Evaluation of Induced Voltages and Currents in 400kV Double Circuit Tunnel Power Cables

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***Abstract*— Routine maintenance activities in multi-circuit cable tunnels often involve work on individual de-energized circuits, while adjacent circuits remain live. Electromagnetic coupling with live circuits results in induced voltages and currents on the de-energized cables. These may present a significant safety hazard to maintenance personnel if not properly identified and mitigated. In this paper we model a double circuit cable tunnel using ATP-EMTP to compute the induced voltages and currents in a de-energised circuit due to steady state operation of the adjacent live circuit. The cable length is 18 km, jointed at approximately 1km intervals. The simulations are performed considering the different load and fault conditions, including nominal load, 10% imbalance load, 3-phase faults, single-phase faults and phase-phase faults. Two different earthing scenarios of the de-energised cable circuit are considered. Results show that induced voltages and currents in the de-energized circuit depend greatly on the earthing configuration of cable sheaths and conductors. The designed model of the tunnel cable system and the study can be used as a reference document to identify the safe working methods for maintenance on tunnel power cables.**

Keywords—ATP-EMTP, induced voltages, electromagnetic effect

I. Introduction

The increased demand for electricity requires a more complex and robust infrastructure for the electrical power system [1] and therefore, there is a need to design such a transmission system with a lower environmental impact and easy maintenance. In the last decade, power tunnels have been installed in the United Kingdom by National Grid Electricity Transmission (NGET) in different regions [2]. Tunnels typically carry two three-phase cable circuits, mounted on the opposite walls as shown in Fig. 1. These cables require regular maintenance, which can be subdivided into routine tasks (e.g., sheath voltage limiter (SVL) testing and replacement, sheath insulation tests) and non-routine tasks (e.g., repairs to a faulted cable or joint). It is essential that maintenance of the cable circuits does not compromise the supply redundancy of the transmission system, and as such, double-circuit outages within a single tunnel span are to be avoided. It will, therefore, might be necessary to undertake maintenance in the presence of an adjacent live circuit, depending upon the situation, if permission is granted from the relevant department. When working on a circuit that is OOS (out of service) in the presence of an adjacent live circuit, any imbalance in the current flowing in the live circuit will establish an electromagnetic field, leading to induced voltages and currents in the de-energised circuit under maintenance, as illustrated in Fig. 1 [3]. The induced voltages and currents on the sheaths and conductors of the de-energised circuit will differ depending on the earthing arrangement of the de-energised cable circuit. The magnitude of these induced voltages will rise significantly in the event of fault current flow in the live circuit, which may present significant safety hazards for maintenance personnel with the risk of electric shock, burns and cardiac arrest.

NGET published a National Safety Instruction (NSI5) in which four different methods are defined for safe working on tunnel cable systems subject to impressed voltages [4]. Similar methods are also defined in the technical brochure CIGRE TB 801 [5]. The selection of a suitable safe working method depends on various conditions, including the availability and effective resistance of earthing points, maintenance type and magnitude of the induced voltages.

Previously, various researchers conducted studies on induced voltage calculations and measurements on power cable sheaths. For example, Guevara *et al.* proposed a generalized formula for calculating induced sheath voltages in underground transmission lines, incorporating internal and earth-return impedances [6]. Their analysis, which compared standard IEEE and CIGRE methods under steady-state conditions, showed that the generalized model yields higher induced voltages—up to 6.5% more in triangular formations and 5% in flat formations. Shaban *et al.* conducted a comprehensive review of analytical methods for calculating induced sheath voltage in underground cables and overhead

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lines, highlighting challenges in modeling electromagnetic coupling between closely spaced cables [7]. Their study emphasizes the impact of cable arrangement and spacing on induced voltage magnitude and compares various bonding configurations for effectiveness. Santos and Calafat (2024) introduced a steady-state simulation approach for modeling induced voltages and currents in high-voltage cable sheaths, accounting for sheath connections and fault conditions [8]. Their method supports automatic coupling of multiple circuits and was validated against theoretical and simulation benchmarks with satisfactory accuracy.

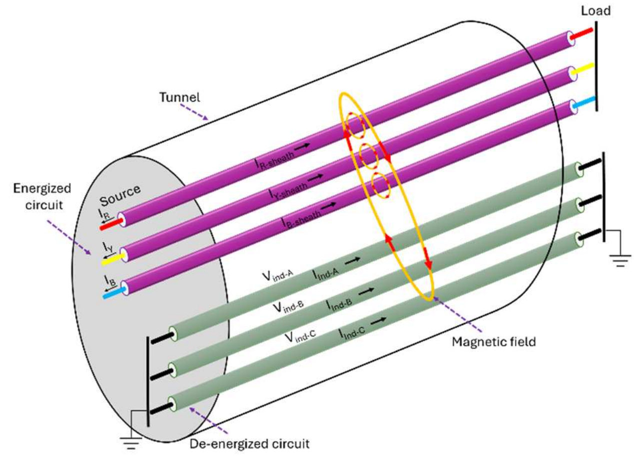

Fig. 1. Mechanism of induced voltages in a de-energised circuit by inductive coupling with adjacent energised circuit in a double circuit tunnel cable system [3].

To date, although there is much literature on calculating induced voltages and currents in buried power cables [9-11], there is not any on induced voltages tunnel power cables in mainstream journals and conferences. To address this gap, this work uses ATP-EMTP simulations to compute and evaluate the induced voltages and currents in a double circuit power tunnel [12]. The tunnel length is around 18 km, with one cable circuit energised and another de-energised. The cable circuits are jointed at approximately 1km intervals, with phase transposition and sheath cross-bonding at two in every three joint bays. The calculations are performed using a steady state Pi model for different load and fault conditions, including nominal 3-phase winter load, 10% load imbalance, 3-phase fault, single-phase faults and phase-phase faults. Two different earthing scenarios are considered for the de-energised circuit for each load and fault condition. The results are evaluated to identify the preferable working method for maintenance in a double circuit tunnel cable system based on existing literature and theoretical background.

II. ATP-EMTP MODELLING

A. Tunnel Modelling

The tunnel houses two circuits with three cables per circuit, mounted in a vertical formation on opposing walls. The tunnel internal diameter is 3 meters and the average burial depth is 34 meters. The convention employed is to assume that circuit 1 (cct1) is the energised circuit, while circuit 2 (cct2) has been de-energised for maintenance. The positioning of the cables is as shown in Fig. 2. The total length of the cable circuit is 18 km and operated at a line voltage of 275 kV_{rms}. The substation earth mats have an assumed resistance to earth of 0.1 Ω and the nominal current capacity of each cable is 2473 A.

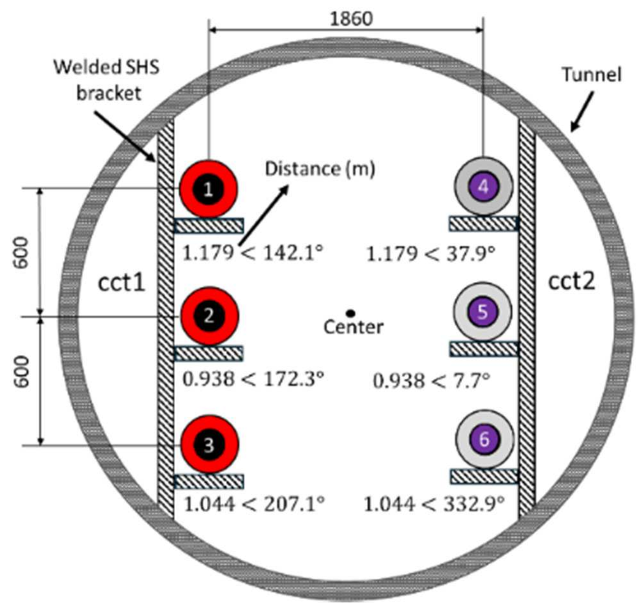

Fig. 2. A double circuit tunnel layout considering circuit cct1 as energised and cct2 as de-energised.

B. Cable Modelling

Cable models are based on the geometric data provided in this section. A simplified schematic for double circuit tunnel cable system for this study is illustrated in Fig. 3. Cable sections are initially modelled as 13-phase, 6-cable enclosing pipe model, with the tunnel wall modelled as a lossy medium of resistivity 30 Ωm, assuming sufficient hydrostatic pressure to maintain a persistent level of moisture content in the concrete. The tunnel is assumed to be buried in a soil of resistivity 100 Ωm. There are 18 cable sections in total, modelled using an LCC routine in ATP-EMTP with phase transposition and sheath cross-bonding between sections. Cable circuits are jointed at approximately 1km intervals, with sheath cross-bonding applied at two out of three joints and straight linking applied at the third. After each joint bay, there is a phase transposition which is mirrored in the adjacent circuit. Conductor and insulation cross-sections are adapted from Table I. Semiconducting layers are ignored for simplicity and treated as an extension of the main XLPE insulation. The relevant electrical parameters of cables are summarised in Table II. The simplified cable geometry is summarised in Table III. The use of a solid core and omission of the semiconductive layers requires that the resistivity of the core and permittivity of the main insulation must be modified from the datasheet values to achieve an equivalent ac resistance and capacitance.

From the stated cable parameters in Table II, the resistivity of the conductor at 90 °C is given by (1).

$$\rho_{Cu\ 50Hz} \approx R_{ac}A = 2.55 \times 10^{-8}\Omega m \quad (1)$$

Where R_{ac} is the stated conductor resistance and A is the conductor cross-sectional area. For a solid conductor representation of radius 32.3 mm, the resistivity must be increased to compensate for the increase in apparent cross-section.

$$\rho'_{Cu\ 50Hz} \approx R_{ac}A' = 3.34 \times 10^{-8}\Omega m \quad (2)$$

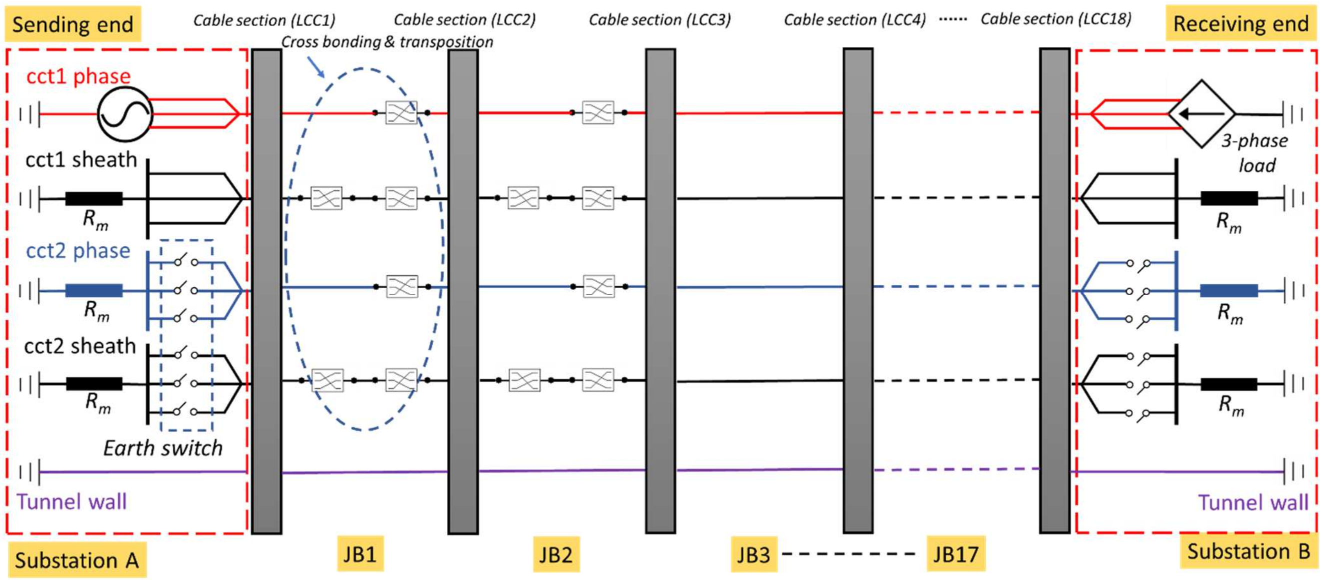

Fig. 3. Schematic diagram for double circuit tunnel power cable system considering cct1 as energised and cct2 as de-energised circuit.

TABLE I. CABLE SPECIFICATION

Material	Material	Thickness nominal (mm)	Outer dia. approx.(mm)
Conductor	Enamel-coated copper wires	-	64.50
Conductor screen	Semiconducting compound	1.5	68.94
Insulation	Cross-linked polyethylene	26.3	121.54
Insulation screen	Semi-conducting compound	1.5	124.54
Water blocking layer	Semiconducting swelling tape Semiconducting copper woven fabric tape	0.5 each 0.5	-
Metallic sheath	Smooth aluminium	1.5	131.54
Bonding layer	Bonding compound	0.1	-
Inner sheath	HDPE (blue)	4.2	140.74
Outer sheath	HFFR (black)	1.0	142.74

TABLE II. CABLE ELECTRICAL PARAMETERS

Parameter	Value
Conductor cross-section	2500 mm^2
Insulation thickness (nominal value)	26.3 mm
Alu Sheath Thickness	1.5 mm
HDPE sheath thickness	4.2 mm
HFFR sheath thickness	1.0 mm
Cable OD	142.7 mm
Conductor dc resistance at 20°C	7.2 mΩ/km
Conductor ac resistance at 90°C	10.2 mΩ/km
Cable capacitance	245 pF/m

TABLE III. SIMPLIFIED CABLE DIMENSIONS USED IN THE EMTP MODEL

Parameter	Outer Radius (mm)
Conductor Core (a)	32.3
XLPE Insulation (b)	64.3
Metallic Sheath	65.7
Overall	71.4

The effective permittivity of the insulation layer is found based on the coaxial cable approximation.

$$\varepsilon_r' \approx \frac{C'}{2\pi\varepsilon_0}\ln\left(\frac{b}{a}\right) = 3.03 \quad (3)$$

The sheath is considered a solid Aluminium tube, having a resistivity at 20 °C of 2.65×10^{-8} Ωm. Assuming a temperature coefficient of 0.0043 and adjusting for a maximal tunnel force ventilation temperature of 50 °C, the resistivity becomes 2.99×10^{-8} Ωm.

The datasheet values for the two over-sheath materials are HDPE = 2.3, HFFR Polyolefin = 3.7. Combining these into a composite layered dielectric, a parallel plate approximation can be used to determine an equivalent bulk permittivity.

$$\varepsilon_r = \varepsilon_2\varepsilon_1 \frac{(d_1+d_2)}{\varepsilon_2 d_1+\varepsilon_1 d_2} = 2.5 \quad (4)$$

Where ε_1, d_1 are the permittivity and thickness, respectively of the HDPE layer, and ε_2, d_2 are those of the HFFR layer.

C. Cross-Bonding & Transposition

The schematic for the designed model of the tunnel cable system is shown in Fig. 3. There are 18 cable sections, jointed at approximately 1km intervals, with continuous cable transposition and sheath cross-bonding applied at two out of three joints and straight linking applied at the third. Cable transpositions and sheath bonds are mirrored in the adjacent circuit. Moving from left to right in Fig. 3, transposition applies to both conductor and sheath and follows the sequence ABC – BCA, while cross-bonding has the effect of reversing each sheath transposition

D. Load and Fault Scenarios

Circuit 1 is energised under nominal winter load, 10% imbalanced load, and various fault conditions to compute induced voltages and currents in circuit 2. A 3x1phase current sink is used to define the load current in each case. Each load scenario and their respective current values in ATP-EMTP on different phases are given in Table IV.

TABLE IV. LOAD AND FAULT SCENARIOS FOR THE EMTP MODEL OF THE TUNNEL CABLE SYSTEM.

Load Condition	**Current I (A Peak)**		
	Phase A	***Phase B***	***Phase C***
3-phase nominal load	-3497	-3497	-3497
-10% imbalance load (on phase B)	-3497	-3147	-3497
3-phase fault	-89k	-89k	-89k
Single-phase fault (phase A)	-89k	-0.1	-0.1
Phase-Phase fault (B - C)	-0.1	89k	89k

E. Earthing Scenarios for Circuit cct2

The induced voltages and currents in the de-energised circuit depend to a great extent on the earthing arrangement of cable sheaths and conductors. NSI5 and CIGRE TB801 defined three working principles for safe work on de-energised cables under induced voltages/currents which include (I) earthed working with inductive currents, (II) earthed working without inductive currents, and (III) insulated working [4, 5]. Considering these working principles, this study defined two earthing scenarios, which are shown in Fig. 4. In scenario 1, both cable sheaths and conductors are earthed at far ends (substations A and B), while in scenario 2, they are unearthed.

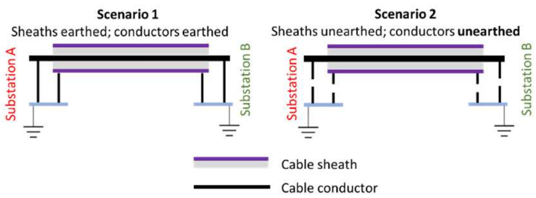

Fig. 4. Earthing scenarios for circuit cct2 cable sheaths and conductors.

III. RESULTS AND DISCUSSION

This section presents the results of induced voltages and currents from ATP-EMTP modelling of double circuit tunnel power cables. The obtained data from simulations is further processed in MATLAB, and the maximum value of voltages and currents along the cable length is reported. Fig. 5 illustrates the maximum voltages and current in the cable sheaths of energised circuit cct1 along with their quantified magnitude, both of which are independent of the earthing configuration of cct2. The results for induced voltages and currents in de-energised cable circuit cct2 are presented in Fig. 6, considering earthing scenarios 1 and 2. In earthing scenario 1, both the cable sheaths and conductors of cable circuit cct2 are earthed. Due to the tunnel's length, the induced voltages in the cable conductors remain low. However, a high induced current flows through both the conductors and the sheaths. In earthing scenario 2, both the cable sheaths and conductors of cable circuit cct2 are unearthed at far ends at substations A and B. As both the conductors and the sheaths are open at far ends of the cable, the "conductor to earth" volts and "sheath to earth volts" are measured between the two ends of the cable to obtain the maximum value. The results show that significant induced voltages have appeared along the cable length (see Fig. 6 (c)). On the other side, practically, there should be zero induced current through the cables due to the open ends, however, there is a slight current present due to the capacitive coupling. From the results, it is worth noting that voltages and currents in the cable sheath of circuit cct1 are enhanced dramatically under fault conditions. The highest voltages appear in 3-phase faults, while the highest current flows in the case of single-phase fault. The induced current in cable sheath of circuit cct1 is significantly higher under single-phase fault compared to the current under nominal load. The rise in voltages and currents in the cable sheaths of cct1 due to the faults also leads to the rise in induced voltages and currents in cable circuit cct2. From the results, the following two key observations are made. First, both induced voltages and currents in de-energised cable circuit cct2 are enhanced significantly when a fault occurs on cable circuit cct1. Second, the induced voltages along the cable length are extremely high when the cable ends are left unearthed compared to the earthed case.

According to NSI5 and CIGRE TB801 [4, 5], if the maintenance on a de-energised cable circuit needs to be carried out using safe working principle 1 as described earlier, the earthing configuration defined in earthing scenario 1 should be used. This working principle involves earthing all conductors, metallic screens, armours and Earth Continuity Conductor (ECC), where available at both remote ends of the cable section. Properly installed and reliable earthing connections are critical to eliminate the risk of arcing. While this approach effectively controls potential differences, it may result in the flow of substantial currents. To ensure safety, all metallic components must be interconnected to maintain a uniform potential and minimize risks arising from voltage differences. This method can transfer earth potential rise (EPR) from remote locations to the workspace, creating potential safety concerns. A major limitation of this approach is the possibility of hazardous voltages occurring between the soil and interconnected conductive parts in the workspace. To address this issue, the ground must either be made equipotential, such as by using earthing mats, or operators must be insulated from the soil, for instance, through the application of working techniques, including insulated sheeting, insulated platforms, insulated gloves and insulating blankets on walls and floors. Advantages of this method include allowing multiple work zones to be active along the cable simultaneously, and it removes any requirement to disconnect the earthing or internal connections in link boxes at the cable sealing ends.

If the maintenance on a de-energised cable circuit needs to be carried out using safe working principle II, the earthing configuration defined in earthing scenario 2 should be used. The maintenance method using earthing scenario 2 involves isolating all conductors, metallic screens, armours and ECC at both remote ends of the section. Earthing is applied exclusively at the work location by establishing a local equipotential zone. By configuring the cable's conductive components as a single-point bonding system, the risk of circulating currents or EPR from remote ends is eliminated at the worksite. One notable advantage of this method is that, when currents at the workplace are minimal (e.g., only a few amperes caused by capacitive coupling between the cable and the ground), the likelihood of hazardous voltages appearing between the soil (ground and walls) and interconnected conductive parts is eliminated. However, a drawback of this approach is that it may result in dangerous voltages occurring outside the work area.

If the maintenance on the de-energised cable circuit needs to be carried out using working principle III (insulated working), the induced voltages/currents must be within the handling capacity of the insulation tools, insulation gloves and insulation boots, etc. From the computed induced voltages in this study, it can be observed that they are within the acceptable limits by NSI5 and CIGRE TB801.

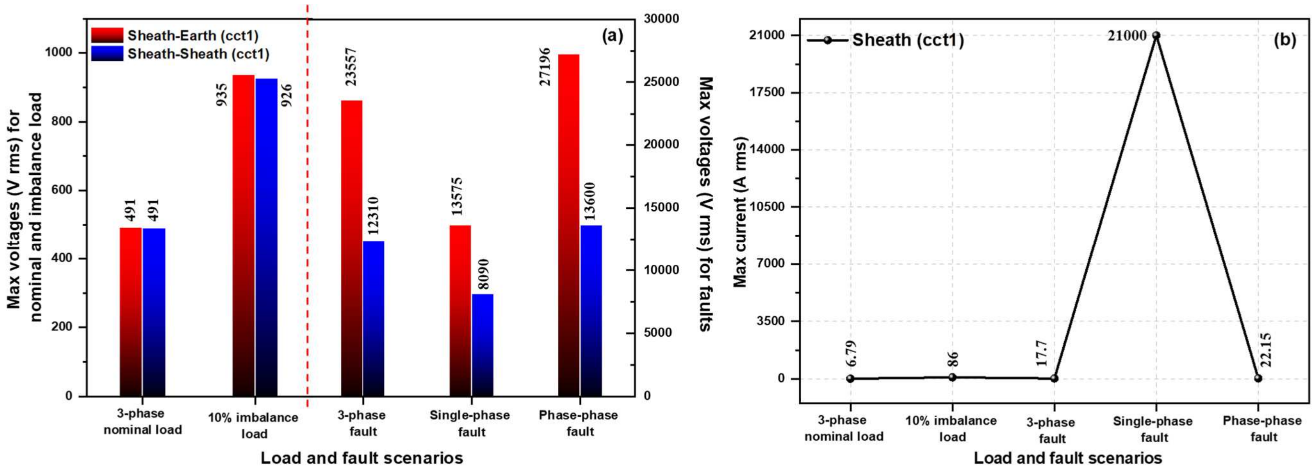

Fig. 5. Maximum voltages and currents in energised cable circuit cct1 considering various loads and fault scenarios, irrespective of the earthing scenario of cable circuit cct2.

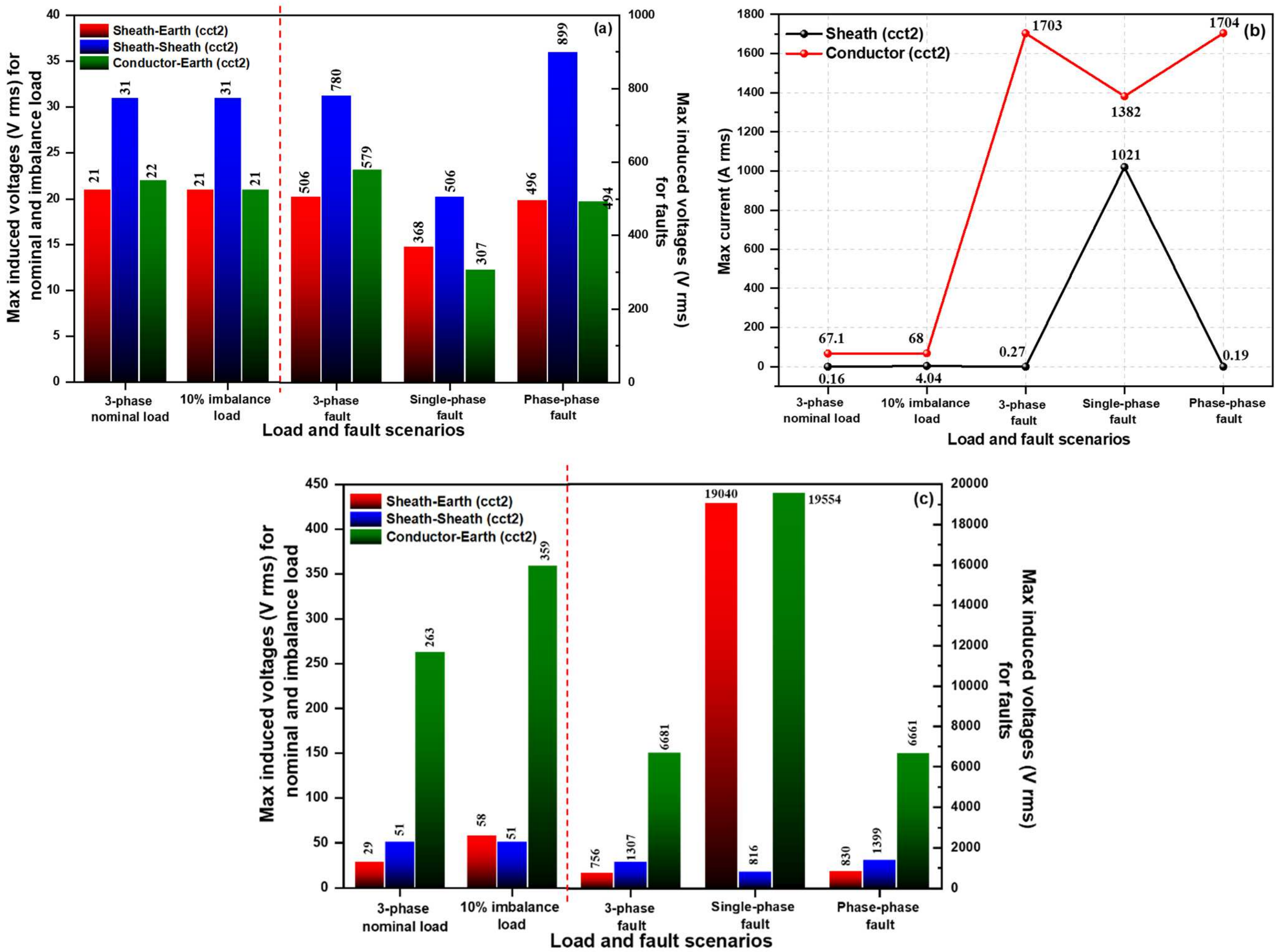

Fig. 6. Maximum induced voltages and currents in de-energised cable circuit cct2 considering various loads and fault scenarios, (a) induced voltages for earthing scenario 1, (b) induced current for earthing scenario 1, and (c) induced voltages for earthing scenario 2.

IV. CONCLUSIONS

This paper computed the induced voltages and currents in a de-energised cable circuit due to the electromagnetic effect from an adjacent live circuit through ATP-EMTP simulations in a double circuit tunnel cable system. The results showed that induced voltages and currents in a de-energised circuit greatly depend on the earthing configuration of cable sheaths and conductors. There are high induced voltages and a negligible amount of current along the cable length when it is left unearthed at the far end substations. On the other hand, a high circulating current flows along the cable when it is earthed at far ends. Moreover, the magnitude of the induced voltages/currents increased significantly due to the faults on the energised cable, especially in case of a single-phase fault. The obtained results, considering the two different earthing configurations of the de-energised cable circuit, are in line with the theoretical background of the safe working methods described in National Safety Instructions 5 by National Grid UK and CIGRE TB801. The study can be used effectively as a reference to proceed with maintenance work on double circuit tunnel power cables.

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