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A TECHNIQUE FOR MORE EFFICIENT TIME INTEGRATION APPLIED TO SEISMIC ANALYSIS OF POWER SUBSTATION EQUIPMENTS

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Key words: *Power substation equipments, Seismic analysis, Time integration, Integration step size, Excitation step size, Computational cost, Accuracy.*

Summary: *The true behavior of structural systems is dynamic that in many cases can not be simplified to static. For analyzing the structural dynamic behaviors, time integration is the most versatile tool, and, hence, under special attention in the analyses of structural systems, becoming more complicated everyday. Nevertheless, the responses of time integration are generally being obtained after considerable computational cost and are inexact. In the last decades, many attempts are carried out for time integration with less computational cost and acceptable accuracy. Considering the digitized nature of ground strong motion records, a technique for considerably reducing the computational costs with small loss of accuracies is recently proposed. Being based on the notion of convergence and its role in time integration analyses, the technique replaces seismic records with excitations, digitized at larger steps. The good performance of the technique is displayed via simple linear and nonlinear examples. In view of the devastating effects of power substation equipments in the past earthquakes, the objective, in this paper, is to examine whether we can successfully implement the technique in time integration of real power substation equipments. The technique is reviewed with special attention to its implementation in seismic analyses of power substation equipments, once ordinarily and then again after implementing the proposed technique. The achievements evidence the good performance of the technique and leads to approaches for more comprehensive researches.*

1 INTRODUCTION

The true behavior of structural systems is dynamic that in many cases can not be simplified to static, e.g. the behavior of power substation equipments subjected to severe earthquakes.

The conventional approach to analyze the structures dynamic behaviours is to discretize the structural systems in space and try to analyze the resulting initial value problems, also repeated below [1-3]:

$$M\ddot{U}(t) + f_{int}(t) = f(t)$$

$$\text{Initial Conditions :}\begin{cases} u(t = 0) = u_0 \\ \dot{u}(t = 0) = \dot{u}_0 \\ f_{int}(t = 0) = f_{int0} \end{cases} \quad (1)$$

$$\text{Additional conditions: } Q \qquad 0 \leq t < t_{end}$$

In Eq. (1), t and t_{end} imply the time and the duration of the dynamic behavior; **M** is the mass matrix; $\mathbf{f}_{int}$ and $\mathbf{f}(t)$ stand for the vectors of internal force and excitation; $\mathbf{u}(t)$, $\dot{\mathbf{u}}(t)$, and $\ddot{\mathbf{u}}(t)$denote the unknown vectors of displacement, velocity, and acceleration; $\mathbf{u}_0$, $\dot{\mathbf{u}}_0$, and $\mathbf{f}_{int0}$ define the initial status of the model; and **Q** represents some restricting conditions, e.g. additional constraints in problems involved in impact or elastic-plastic behavior [4,5], all in view of the degrees of freedom [1,2]. The most versatile tool to analyze Eq. (1) is time integration [6, 7]. However, due to the essentiality of implementing approximate formulations, and meanwhile, the step-by-step nature of time integration analyses, the computational cost is high and the responses are inexact. In more detail, time integration can analyze the behaviors of almost all types of structural dynamic problems, expressed as stated in Eq. (1), approximately and with considerable computational cost. The accuracy and computational cost both diminish, when we implement larger steps [8, 9]. Consequently, it is conventional to implement steps small enough, providing sufficient accuracy and not less. Considering this, besides the additional restriction because of the digitization steps of seismic excitations, the integration step size are conventionally being set such that to satisfy the inequality below; see also [10,11]:

$$\Delta t = \text{Min}\left(h_s, \frac{T}{10}, {}_f\Delta t\right) \quad (2)$$

In Eq. (2), h_s represents the requirements regarding responses numerical stability and consistency [8-11], T, denoting the dominating period of oscillations, not precisely known in advance, when divided by 10, controls the accuracy, and f Δt implies the smallest size of steps, by which, the excitation is recorded, e.g. analysis of structural systems against seismic records (see [12]). When ${}_f\Delta t$ governs Eq. (2), i.e.

$$\Delta t = {}_f\Delta t \leq \text{Min}\left(h_s, \frac{T}{10}\right) \quad (3)$$

The analysis suffers from computational cost additional to that needed for accuracy. Recently, a technique is proposed for eliminating the computational cost [13]. The objective in this paper is to examine the performance of the recent technique when applied to power substation equipments, by time integration. In Section 2, the technique is briefly reviewed. In Section 3, power substation equipments model is analyzed, when implementing the recent technique. And, finally, in Section 4, the paper is concluded with a brief set of achievements and comments.

2 THE RECENT TECHNIQUE IN BRIEF

The most important essentiality of approximate analysis methods, including time integration, is the convergence of approximate responses to the exact responses [14, 15]. Based on this, and in order to preserve the second order convergence of the analyses results [16], the recent technique [13] is set to replace the digitized ground strong motions with strong motions digitized at larger steps. In more detail, under the assumptions, implied in Fig. 1 and noted below:

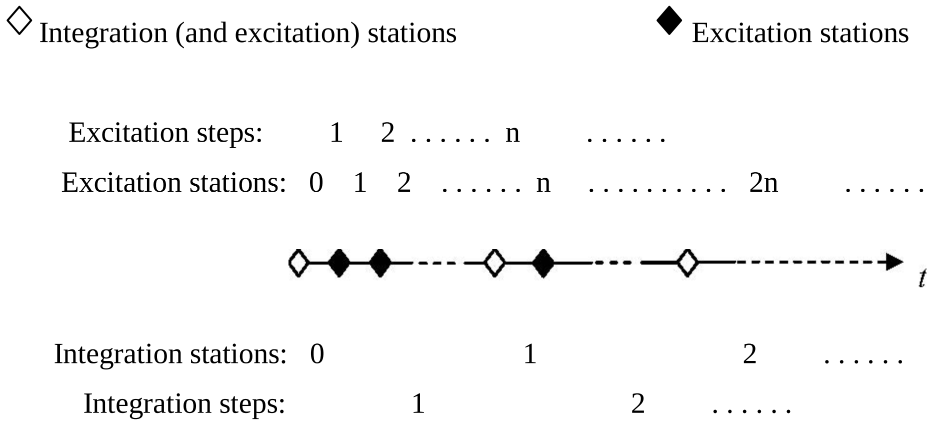


Figure 1. Typical distribution of excitation and integration stations in the recent technique [13].

1- The excitation steps, ${}_f\Delta t_i$ $i = 1,2,\ldots$, are equally sized,

$$\forall\ i, j \quad {}_f\Delta t_i = {}_f\Delta t_j = {}_f\Delta t > 0 \tag{4}$$

2- The excitation steps, Δt_i $i = 1,2,\ldots$, are equally sized,

$$\forall\ i, j \quad \Delta t_i = \Delta t_j = \Delta t > 0 \tag{5}$$

3- The excitation steps are embedded by the integration steps (the first time station, i.e. t_0, is a station for both excitation and integration),

$$\exists \quad n \in Z^{+} \quad \frac{\Delta t}{f\ \Delta t} = n < \infty \tag{6}$$

4- The **f**(t) in Eqs. (1) is a digitized representation of an actual excitation, **g**(t) , smooth with respect to time [17], i.e.,

$\mathbf{f}(t) = \mathbf{g}(t)\ \delta(\,t - \alpha_i\,)$

$\mathbf{g}(t)$: smooth with respect to time

$$\alpha_i = i_f \Delta t \ , \ i = 0,1,2,\ldots$$

$$\delta(t - \alpha_i) = \begin{cases} 1 & t = \alpha_i \\ 0 & t \neq \alpha_i \end{cases} \tag{7}$$

(and hence, the temporal derivatives of f(t), though rarely known, exist).

the new excitation, $\hat{\mathbf{f}}$, defined by:

$$t_i = 0: \qquad \hat{\mathbf{f}}_i = \mathbf{f}(t_i),$$

$$0 < t_i < t_{end}: \ \hat{\mathbf{f}}_i = \frac{1}{2}\mathbf{f}(t_i) + \frac{1}{4\acute{n}}\sum_{k=1}^{\acute{n}} [f(t_{i+k/n}) + f(t_{i-k/n})], \tag{8}$$

$$t_i = t_{end}: \qquad \hat{\mathbf{f}}_i = \mathbf{f}(t_i),$$

where,

$$t = \Delta t: \quad \acute{n} = n\text{-}1$$

$$\Delta t < t < t_{end} - \Delta t: \quad \acute{n} = \begin{cases} \frac{n}{2} & n = 2j \quad j \in Z^+ \\ \frac{n-1}{2} & n = 2j+1 \quad j \in Z^+ \end{cases} \tag{9}$$

$$t = \Delta t: \quad \acute{n} = n\text{-}1$$

and Δt and n ($n \in Z^+$) are the largest values satisfying

$$\Delta t = n_f \Delta t \leq \text{Min}\left(h_s, \frac{T}{10}\right) \Delta t \leq t_{end} \tag{10}$$

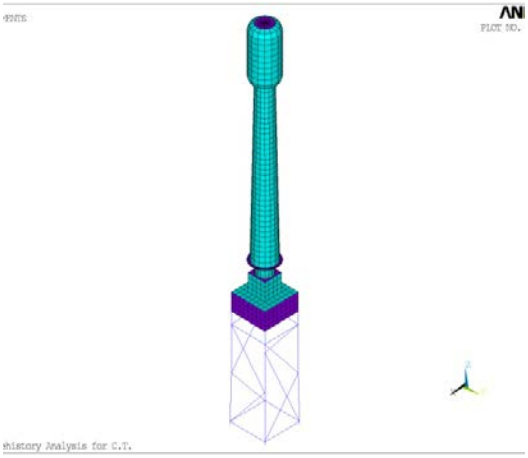
is an excitation recorded at steps equal to $n_f \Delta t$ and hence when considered instead of the original excitation can cause a reduction in computational cost, A_C , about and not more than:

$$A_C = 100\left(\frac{n-1}{n}\right)\% \tag{11}$$

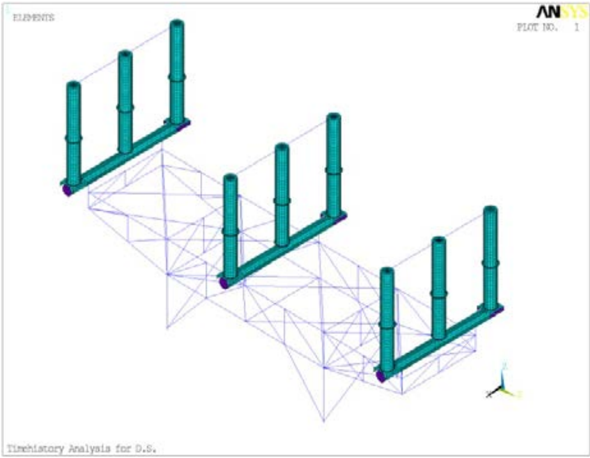
3 IMPLEMENTATION THE SEISMIC ANALYSIS OF POWER SUBSTATION EQUIPMENTS

The finite-element method provides a good platform to perform additional studies for better evaluation of the equipments response characteristics. Functionally, in this study two components of important equipments that are known within a power substation, namely: current transformer (CT), live-tank circuit breaker (CB) and disconnect switch (DS), are modeled by 3-D finite-element method with using the finite-element package ANSYS12 [18-19].

Consider the power substation equipments introduced in below figures:



Model of the 230kv CT



Model of the 230kv DS

Figure 2. The 3D models of 230kv current transformer and circuit breaker

Table 1: Structural and geometry specifications of the 230 kv CT, CB and DS system

Specifications	Current transformer	Circuit breaker	Disconnect switch
Dimensions of main structure (m)	0.62*0.62	4.75*1.125	9.4*2.7
Height of main structure (m)	1.7	1.85	2.79
Total height of bushing (m)	3.65	4.02	2.45
Height of total system from the top of foundation (m)	6.2	5.87	5.24
Section of brace elements (mm)	L50*50*6	L45*45*4	L45*45*4
Section of column elements (mm)	L65*65*8	L70*70*8	L100*100*10
Modulus of elasticity of steel parts (MPa)	206,000	206,000	206,000
Modulus of elasticity of porcelain (MPa)	99,800	99,800	99,800
Diameter of porcelain at bottom (cm)	40.0	30.0	30.0
Thickness of porcelain (cm)	2.5	2.5	2.5
Diameter of head part of bushing (cm)	45	50	30
Number and size of volts in each facility (mm)	8*M16	24*M14	16*M12
Type of supports	Fixed	Fixed	Fixed

In this study equipments subjected to Ab-bar record of the 1990 North Iran Earthquake [20], that original Ab-bar strong motion with three component display below:

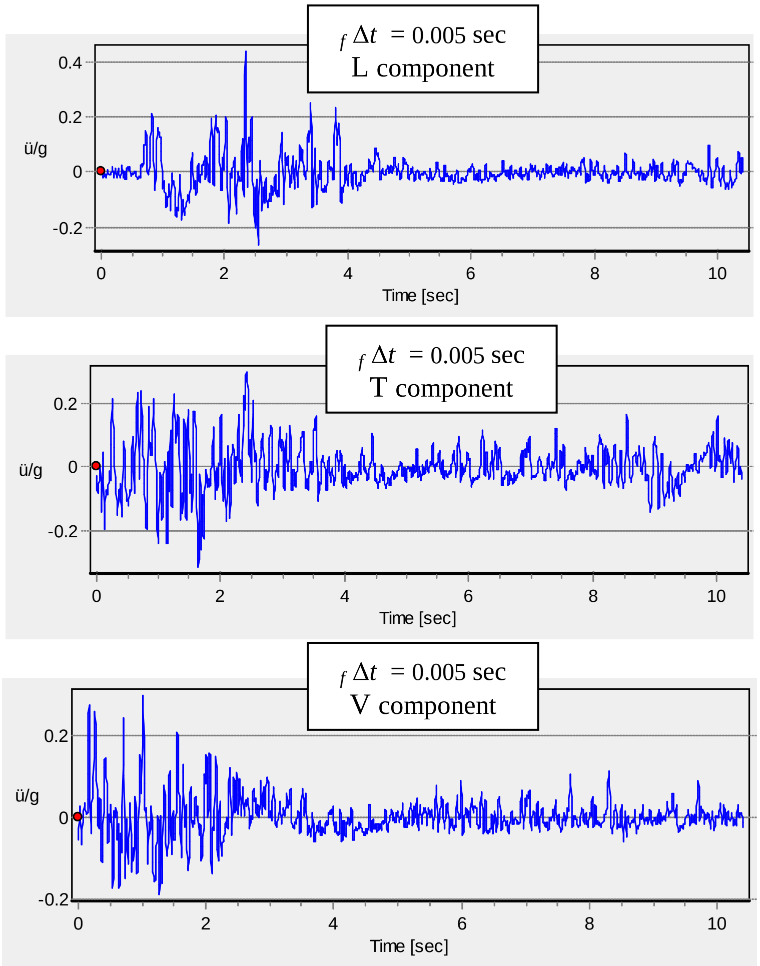


Figure 3. Original Ab-bar strong motion

The past experiences regarding the implementation of the new technique [13, 22], we should be able to replace the original excitation, **f**, with a new excitation, $\hat{\mathbf{f}}$, digitized at steps 2 times larger than the steps in the original excitation, with no significant loss of accuracy. Nevertheless, to also make an idea about the least reduction of computational cost, the case $n = 2$, $n = 4$ and $n = 10$ is taken into account in the analyses. Figure 4 displays the performance of the new technique for $n = 2$, $n = 3$, $n = 4$ and $n = 10$ and also comparison each response under original record ($n = 1$) .

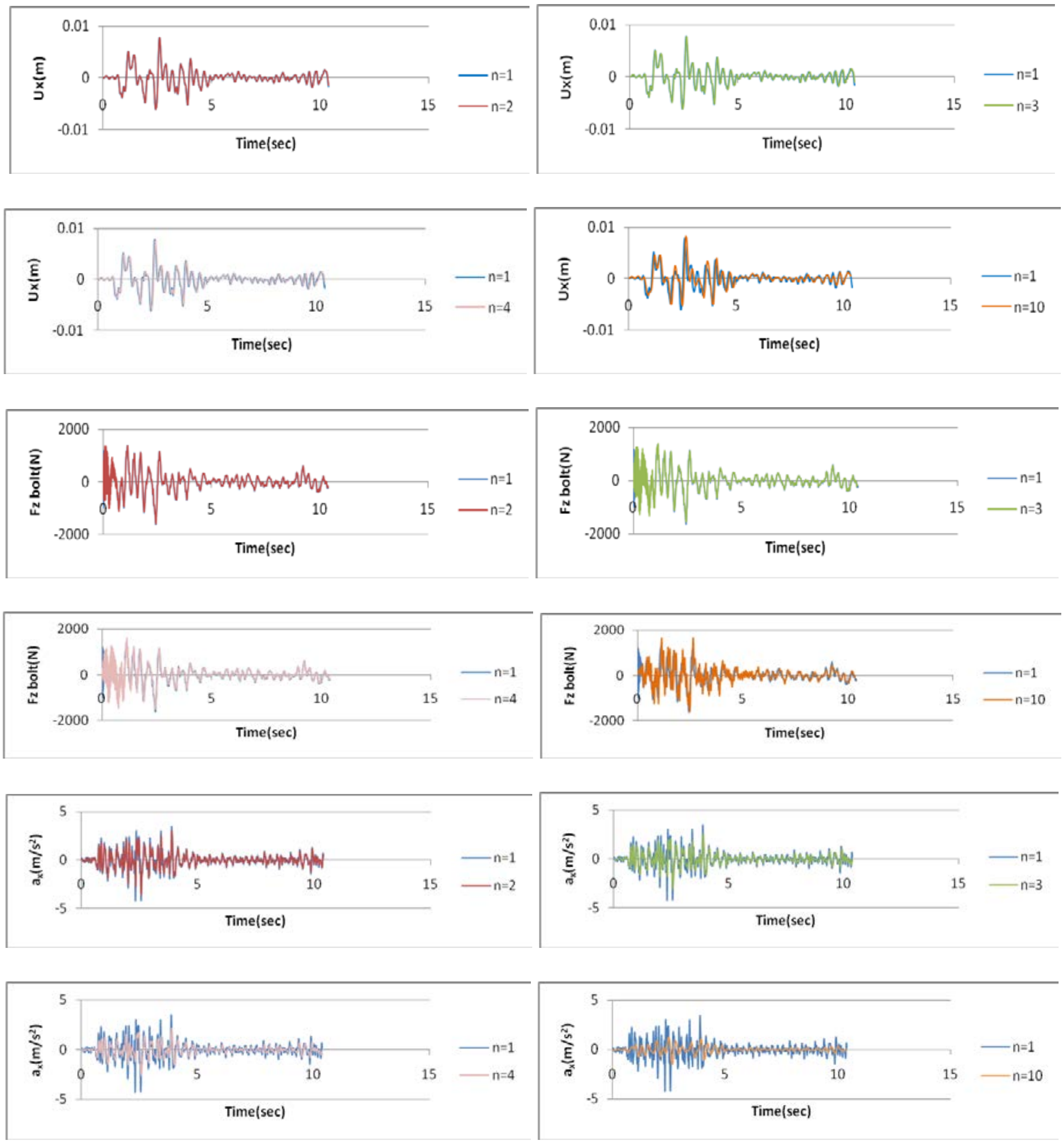


Figure 4. Response histories obtained for the CT under consideration after implementing the new technique in time integration by the average acceleration method: (a) top displacement, (b) force in support bolts, (c) top acceleration.

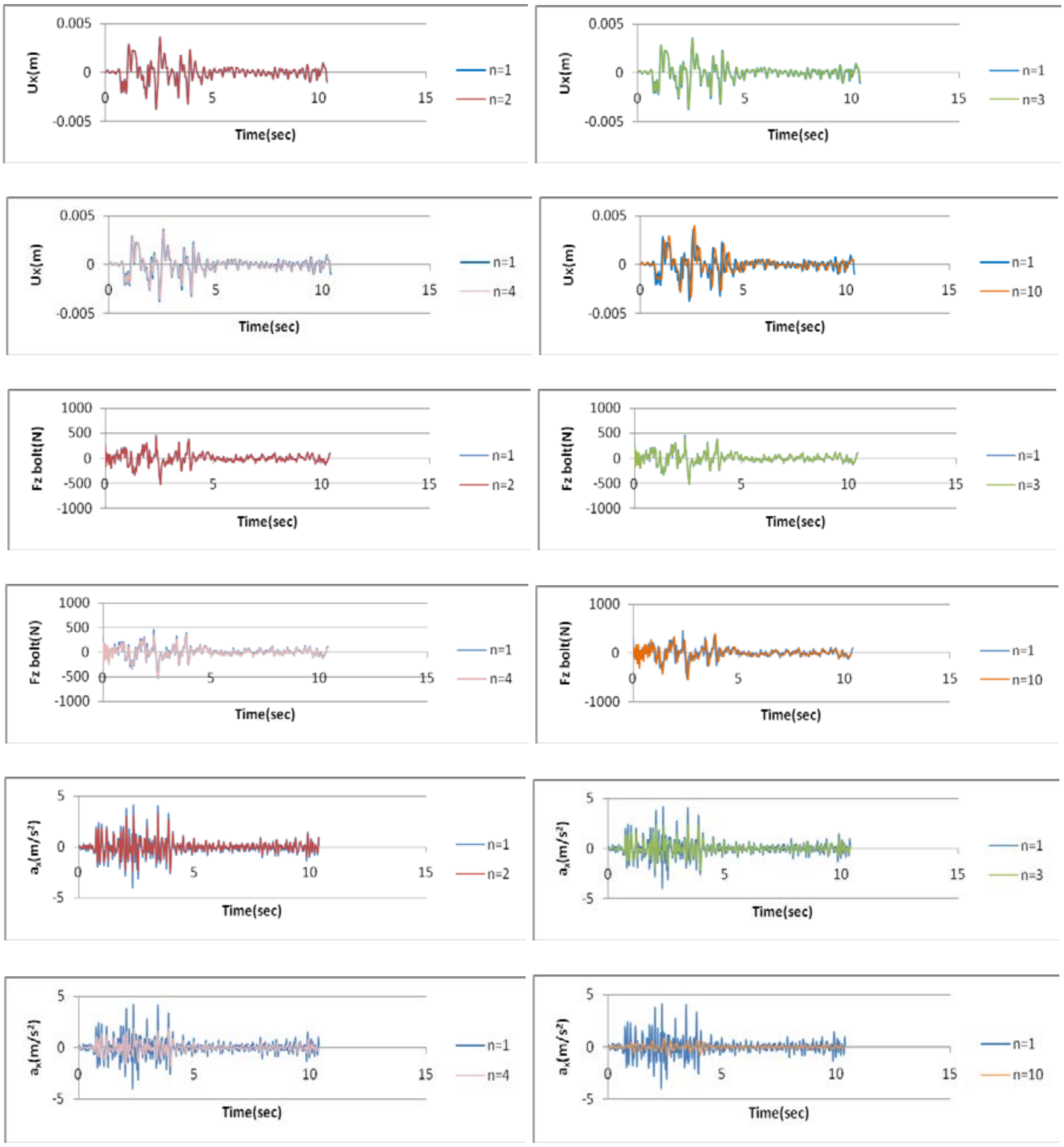


Figure 5. Response histories obtained for the DS under consideration after implementing the new technique in time integration by the average acceleration method: (a) top displacement, (b) force in support bolts, (c) top acceleration.

After some brief analyses for arriving at an approximation value for T, and setting the HHT method of Newmark [22], for time integration ($h_s = \infty$), from Eqs. (10), we can arrive at the appropriate size for integration and the value for n. Besides the past experiences regarding the implementation of the new technique [13,23], we should be able to replace the original excitation, $\mathbf{f}$, with a new excitation, $\hat{\mathbf{f}}$, digitized at steps two times larger than the steps in the original excitation, with no significant loss of accuracy.

It is also constructive to have an overview on the effect of the recent technique on the excitation; see Figures 6 through 8. Though the study is limited to a special structural system subjected to a special excitation and analyzed by the HHT time integration method, it can be deduced that the technique have the chance to be successful when implemented in the analysis of power substation equipments by time-integration. Further study is essential.

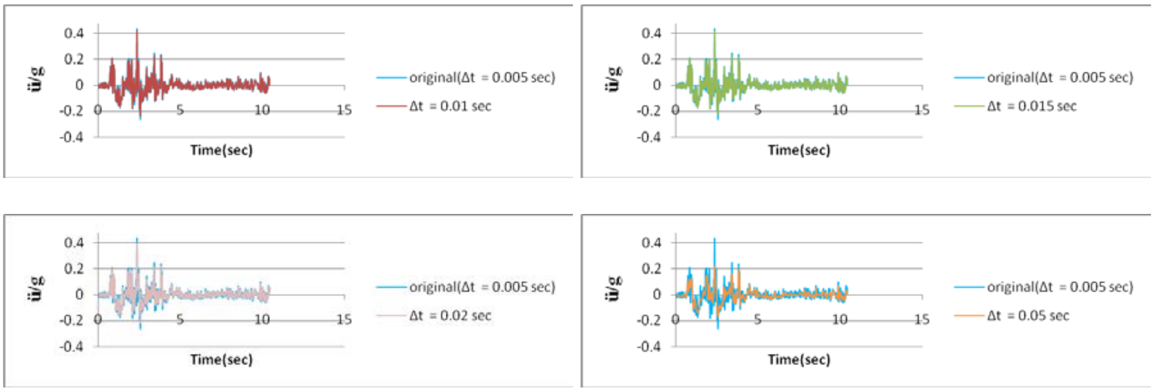


Figure 6. A comparison between the L component of Ab-bar excitation before and after implementing the new technique when implementing the recent technique with (a) n=2, (b) n=3, (c) n=4 and (d) n=10.

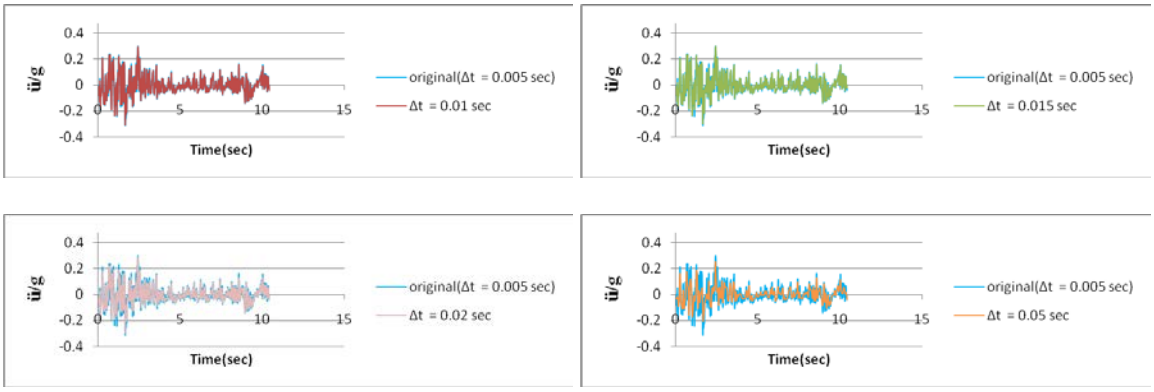


Figure 7. A comparison between the T component of Ab bar excitation before and after implementing the new technique when implementing the recent technique with (a) n=2, (b) n=3, (c) n=4 and (d) n=10.

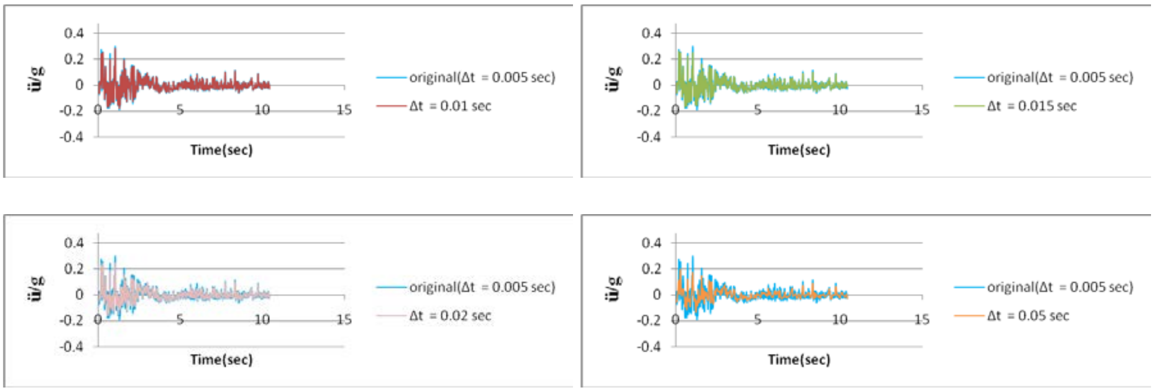


Figure 8. A comparison between the V component of Ab bar excitation before and after implementing the new technique when implementing the recent technique with (a) n=2, (b) n=3, (c) n=4 and (d) n=10.

4 CONCLUSIONS

As expected theoretically, and also experienced in the past numerical investigations, implementation of a convergence-based technique, recently proposed for reduction of the computational cost, is successful, regarding seismic analysis (by time integration) of two power substation equipment (CT, and DS) structural systems, against the Ab-bar excitation. In view of the frequency contents and their effect in the integration step size selection, a good chance for the technique to be applied in time integration of power substation equipment systems against strong motions with rich frequency content can be anticipated. Studies, considering variations of structural systems, excitations, and integration methods, are being suggested for further research.

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