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Electromagnetic and structural analyses of the vacuum vessel and plasma facing components for EAST

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HIGHLIGHTS

- The electromagnetic and structural responses of VV and PFCs for EAST are analyzed.
- A detailed finite element model of the VV including PFCs is established.
- The two most dangerous scenarios, major disruptions and downward VDEs are considered.
- The distribution patterns of eddy currents, EMFs and torques on PFCs are analyzed.

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ABSTRACT

During plasma disruptions, time-varying eddy currents are induced in the vacuum vessel (VV) and Plasma Facing Components (PFCs) of EAST. Additionally, halo currents flow partly through these structures during the vertical displacement events (VDEs). Under the high magnetic field circumstances, the resulting electromagnetic forces (EMFs) and torques are large. In this paper, eddy currents and EMFs on EAST VV, PFCs and their supports are calculated by analytical and numerical methods. ANSYS software is employed to evaluate eddy currents on VV, PFCs and their structural responses. To learn the electromagnetic and structural response of the whole structure more accurately, a detailed finite element model is established. The two most dangerous scenarios, major disruptions and downward VDEs, are examined. It is found that distribution patterns of eddy currents for various PFCs differ greatly, therefore resulting in different EMFs and torques. It can be seen that for certain PFCs the transient reaction force are severe. Results obtained here may set up a preliminary foundation for the future dynamic response research of EAST VV and PFCs which will provide a theoretical basis for the future engineering design of tokamak devices.

1. Introduction

Experimental Advanced Superconducting Tokamak (EAST) is an advanced steady-state plasma physics experimental device which has been built in ASIPP CAS. Its main objective is the wide investigation of both the physics and technology for state advance tokamak. EAST has Plasma Facing Components (PFCs) mainly including inner limiter, divertor, passive stabilizer and horizontal protective plate to protect the vacuum vessel (VV), heating systems and diagnostic components from the plasma particles and heat loads. All PFCs are composed of graphite tiles, heat sink, support and cooling system. Fig. 1 shows the elevation view of EAST PFCs. The PFCs are designed up-down symmetrical to the midplane, to meet the requirement of operation with single or double null plasma shape [1,2].

During plasma disruptions, time-varying eddy currents are induced on VV and PFCs. Additionally, halo currents will flow along the scrape layer to these structures and return to the scrape layer during the vertical displacement events (VDEs). Eddy currents and halo currents interact with high toroidal magnetic field will cause large electromagnetic forces (EMFs) and torques on VV and PFCs. As these forces change drastically with time, the structural response is dynamic [3]. This response determines important design drivers such as the reaction forces of supports, the displacements and stress of the structure.

In this paper, analytical and numerical methods are used to calculate eddy currents and the resulting EMFs on EAST VV and PFCs including the supports. A detailed finite element model of EAST VV including double-walls, the ribs between the walls, all major PFCs and their supports which allow the currents flow through them between VV and PFCs is established. Two most dangerous situations: major disruptions (MD) and downward VDEs are examined in detail.

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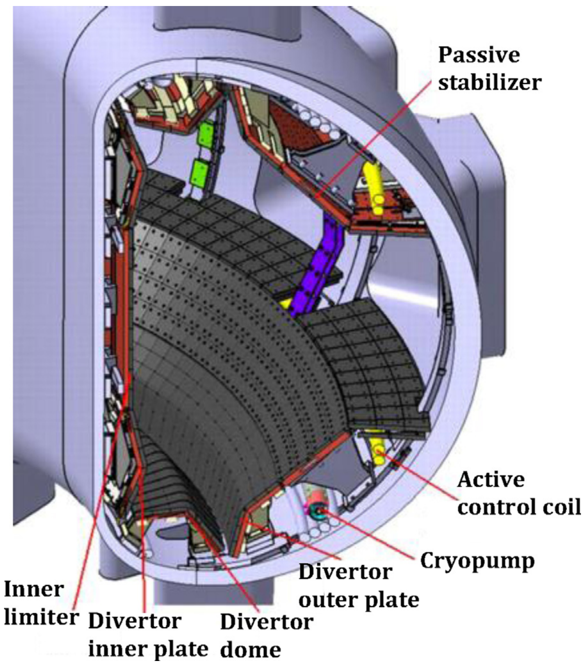

Fig. 1. Elevation view of EAST PFCs.

2. Analytical analysis of eddy currents for VV during MD

Major disruption is a typical load case for the electromagnetic analysis of Tokamak VV and PFCs. During MD, the plasma current is modeled by one coil of which the current varies rapidly with time but the position in space is constant. The sudden change of plasma current will induce eddy currents and result in electromagnetic forces on conducting structures around the plasma. According to the principle of electromagnetic induction, by simplifying the double-shell of VV to several dozens of circular coils, the distribution of eddy currents and their effects on the background magnetic field can be simulated, and the resulting electromagnetic forces can be calculated with Fortran software codes. Here, the vacuum vessel is divided into 120 conducting rings, and a current couple model is established to calculate eddy currents for different conducting elements. The current couple model is given as:

$$L_i \frac{dI_i}{dt} + \sum_{j(j \neq i)} M_{ij} \frac{dI_j}{dt} + M_{i,plasma} \frac{dI_{plasma}}{dt} + R_i I_i = 0 \quad (1)$$

where R, I, L and M represent the resistance, current, self-inductance and mutual inductance respectively.

For EAST, the current decay of plasma during MD can be supposed as below:

$$I = I_0 \, e^{-t/\tau} \quad (2)$$

where $I_0 = 1$ MA, $\tau = 3$ ms.

Eddy currents can be calculated from Eq. (1). The total eddy current on VV and eddy current density at different positions of the upper half vessel can be obtained, just shown in Fig. 2. Results show that when plasma current decays exponentially, eddy currents firstly grow rapidly and then decrease over time. The maximum total eddy current on VV is 0.71 MA at about 7 ms. The maximum current density occurs at the center of inner limiter at about 5 ms and the value is 21 MA/m^2. The amplitude and response velocity of eddy currents on every coil have an inverse relationship with its distance to the plasma. At the same position, inner shell will reach the peak current earlier than outer shell.

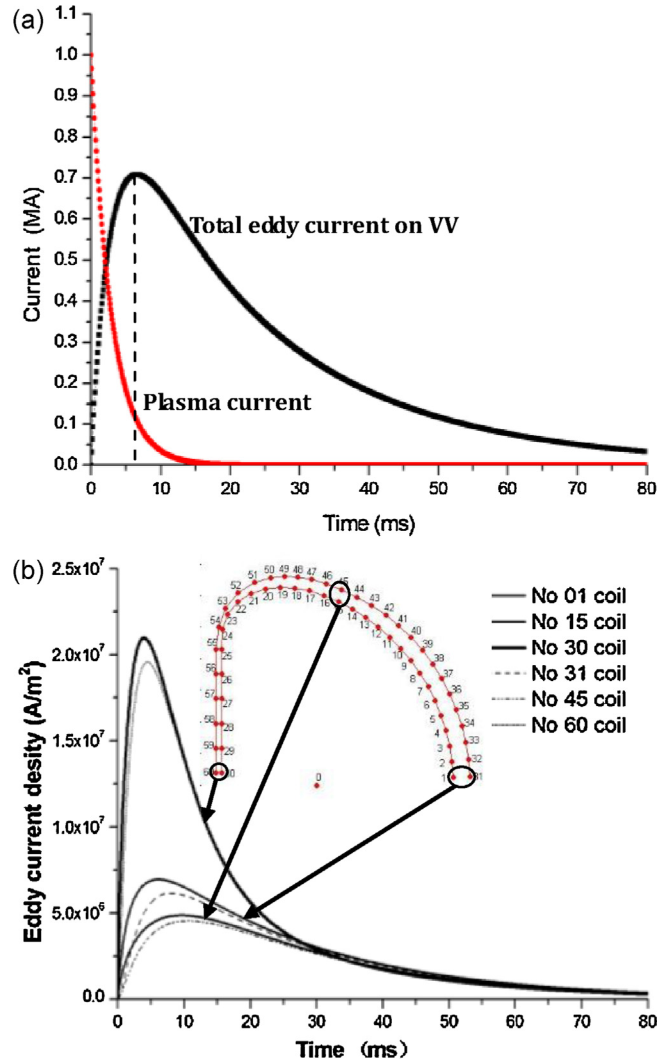

Fig. 2. (a) Total eddy current on VV and (b) eddy current density at different positions.

When the large toroidal eddy currents interact with high poloidal magnetic field, large electromagnetic forces will emerge on VV. Since the background magnetic field caused by plasma current changes sharply as plasma current decay, the total magnetic field's direction may even reverse at some places [5], which result in the electromagnetic force there reversing. Fig. 3 has shown how the stress distribution changes gradually. The pressure at region A points inward at first and gradually turns outward, while the pressure at regions B and C points outward and inward respectively all

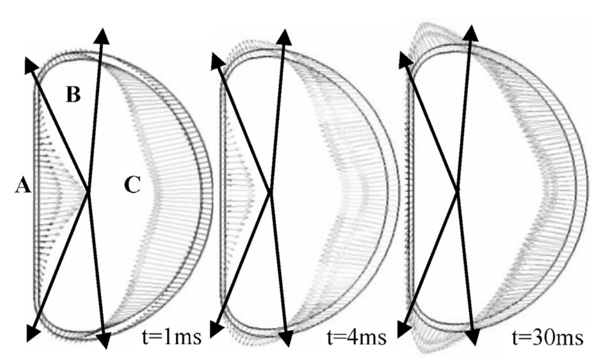

Fig. 3. Force distribution on PFCs at different time during MD.

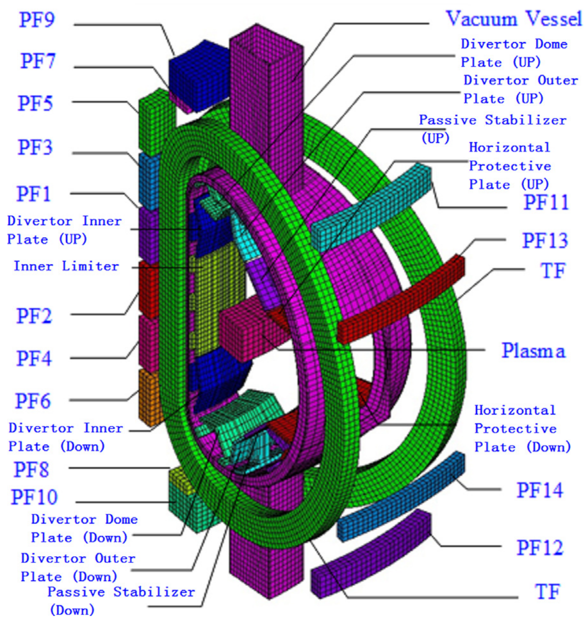

Fig. 4. Finite element model of 1/16 EAST.

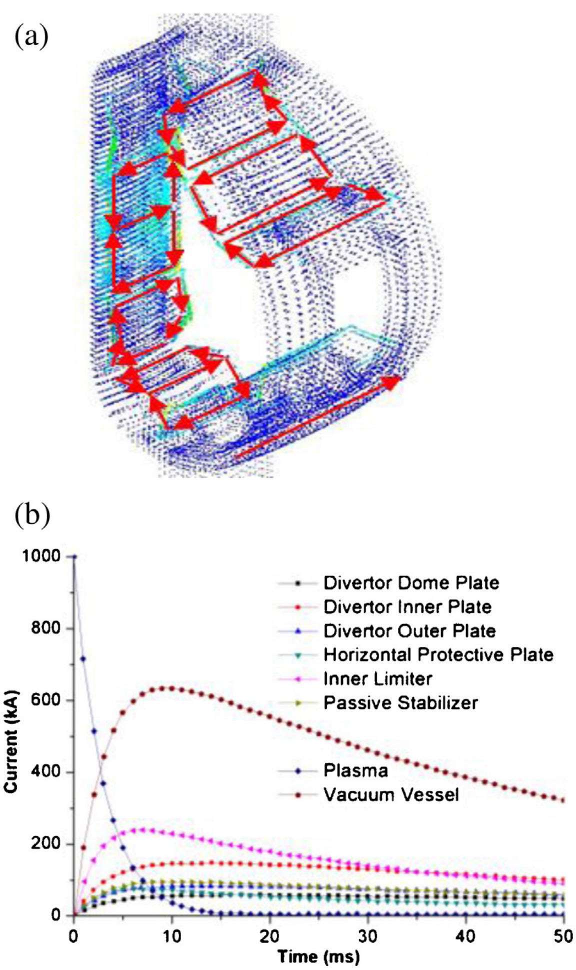

Fig. 5. Eddy currents on VV and PFCs during MD: (a) eddy current loops and (b) eddy currents.

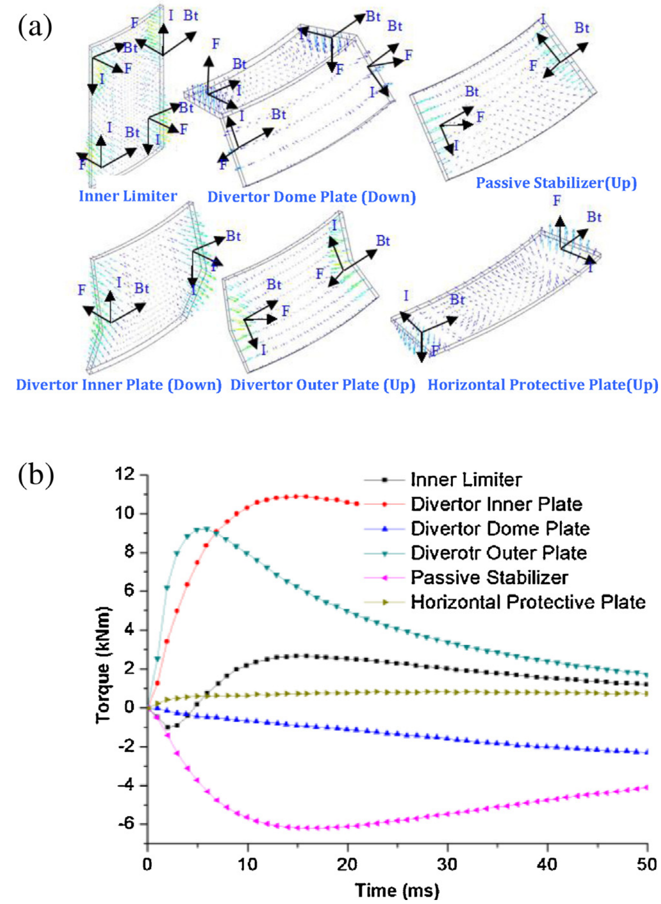

Fig. 6. Force and torque acting on PFCs during MD: (a) force acting on PFCs and (b) radial torque.

the time. The maximum stress is 0.034 MPa, occurring at the center of inner limiter at 3 ms.

3. Numerical analysis of eddy currents for VV and PFCs

3.1. Finite element model

EAST vacuum vessel is a D-shaped cross-section and double wall torus assembled by 16 sections. Each section has an upper vertical port, a lower vertical port, a horizontal port, a flexible support and two middle poloidal ribs. As shown in Fig. 1, PFCs and other in-vessel components are installed in VV. PFCs contain inner limiter, divertor, passive stabilizer and horizontal protective plate. All PFCs are composed of heat sinks including their supports, cooling system and graphite tiles which are bolted to heat sinks. Since the material electrical conductivity and geometric dimensioning of graphit tile are both much smaller than heat sink, when calculating eddy currents on PFCs, only heat sinks and their supports are considered. The material of VV and heat sink are 316 L stainless steel and CuCrZr respectively.

Simulations are performed with ANSYS software. The electromagnetic finite element model for subsequent analysis consist of 2 halves toroidal field (TF) coils, 14 poloidal field (PF) coils, a 22.5° VV sector, the nearby PFCs modules and their supports, as shown in Fig. 4.

For the analyses presented in this paper, the two most dangerous scenarios are considered: major disruptions and downward VDEs.

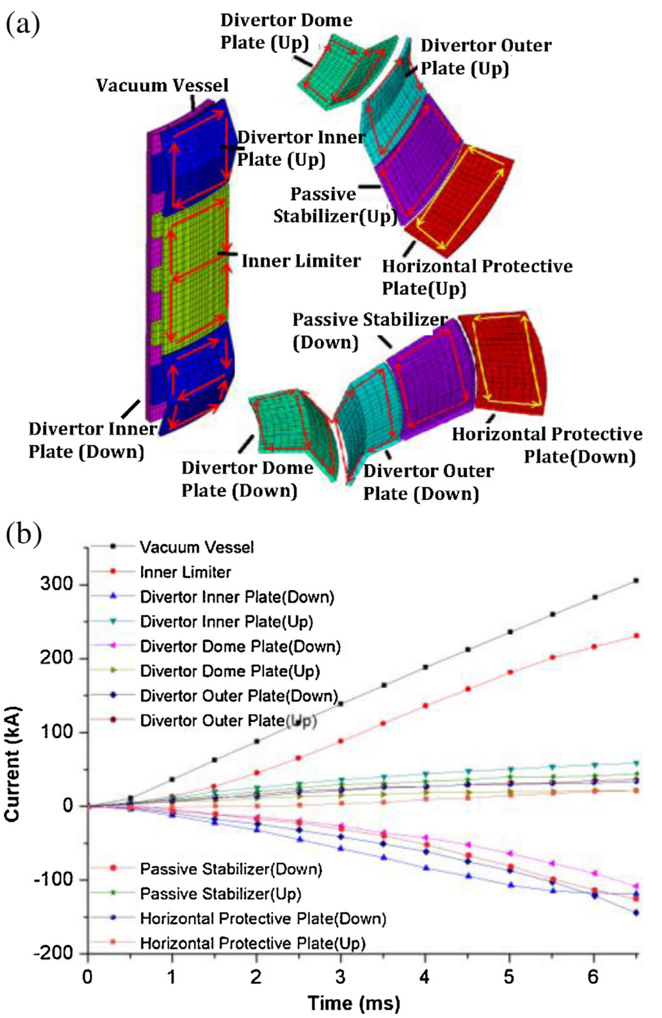

Fig. 7. Eddy currents on VV and PFCs during downward VDE: (a) eddy current loops on PFCs and (b) eddy currents.

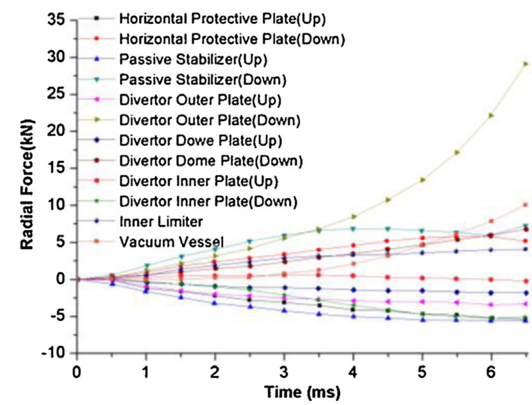

Fig. 8. Radial forces on VV and PFCs for the downward VDE.

3.2. Major disruption

During MD, plasma current is modeled by one coil of which the current varies rapidly with time but the position in space is constant—equivalent to plasma current described in Eq. (2).

Results show that for VV, eddy current loop is along the toroidal direction, detouring around the ports; as for PFCs, independent eddy current loops flow on them since these components are normally electrically isolated from one another, as shown in Fig. 5(a); and along PFC supports, currents flow between VV and PFCs. Fig. 5(b) shows that eddy currents on each PFC is much less than it on VV. The maximum eddy current on VV is about 63% of the initial plasma current, while the maximum eddy current on PFCs is only about 24%, occurring on inner limiter.

Once eddy current distribution is obtained, the forces and torques can be calculated. The distribution of the resulting Lorenz forces is shown in Fig. 6. Results show that the maximum stress is 106 MPa, occurring at the support of inner limiter at about 7 ms. If PFCs are not considered, the maximum stress acting upon VV is only about 30 MPa, which indicating that the forces transferred to VV from PFCs are significant. The largest torque is in the radial direction, and those results are shown in Fig. 6(b).

3.3. Vertical displacement events

During VDEs, plasma current is modeled by one loop with constant current while the position varies with time—drifting downward at a velocity of 100 m/s [6]. The loading assumption is rough, but it can reflect the effect of the vertical plasma movement on eddy current distribution on PFCs and VV. Fig. 7 shows that the maximum eddy current reaches the value 300 kA on VV and 230 kA on PFCs (occurring on inner limiter).

Results show that the maximum force occurs at down divertor outer plate in radial direction, as shown in Fig. 8. And the maximum torque occurs at the lower horizontal protective plate in axial direction.

At the end of VDEs, plasma may touch the first wall, and the currents will flow into PFCs and VV due to the lower electrical resistivity. These currents are called halo currents, which are quite harmful to the device due to the resulting huge dynamic EMFs. According to EAST experiment datas, the path of halo currents is assumed approximately as Fig. 9(a), flowing and exiting from divertor inner plate and outer plate respectively, and the current magnitude is about 50% of plasma current [6].

In FEM model, the AMPS (indicating current in ANSYS) value is applied to down divertor inner plate as halo currents' entrance, and the VOLT degrees of divertor outer plate are set to zero as halo currents' exit. And the flowing path, the distribution of halo currents and the resulting EMFs can be obtained. Results show that halo currents will flow along two paths, as shown in Fig. 9(b), one through VV and the other along divertor dome plate. Fig. 10 shows that the maximum current density and stress are about 5.5 MA/m^2 and 19.9 MPa, occurring at the support of divertor inner plate.

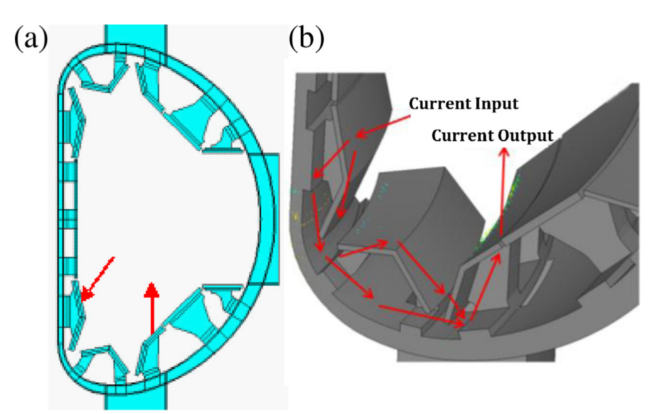

Fig. 9. Halo current loading and path: (a) assumed entrance and exit and (b) calculated flowing path.

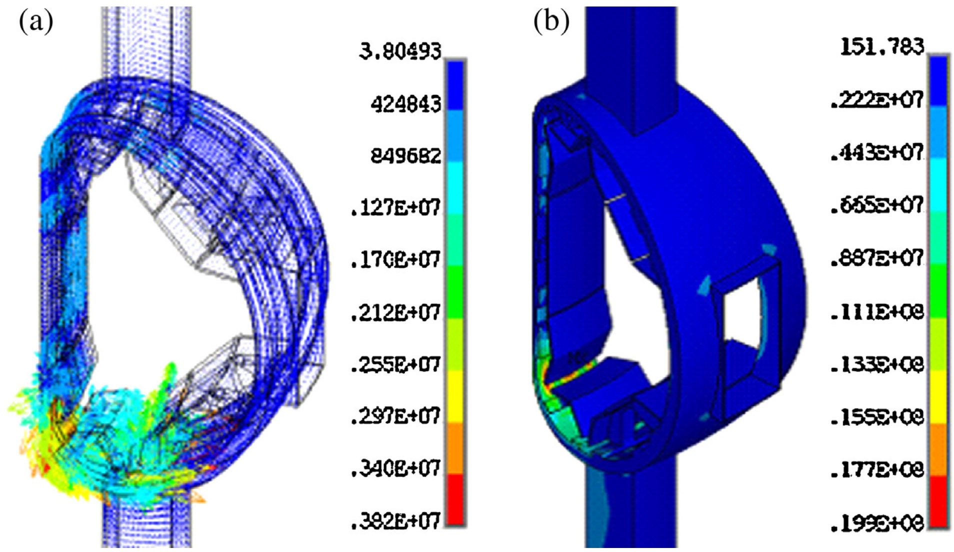

Fig. 10. Halo current distribution and the stress distribution: (a) halo current distribution and (b) stress distribution.

4. Conclusion

The electromagnetic and structural responses of VV and PFCs for EAST are analyzed by analytical and numerical methods. The two most dangerous scenarios: major disruptions and downward VDEs are considered. Results show that the distribution pattern of eddy currents for different PFCs differ greatly, therefore the resulting EMFs and torques cause different mechanical responses. It can be also seen that for certain PFCs' supports, the transient reaction forces are severe. As these forces vary drastically with time, the dynamic effects must be considered. Based on the results obtained here, the subsequent dynamic response of the structure need to be analysed in the future.

Acknowledgments

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