe shutdown earthquake events, and damage status to structure, system, and components. Multidecision parameters such as cumulative absolute velocity, peak ground acceleration, Modified Mercalli Intensity Scale, floor response spectrum, and cumulative fatigue are discussed. The implementation scope on the field-programmable gate array platform of this work is limited to cumulative absolute velocity, peak ground acceleration, and Modified Mercalli Intensity. It can ensure better availability of the plant through integrated decision-making process by automatic assessment of NPP structure, system, and components.

1. Introduction

Many nuclear power plants (NPPs) in the world face unnecessary shutdown and wastage time to follow long procedures to restart the plant. Onagawa Plant, Japan, 2005—Base mat accelerations exceeded safe shutdown earthquake (SSE) ground motion. No damage was found to safety-related (SR) structure, system, and components (SSCs). Time to restart was 5–7 months for three units [1]. Shika Plant, Japan, 2007—In-structure response spectra (ISRS) exceeded SSE-based ISRS. No damage was observed to SR SSCs. Time to restart was 1 year [1]. Kashiwazaki-Kariwa Plant, Japan, 2007—All ground spectra exceeded SSE; ISRS significantly exceeded ISRS for SSE. No damage was found in SR SSCs. Time to restart was 22–40 months for seven units [1]. North Anna Plant, VA, USA, 2011—Base mat spectra exceeded SSE above and below 10 Hz. No damage was detected to SR SSCs. Time to restart was 2–3 months for two units (information provided by Dominion Energy). On the 12th of September 2016, South Korea experienced the most powerful earthquake ever recorded in the country since measurements began in 1978. A 5.8-magnitude earthquake struck the historic city of Gyeongju, and the people have been subject to a series of aftershocks affecting their daily lives [2]. However, the frequency of the earthquake wave was higher than 16 Hz, and a disastrous falling down of structure was not experienced. Continuous research is being carried out for accurate response to an earthquake event to avoid pseudo shutdown of the plant. Calculation of cumulative absolute velocity (CAV) has been revised as standardized cumulative absolute velocity [3]. But, a well-defined complete response to an earthquake event is still necessary for more availability of the plant with confirming integrity of SSC. Therefore, existing earthquake instrumentation and procedures should be reviewed and updated.

Design of earthquake instrumentation which is composed of Micro-Electro-Mechanical System (MEMS) sensor and field-programmable gate array (FPGA)–based seismic data processing system is developed in this work for quick assessment of the events comparing with design operating basis earthquake (OBE) and SSE levels of the plants. In addition, this design suggests a method to assess fatigue levels of NPP SSCs. Seismic sensor and its data

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https://doi.org/10.1016/j.net.2018.04.004

processing are the major parts of the earthquake instrumentation. The traditional sensor performs tremendous job in earthquake instrumentation, but it suffers significant reduction in recorded velocity-domain amplitudes and below their natural frequency. MEMS sensor, which is applied to our design, has multidimensional advantage over traditional sensors. The Digital Sensor Unit (DSU) consumes low power and shows accurate functionality at any tilt angle. It is reliable for all operations with high performance and power efficiency. The data from a single ground location is digitized by the DSU. It records accurately the ground motion on all the three axes allowed by its three orthogonal components. On the other hand, the analog sensor records the vertical component only. The performance parameters such as noise floor, full scale, dynamic range, sensitivity, and data quality prove suitability of the MEMS sensor over the traditional geophone sensor [4–6]. An important factor is that the installation and maintenance cost of the MEMS is lower than that of other sensors. MEMS response to acceleration is constant from frequency 0 Hz to 800 Hz, both in amplitude and in phase, which is optimal to capture a broadband signal [7]. Therefore, MEMS sensor response is linear in the acceleration domain down to direct current, and there should be no attenuation and sufficient signal-to-noise ratio toward the low end of the spectrum. The MEMS sensor shows the best potentiality among various seismic sensors for digital data output which is essential for interfacing with FPGA. This accelerates to design MEMS-based earthquake instrumentation with FPGA data processing system for NPPs.

After designing the new earthquake instrumentation, the various earthquake-level parameters are clarified as mathematical equation and theoretical explanation for synthesizing the design. It can provide automatic information on various parameters. If CAV exceeds threshold level (0.16 g s), OBE level exceeds. The exceedance of SSE level can be confirmed by comparing receiving and design FRS. Receiving FRS is the calculated FRS found from recorded earthquake event. If it exceeds design FRS, then the impact of the earthquake exceeds SSE level. The system can also give peak ground acceleration (PGA), Modified Mercalli Intensity (MMI), and cumulative fatigue information. Fatigue can provide current damage status information of the equipment and structure of the plant. However, in this study, CAV, PGA, and MMI parameters are focused for implementation of the FPGA platform. FRS and cumulative fatigue are excluded in consideration of workload of this study. This study will help to do quick assessment of the earthquake events and encourage updating the existing procedure in response to an earthquake event so that more availability of the plant can be ensured.

2. Materials and methods

2.1. Design architecture

Earthquake instrumentation consisting of the DSU and FPGA-based data processing system for the NPP is newly designed. The design consists of two blocks. One is for MEMS digital sensor, and another block is FPGA board. There is a relationship among magnitude, wave frequency, and the devastating power of earthquake. Seismic-measuring and detection instrumentation, i.e., sensor has been improved to detect the frequency and magnitude of the earthquake wave effectively. A single seismic instrument can be defined as mass, spring, and dashpot as shown in Fig. 1 through investigating both theory and application of earthquake instruments [8]. Seismic energy is absorbed by the dashpot. This spring-mass-dashpot system can be expressed using Newton's second law as represented in Equation (1).

$$\text{D.E.)}\ m\ddot{y} = -ky - b\dot{y} + u \qquad (1)$$

$$\text{T.F.)}\ ms^2Y(s) = -kY(s) - bsY(s) + U(s) \qquad (2)$$

$$G(s) = \frac{Y(s)}{U(s)} = \frac{1}{ms^2 + bs + k} \qquad (3)$$

The mathematical expression of the system aforementioned can be expressed as Equation (1). The transfer function of Equation (1) can be obtained as Equations (2) and (3) by taking Laplace transformation. The motion of the mass as a function of the ground displacement is expressed by a differential equation resulting from the equilibrium of forces as shown in Equation (4) [9].

$$F_s + F_r + F_g = 0[9] \qquad (4)$$

where $F_s = -kx$ (F_s is force due to spring constant, s refers to spring, k is spring constant, and x is mass displacement).

$F_r = -b\dot{x}$ (F_r is force due to friction, r refers to friction, and b is friction coefficient).
$F_g = -m\ddot{u}$ (F_g is force due to ground acceleration, g refers to ground, m is spring mass, and u is the ground displacement).

The digital sensor which follows same rules which contains inertial mass, analog-to-digital converter, feedback, force-feedback actuator, and digital filter is shown in Fig. 2. In the digital sensor, a MEMS casing (blue) is attached to a sensor casing (not represented). Stiff springs (black) maintain the inertial mass (green) which moves with casing/ground motions. Electrodes (red) measure the displacements of the inertial mass, when it is subjected to seismic acceleration. A closed-loop MEMS accelerometer is driven mainly by the electrostatic feedback force; so, sensitivity is no longer a function of such mechanical parameters. The closed loop also minimizes the mass displacement because any force on the mass induced by acceleration is counteracted immediately by an opposite electrostatic force. A force-feedback actuator generates within microseconds a voltage that brings the electrodes back to their rest positions. Actually, the original mass displacement is very small, and it is negligible (a few nanometers), and spring-stiffness nonlinearity does not induce any distortion. The FPGA board receives ground motion acceleration data from the digital filter of the sensor and performs interfacing with the sensor. Here, seismic signal analysis is analyzed for calculating CAV, MMI, PGA, FRS, and cumulative fatigue. It gives OBE, SSE-level vulnerability alarm, and SSC damage information to the status logging and external interface.

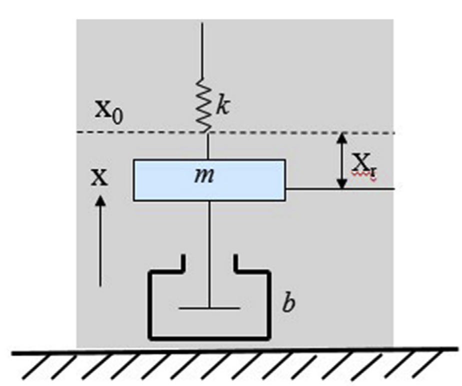

Fig. 1. Spring-mass-dashpot system.