Complete Method to Assess the DC Corrosion Impact on Pipeline Systems During the Planning and Approval Stages of HVDC Systems With Earth Current Return

CHARALAMBOS A. CHARALAMBOUS1, (Member, IEEE), AND ALEXANDROS I. NIKOLAIDIS2

1Power Systems Modeling (PSM) Laboratory–EMI, Earthing and Corrosion, Department of Electrical and Computer Engineering, University of Cyprus, 1678 Nicosia, Cyprus
2Transmission System Operator-Cyprus, 2057 Nicosia, Cyprus

Corresponding author: Charalambos A. Charalambous (cchara@ucy.ac.cy)

ABSTRACT The technology of HVDC systems defines the current return process, which can be through a dedicated metallic conductor or through a conducting medium, such as the earth or sea. Although the magnitude of the earth/sea return current is normally specified in local regulations or project specifications, there is no explicit methodology to estimate the intermittent, time duration of this current, over the life-span of a system. However, dc interference/corrosion impacts related to the development of HVDC links are, to a large extent, associated to the time duration of the earth current. In the absence of any explicit methodology, the potential influence of the earth/sea return current on nearby critical infrastructures is often based on unrealistic or on conservative interference impact studies. The purpose of this paper is to firstly provide a methodology to quantify the expected intermittent duration of the earth return current - in point-to-point bipolar HVDC systems, which arises from their partial-availability or the emergency conditions. Subsequently, the proposed methodology is applied in a realistic dc interference/corrosion study of a critical pipeline system that operates near a HVDC link currently being constructed. In essence, the paper describes a top-down complete approach for HVDC de interference modelling endeavors in an attempt to avoid conservative and costly mitigation measures concerning third-party critical infrastructures in the nearby vicinity.

INDEX TERMS HVDC, DC interference, corrosion, gas pipelines, planning, approval, electrodes.

I. INTRODUCTION
DC interference studies are extremely critical, both at the planning and the environmental approval stages of HVDC projects with earth current return [1]. These studies aim to investigate the extent of the possible interference of electrode operation on nearby critical metallic infrastructure and natural environment. Normally, such investigation studies consider both local and remote aspects of possible impacts arising from the electrode use. The local impacts near the electrode site, mostly involve electrical safety (i.e. touch, step and transferred potentials) or release of chlorine gas and/or metals from the electrodes to the surrounding environments. Other local impacts include issues related to soil or seawater overheating [2]. With regard to remote impacts, the primary concerns lie with accelerated corrosion or electrical interference on existing or new critical infrastructure in the nearby vicinity [3]. Such infrastructure includes pipelines, railways, and electrical power & telecommunication apparatus [4], [5].

In a DC interference study, it is particularly important to investigate whether any of the local and remote impacts are restrictive in the selection of the HVDC electrode installation site, or if the anticipated consequences can be mitigated or ignored—in case they are insignificant. Moreover, thermal effects near land/sea electrodes can be
of concern, depending on whether the electrode is used intermittently or in continuous operation [2].

Taking a step back, it is important to specify that DC interference is a disturbance, generated by DC systems, through the intentional or unintentional flow of currents in the earth or in any other electrolyte [4]. Thus, this type of interference affects buried metallic infrastructures primarily by conduction, which occurs through the earth or any other electrolyte. The impact is particularly associated with the potentially corrosive charge, which is a product of the earth current magnitude and its time duration.

However, DC interference also depends on the underlying HVDC technology that defines whether the earth current return process is continuous (e.g., asymmetric monopolar or homopolar systems with ground return) or intermittent (i.e., emergency monopolar mode of bipolar systems with ground return). In such systems, the requirements on selecting an appropriate electrode location and size are dependent upon the current magnitude, the direction of current flow and the time that the system will discharge/collect current into/from the environment (earth/sea). For example, if we consider a 10 A unbalanced current –from a bipolar HVDC system– discharging continuously for one year through an electrode station, this will result in 87600 Ampere-Hours of potentially corrosive charge per annum. This is equivalent to the corrosive charge that will result from a monopolar (emergency) operation of the same system, having a return current of 1000 A for 87.6 hours [3].

Bearing in mind the above discussion, the magnitude of current that will be injected into (or collected from) the earth/sea at the electrodes is normally specified in local regulations or project specifications. However, there is no explicit methodology to estimate the time duration of the earth return current over the life-span of a HVDC system. Nonetheless, in a mathematical model, as the one used in planning and approval studies, a commonly asked question is: “What is the expected time duration of the earth/sea return current under emergency conditions - over the expected life of HVDC system’s operation?” Hence, in this paper we will attempt to provide an informed answer to this question and further illustrate how to apply this answer in a relevant dc interference simulation activity.

A. CONTRIBUTIONS BEYOND THE STATE OF THE ART
The method we present in this paper is exclusively tailored to quantify the expected intermittent duration of the earth return current (and hence electrode usage) –in point-to-point (P2P) HVDC systems. This is achieved by suitably incorporating component availability calculations. In effect, our method directly correlates availability calculations –usually applied to assess the transfer capability of interconnection projects– with the fundamental topology/configuration of HVDC systems. This allows for an explicit calculation, merely relating to the expected time of electrode usage at full operational current. It is apparent that the proposed method is redundant when evaluating HVDC system options that do not make use of electrodes (e.g., bipolar systems with dedicated metallic return, four-pole systems [6], etc.).

Finally, by means of an example, we apply this method in a study that relates to DC corrosion evaluation of a pipeline system that operates in the nearby vicinity of a P2P HVDC system with electrodes. We highlight, however, that the method can be applied in other type of environmental impact studies that are related to the HVDC systems’ electrode operation. These kind of studies are extremely critical, both at the planning and environmental approval stages of a project by avoiding conservative and costly mitigation measures concerning third-party critical infrastructures in the nearby vicinity of HVDC systems’ electrodes.

B. ORGANIZATION OF PAPER
The paper is organized as follows: Section II provides some important background information on P2P HVDC system configurations. Section III describes the fundamental logic of the developed method to quantify the expected duration of the earth return current, with particular emphasis on P2P HVDC systems. To facilitate the method’s use and understanding, we provide a numerical evaluation in Chapter IV while in Chapter V we use the latter (numerical evaluation) to perform an informed DC corrosion study on a nearby third-party infrastructure.

II. HVDC SYSTEM CONFIGURATIONS
Most of the existing HVDC transmission projects rely on P2P links with Line Commutated Converter (LCC) HVDC transmission technologies, Voltage Source Converter (VSC) HVDC transmission technologies or a combination of the two [7]. At a high level, P2P HVDC systems comprise two converter stations at remote ends and at least one DC power line (i.e., overhead line and/or underground/submarine cable) that interconnects the stations. Each converter station contains components that are serially connected, operated and interrelated in order to provide a functioning electrical pathway from the AC to the DC side (and vice versa). Usually, a VSC station (which is the main focus of this paper) consists of the following components [8]: a) an interface transformer, b) a coupling reactor, c) a converter unit, d) a control system of the converter unit, and e) a DC switchyard (Note: the list is not meant to be exhaustive, but captures the core components which may be considered in the availability analysis of the converter). We refer the readers to [9] for more detailed description on the role, function and characteristics of each of the main converter components.

Thus, P2P HVDC systems are largely categorized based on the relevant configurations of the components in their converter stations and the DC power line(s). The most widely used HVDC configurations, of this type, are the asymmetric monopolar and the bipolar. Figure 1 illustrates an example of an asymmetric monopolar configuration with electrodes, whilst Fig. 2 illustrates a bipolar configuration with electrodes. For the asymmetric monopolar configuration (Fig. 1), the converters are connected between the HVDC...
pole and the electrode. Under normal operating conditions, the earth return current is continuous and equal to the full operational current.

The bipolar configuration (Fig. 2) is a combination of two asymmetrical monopole configurations with a common neutral bus (N). The neutral point is connected, through a dedicated electrode line, to an electrode. Under normal operating conditions both converter units (at each station) are equally loaded, so that both DC lines (poles) may carry approximately the same current. Any unbalance current is typically limited to 0.5 % to 1 % of the rated DC of each pole [3].

III. METHOD TO ESTIMATE THE DURATION OF EARTH RETURN CURRENT

At this point, we reiterate that the first objective of this paper is to provide a method that will assist in quantifying the expected intermittent duration of the earth/sea return current –in P2P HVDC systems. We note that, in asymmetric monopolar configurations, the earth electrodes are required to operate continuously, bearing the full operational current of the circuit. This entails that in these systems, the time duration of the earth current can be estimated a priori –as it is related to the availability of the converter stations and transmission lines/cables.

However, estimating the intermittent duration of the earth return current in bipolar configurations is a more complex exercise. In the following sub-chapters, we will outline the parameters that introduce this complexity and we will propose an appropriate calculation method for the expected duration of the earth return current.

A. GENERAL DESCRIPTION OF APPROACH

Availability is defined as the probability that a repairable system or system element is operational at a given point in time, under a given set of environmental conditions [10]. In the context of this paper, the availability analysis entails the probabilistic modelling of the HVDC system components. These components are the pole conductors and the subcomponents of the converter stations (i.e., the transformer, the coupling reactor, the converter unit, the control system of the converter unit and the DC switchyard).

The probabilistic modelling of the HVDC system components can be based on relevant measurements, data and information provided by manufacturers and/or operational records. Such information can be used to quantify the probability of the HVDC system being in a specific state by using three important parameters [10], [11], as shown in Table 1.

TABLE 1. Definition of parameters.

| Description                  | Acronym | Remarks                                      |
|------------------------------|---------|----------------------------------------------|
| Mean Time to Failure         | MTTF    | Average/expected time it takes until the component fails |
| Mean Time to Repair          | MTTR    | Average/expected time or duration it takes to repair the component |
| Mean Time between Failures   | MTBF    | Average/expected time between two consecutive failure of the component |
The relationship between the three parameters shown in Table 1 is given in (1) [10].

\[ MTBF = MTTF + MTTR \]  

(1)

The Availability (A) of a component, which is the probability that the component is in a normal and healthy condition at an arbitrary time, can be expressed as in (2) [10].

\[ A = \frac{MTTF}{MTBF} = \frac{MTTF}{MTTF + MTTR} \]  

(2)

Consequently, Unavailability (U), which is the probability that, at an arbitrary time, the component is out of service and under repair, can be calculated as per (3) below [10].

\[ U = \frac{MTTR}{MTBF} = \frac{MTTR}{MTTF + MTTR} = 1 - A \]  

(3)

To this extent, the aforementioned parameters of each component, comprising the P2P-HVDC system, can be combined as per their serial or parallel operational dependency, in order to determine the duration of the electrode usage for each configuration [12]. Specifically, we take advantage of the fact that the probability of a system being in a specific state of operation is the product of the availability of its working subsystems and the unavailability of its (potentially) failed subsystems. This implicitly means that the sum of the probabilities of all states should be equal to one [10], [11]. In this respect, the probability of each state can be derived as in (4).

\[ P_s = \prod A_i \times \prod U_j \]  

(4)

Within (4), \( P_s \) denotes the probability of the HVDC system being in state \( s \) (from a set \( S \) containing the total number of possible system states), \( \Pi \) denotes the product operation, \( A_i \) refers to the availability of subsystem \( i \) (from a set \( I \) containing the available/working subsystems), whilst \( U_j \) refers to the unavailability of subsystem \( j \) (from a set \( J \) containing the unavailable/failed subsystems). For clarity purposes, we note that the sets \( I \) and \( J \) are complementary and \( I \cup J \) containing the unavailable/failed subsystems. For clarity purposes, we note that the sets \( I \) and \( J \) are complementary and effectively their addition contains all subsystems comprising the HVDC system.

The above approach entails an important subtlety; that is, in order for the method to produce meaningful results, an accurate identification of the interdependence amongst the pertinent subsystems of the underlying HVDC configuration must be performed. To make the latter clause more explicit, the interdependence inference is thoroughly described in the next two subsections, for the monopolar and bipolar P2P HVDC configurations, respectively.

1) HVDC SYSTEM OF MONOPOLAR CONFIGURATION WITH EARTH/SEA RETURN

A P2P HVDC system of monopolar configuration with earth/sea return consists of the following subsystems (as per Fig. 1):

- a. one (1) converter at converter station 1,
- b. one (1) converter at converter station 2, and,
- c. one (1) DC line/cable connecting converter station 1 to converter station 2.

A monopolar system uses its electrodes continuously when all subsystems are available. Specifically, the dependence amongst these subsystems is serial; that is, if one of the subsystems fails, the whole system is shut down. Therefore, no electrode usage would take place in case of any equipment outage (either planned or unplanned).

Thus, the probability of the whole HVDC system \( (A_{HVDC}) \) being available can be quantified as per (5) below.

\[ A_{HVDC} = A_{C1} \times A_{C2} \times A_{DC1-2} \]  

(5)

Within (5), \( A_{C1} \) and \( A_{C2} \) refer to the availability of the converter at station 1 and station 2, respectively, whilst \( A_{DC1-2} \) refers to the availability of the DC power line, connecting station 1 to station 2.

Relatedly, in order to quantify the converter availability at each converter station, we need to account that the components, making up the converter, are serially dependent. Thus, the availability of the converter \( (A_{CX}) \) is derived as in (6) [8].

\[ CX = A_{TRX} \times A_{CRX} \times A_{CUX} \times A_{CSX} \times A_{SWX} \]  

(6)

Within (6), \( A_{CX} \) refers to the availability of the converter, \( A_{TRX} \) to the availability of the transformer, \( A_{CRX} \) to the availability of the coupling reactor, \( A_{CUX} \) to the availability of the converter unit, \( A_{CSX} \) to the availability of the control system and \( A_{SWX} \) to the availability of the DC switchyard, at converter station \( X \) (i.e. either station 1 or station 2). Figure 3 elaborates on (6) by means of an illustrative example of a monopolar HVDC system with two converters at each end.

Finally, based on (5) and (6), the expected duration of the electrode usage per annum for the monopolar configuration \( (T_{el-m} \text{ in hours}) \) can be quantified as in (7):

\[ T_{el-m} = A_{HVDC} \times (8760 - MP_m) \]  

(7)

Within (7), \( MP_m \) refers to the planned yearly maintenance period (in hours), whereby the specific monopolar HVDC system would be shut down and, consequently, no electrode use would take place.
2) DURATION OF ELECTRODE USAGE FOR POINT-TO-POINT HVDC SYSTEM OF BIPOLAR CONFIGURATION

A P2P HVDC system of bipolar configuration with earth/sea electrodes consists of the following subsystems (as per Fig. 2):

a. two (2) converters at converter station 1 (e.g. $C_{1p}$ and $C_{1n}$, for the positive and negative pole, respectively),
b. two (2) converters at converter station 2 (e.g. $C_{2p}$ and $C_{2n}$, for the positive and negative pole, respectively), and,
c. two (2) DC power lines connecting converter station 1 to converter station 2 (e.g. $DC_{1−2p}$ and $DC_{1−2n}$, for the positive and negative pole, respectively).

These six (6) components/subsystems define the operational state of a P2P, bipolar HVDC system. Thus, the complete enumeration of system states would amount to 26, or 64 states, in total. The probability of each of these states can be derived by virtue of equation (4).

To make the latter more explicit, Table 2 tabulates some common states (out of the possible 64 states) of a P2P bipolar HVDC system, exemplifying how the respective probability of each state can be derived via the multiplication of the respective probabilities (i.e., availability/unavailability of each pertinent component/subsystem). For example, State 0 in Table 2 refers to the case where all subsystems are available (i.e. $C_{1p}$, $C_{2p}$, $DC_{1−2p}$, $C_{1n}$, $C_{2n}$, $DC_{1−2n}$). This effectively represents the healthy state of operation. As a subsequent example, State 3 refers to the case where the DC power line of the positive pole is unavailable (i.e. $DC_{1−2p}$), whereas all other subsystems are available (i.e. $C_{1p}$, $C_{2p}$, $C_{1n}$, $C_{2n}$, $DC_{1−2n}$).

Moreover, it is important to note that, in an electrode use duration analysis, we should consider whether the P2P bipolar HVDC system operates in the presence (or lack thereof) of a specialized equipment. This is commonly referred to as metallic return transfer breakers (MRTBs), on the DC side [7], [13], [14]. Analytical details on such equipment can be found in [7]. Essentially, in case there is a converter outage in one of the poles, the presence of MRTBs can facilitate the switching to change over from the earth return mode to metallic return mode, without having to completely de-energize the HVDC system (in order to allow for a network topology reconfiguration) [14]. Therefore, the presence (or lack thereof) of MRTBs is taken into account in our analysis as follows:

- **Systems with MRTBs**: we assume that full current electrode usage takes place only when one DC power line is unavailable.
- **Systems without MRTBs**: the full current electrode usage takes place whenever any of the pole components is unavailable.1

1This is for assuming the same power transmission availability as the case with MRTBs (thus, comparing electrode usage on an equal footing) and accounting for the worst case scenario in terms of electrode usage, at the same time.

| State (0) | Positive pole (p) | Negative pole (n) | MRTBs presence | FEU index* |
|----------|------------------|------------------|----------------|------------|
| C1p      | C1n              | DC1−2p           | Yes            | 0.5        |
| 1        | U1p              | A1n              | No             | 0.0        |
| 2        | A1p              | U1n              | Yes            | 0.5        |
| 3        | A1p              | U1n              | No             | 0.0        |
| 4        | U2p              | A2n              | Yes            | 0.5        |
| 5        | A2p              | U2n              | No             | 0.0        |
| 6        | A2p              | U2n              | Yes            | 0.5        |

*FEU index is a binary index, determined as per the availability ($A$) and unavailability ($U$) of each subsystem $j$ ($C_{jp}$, $C_{jn}$, $DC_{1−2p}$, $DC_{1−2n}$) in each operating state ($s$), depending on whether the HVDC system benefits from MRTBs or not. More specifically:

- **FEU index = 0**, if the operating state ($s$) does not require the electrodes usage at full operational current, or,
- **FEU index = 1**, if the operating state ($s$) requires the electrodes usage at full operational current.

Considering the above, it is clear that the duration of full current electrode usage is affected by the presence of MRTBs; this is reflected in Table 2 (i.e. MRTBs presence).

Thus, in order to express mathematically the effect of the presence of MRTB (or not) on the full current electrode usage of the HVDC system, we introduce a binary index, the $FEU_{index}$ (0 or 1), for each operating state $s$. This index is derived based on the DC network topology resulting from the availability/unavailability of the system’s components. This index is set to zero (0) if the operating state does not use the electrodes at full operational current. Conversely, the index is set to unity (1) if the operating state uses the electrodes at full operational current. For example, in State 2 (see Table 2), the positive pole converter at Station 2 is unavailable (i.e. $U_{C2p}$). This results in the $FEU_{index}$ being zero in the presence of MRTBs and the $FEU_{index}$ being unity in the absence of MRTBs. However, the $FEU_{index}$ would be equal to unity, regardless of the presence of MRTBs, when either of the power lines connecting converter station 1 to converter station 2 (i.e. $DC_{1−2p}$ or $DC_{1−2n}$) is unavailable. The latter is captured in States 3 and 6 (see Table 2) for the positive and negative pole line, respectively.

a: **P2P BIPOLAR HVDC SYSTEM – ELECTRODE USAGE DURING REGULAR OPERATION PERIOD**

Based on the above discussion, the duration of full current electrode usage for the bipolar configuration is effectively determined by the sum of the probabilities of those operating states that lead to full current electrode usage, multiplied by the $FEU_{index}$. Thus, the duration of electrode usage for a bipolar configuration during regular operation periods can be mathematically formulated as per (8) below.

$$T_{RCel−b} = (\sum_{s} [P_s \times FEU_{index}]) \times (8760 - MP_b) \quad (8)$$

Within (8), $T_{RCel−b}$ refers to the duration of full current electrode usage, $P_s$ denotes the probability of the HVDC system being in state $s$ whilst $MP_b$ refers to the planned yearly
maintenance period (in hours) of the bipolar HVDC system. With regard to $MP_b$, we elaborate on its derivation in the next subsection, leading into equations (9) and (10).

b: P2P BIPOLAR HVDC SYSTEM – ELECTRODE USAGE DURING MAINTENANCE PERIOD

During maintenance periods, a P2P bipolar configuration is able to operate under monopolar configuration. It should be noted that the relevant maintenance requirements and the respective time periods are determined by the HVDC system’s characteristics (e.g., circuit length, submarine or overhead line project, location, weather conditions, etc.) and are essentially provided by the equipment manufacturers, in coordination with the HVDC system owners/operators.

The monopolar operation of bipolar HVDC systems aims to allow for less downtime of their transmission capability, at the expense of increased usage of the electrodes at full operational current. That is, a trade-off between the transmission capability (and associated electrode usage) and the total downtime of the system is considered.

Bearing the latter in mind, we assume a coordinated maintenance plan for the bipolar HVDC system. In particular, we assume that the complete shutdown of the bipolar HVDC system is avoided\(^2\) (i.e., worst-case scenario in terms of electrode usage at full operational current), and, consequently, the following stages of the maintenance period are identified:

a. Positive pole maintenance period – $MP_p$

b. Negative pole maintenance period – $MP_n$

Effectively, the total maintenance period of the bipolar HVDC system ($MP_b$) is the sum of these two stages, as per (9) below.

$$MP_b = MP_p + MP_n \quad (9)$$

It is further assumed that the maintenance of each pole (positive or negative) entails the following activities: a) the maintenance of the pole converter at each station, and, b) the maintenance of the DC power line of each pole. Furthermore, it is assumed that these two activities are independent of each other and, therefore, can be performed in parallel.

The total maintenance period of each pole is dependent on the duration of maintenance of the subsystems comprising it (i.e., the pole converters and the respective DC line/cable). This is mathematically expressed in (10.a) and (10.b), for the positive and negative pole, respectively.

$$MP_p = \max\{\max\{T_{C1p}, T_{C2p}\}, T_{DC1−2p}\} \quad (10.a)$$

$$MP_n = \max\{\max\{T_{C1n}, T_{C2n}\}, T_{DC1−2n}\} \quad (10.b)$$

\(^2\)There exist several reasons that HVDC stations must be completely deenergized, e.g., for inspection and maintenance purposes. However, such requirements are usually less frequent. To this extent, by omitting such considerations, the expected duration of electrode usage at full operational current is increased, therefore, this is considered to be the worst case scenario in terms of electrode usage.

Within (10), $T_C$ refers to the maintenance period (in hours) of a converter whilst $T_{DC}$ refers to the maintenance period (in hours) of a DC power line. Moreover, subscripts 1/2 and p/n are used to denote the converter station and pole polarity, respectively.

To this extent, for a bipolar HVDC system without MRTBs, the duration of electrode usage at full operational current ($T_{MPel}$), can be quantified via (11) below.

$$T_{MPel} = A_{HVDC} \times MP_b \quad (11)$$

However, in case where the bipolar HVDC system is equipped with MRTBs, then, the full current electrode usage would only take place for the time needed to maintain the DC power line of each pole. Bearing this in mind, for a bipolar HVDC system with MRTBs, the duration of electrode usage at full operational current within the maintenance period of DC power line of each pole ($T_{MPel−MRTB}$), can be quantified via (12) below.

$$T_{MPel−MRTB} = A_{HVDC} \times (T_{DC1−2p} + T_{DC1−2n}) \quad (12)$$

Within (11) and (12), $A_{HVDC}$ refers to the availability of the HVDC system (as already described in (5)) operating under a monopolar configuration during the maintenance period of the other pole.

3) TOTAL DURATION OF FULL CURRENT ELECTRODE USAGE FOR BIPOLAR HVDC SYSTEMS

Having formulated the duration of full current electrode usage both due to planned and unplanned monopolar operation, it follows that the total duration of full current electrode usage for bipolar HVDC systems ($T_{el−b}$) is simply the sum of these two expected time periods, as per (13) and (14) for the case with and without MRTBs, respectively.

$$T_{el−b} = T_{RCel−b} + T_{MPel−MRTB} \quad (13)$$

$$T_{el−b} = T_{RCel−b} + T_{MPel} \quad (14)$$

IV. NUMERICAL EVALUATION OF PROBABILISTIC METHOD FOR P2P BIPOLAR HVDC SYSTEMS

In order to demonstrate how the method proposed in the previous section produces results, a numerical case study is presented in this section. Specifically, due to the growing interest in submarine bipolar HVDC cables, proven by a series of recent relevant projects (e.g., COBRAcable, BritNed, ElecLink, North Sea Link), our case study pertains to the way that the expected duration of full current electrode usage would be derived at the planning stage of such projects. Nevertheless, the method is applicable to overhead line projects as well; the difference would lie in the considered availability data of the DC power lines and their maintenance requirements. It is reiterated that the goal of the method is to provide useful insights to system planners, in order to minimize technical and environmental impacts related to the electrode usage.

For the purposes of the numerical case study, we divide the study into two cases (i.e., Case 1 and Case 2); Case 1
TABLE 3. Availability and unavailability calculation of a 100-km DC cable.

| Reference | MTTF (hours/100 km) | MTTR (hours) | $A_{DC1-2}$ (%) | $U_{DC1-2}$ (%) |
|-----------|---------------------|--------------|-----------------|-----------------|
| [15]      | 245448              | 1440         | 99.42%          | 0.58%           |
| [16]      | 168557              | 2160         | 98.73%          | 1.27%           |
| [17]      | 125142              | 1440         | 98.86%          | 1.14%           |

corresponds to HVDC system with MRTBs, whereas Case 2 corresponds to HVDC system without such a feature.

A. CASE 1: DC CABLE AVAILABILITY – DURATION OF FULL CURRENT ELECTRODE USAGE OF BIPOLAR HVDC SYSTEMS WITH MRTBS

Firstly, the way that the derivation of the DC cables availability takes place is discussed. The two factors that determine the availability/unavailability index of a DC cable are the MTTF and MTTR, as per (2) and (3). Relatedly, it is noted that MTTF values are most commonly a function of the DC link’s length and are usually reported on a per 100-km basis. Table 3 tabulates data for DC cables from relevant literature and industry reports [15], [16], [17].

Furthermore, it is important to note that, according to relevant industrial practice [18], submarine DC cables usually require virtually no planned maintenance. Consequently, in cases of submarine HVDC systems equipped with MRTBs, monopolar operation during converter maintenance is avoided, since the cables can be used as metallic return (instead of using the electrodes). Therefore, the duration of full current electrode usage is essentially determined by such unplanned maintenance/repair requirements of the DC cables.

However, DC cables’ repair time in case of unplanned failures (e.g., due to damage caused by boat anchors) can be rather substantial (durations of up to 6 months may be needed, under certain conditions [19]). As explicitly noted in [18], “... quantifying the time needed to repair failures of HVDC subsea cables is a complex exercise, depending on the type of fault, vessel and crew availability and notably weather conditions”.

In order to showcase the dependence of the duration of full current electrode usage on the repair times of DC cables, three MTTR values are used, equal to 720 hours, 1440 hours and 4320 hours, respectively. Subsequently, by means of (8) and Table 3 (using MTTF equal to 245448 hours), the full current electrode usage of a bipolar submarine HVDC system can be derived. Figure 4 presents the expected annual hours of full electrode usage, as a function of the DC link’s length and MTTR value.

Figure 4 can be interpreted as follows: if, for example, a 400-km DC link is under consideration, then the expected duration of full current electrode usage will be in the range of 201 to 1077 hours (i.e., 2.29% to 12.30%) of its annual operation period. In essence, Fig. 4 can be perceived as a “screening curve” tool for planners, in order to appropriately capture the expected duration of full current electrode usage for P2P submarine HVDC systems.

B. CASE 2: DC CONVERTER AVAILABILITY – DURATION OF FULL CURRENT ELECTRODE USAGE OF BIPOLAR HVDC SYSTEMS WITHOUT MRTBS

Having analyzed the case of bipolar HVDC systems with MRTBs, the case without such an option will now be discussed, in order to compare the two cases. The main difference between the two configurations is that for HVDC systems without MRTBs, every outage, either planned or unplanned, will lead to full current electrode usage.

The way that we apply the proposed method aims to capture the fact that opting for MRTBs comes at an increased cost of the DC-side equipment. Therefore, this increased cost would have to be outweighed by the reduced electrode usage and its associated costs or environmental impacts; therefore, the difference between the results of Case 1 and Case 2 can be used as a means to account for this fact, in a cost-benefit analysis at the planning stage.

Once again, (8) is used to quantify the expected duration of full current electrode usage. However, in order to use (8), firstly the converter availability is quantified (as per (6)). For this purpose (i.e., converter availability calculation), relevant data taken from [12] and [20] are used, as tabulated in Table 4.

Subsequently, the converter availability/unavailability is used in (8), thus allowing for the determination of those states that lead to full current electrode usage (modeled by the FEU_index) and the quantification of the respective duration.

Once again, three MTTR values are used, equal to 720 hours, 1440 hours and 4320 hours, respectively (assuming MTTF is equal to 245448 hours). Then, by means of (8), Table 3 and Table 4, the full current electrode usage of a...
bipolar submarine HVDC system without MRTBs can be derived. The results are shown in Fig. 5.

C. COMPARISON OF CASE 1 AND CASE 2
Comparing the results in Fig. 4 and Fig. 5, we observe that the two cases differ by approximately 3.5% of their regular operation time, i.e., HVDC systems without MRTBs can use the electrodes at full current for an extra ∼300 hours of operation per year. This offset is due to the fact that the lack of MRTBs does not allow for the use of the DC cable as metallic return when a converter is in outage (without completely de-energizing the HVDC system). To this extent, at the planning stage, the additional cost of MRTBs could be juxtaposed with the implicit costs of the environmental and economic costs of increased electrode usage and associated potentially reduced HVDC system availability. It is also rather important to note that this difference in electrode usage is not dependent on the length of the DC link. More specifically, the results suggest that, for submarine HVDC projects in the order of 300-400 km in length, the electrode usage caused by converter unavailability dominates over the electrode usage that is caused by DC power lines. This attests to the flexibility that could be provided by MRTBs, in order to avoid the complete shutdown of the link and associated electrode usage.

V. APPLICATION OF METHOD IN DC CORROSION STUDY OF A REAL SYSTEM
The objective of this section is to calculate the dc interference impact (i.e., corrosion rate) of a pipeline under the expected monopolar (emergency) operation of bipolar HVDC system, by capitalizing on the method described in the previous two sections. We highlight that the simulation activities described in the following subsections pertain to a real system that is currently being constructed.

A. BRIEF DESCRIPTION OF HVDC SYSTEM
The considered HVDC link has a nominal voltage ±500 kV and transfer capability of 1000 MW (2 × 500 MW) according to the information described in [21] (and reproduced hereby), the link will have an on-shore cable section (at the North side) as well as a submarine cable section. The onshore section will have an approximate length of 32 km, while the submarine section, 330 km. The transmission of power, for both sections, is achieved by two dc power cables. Moreover, there will be two shoreline electrodes (see Fig. 6). The shoreline electrode station at the North side is planned approximately 50 km away from the corresponding converter station. The connection between the converter station and the electrode station (North side), will be through an electrode line that is planned as a combination of buried (32 km) and submarine (18 km) cable conductors. Moreover, each converter station will house two converter units, which will be completely independent in operation and maintenance. Each converter unit will include one set of three single-phase converter transformers. Converter valves will be of Multi-level Modular Converter (MMC) design, using half-bridge type submodules.

During normal operation the bipolar link will assume balanced operation. This entails that both converter units, in each station, will be loaded equally and both DC cables will carry approximately the same current. The inevitable unbalanced current through the shoreline electrodes is assumed to be ≤1% of the rated load current under normal operation. In case of pole fault, the electrodes are expected to conduct high load current through the sea. We further note that the two shoreline electrodes will be bi-directional hence they will be both capable to operate in anodic and cathodic mode.

Finally, there are two major gas pipeline systems that are running near the inland parts of the HVDC cables, at the North side. (See Fig. 6). The nearest distance of these two pipelines from the shoreline electrode (North side) are given in Table 5. As a worst case scenario and in the interest of space the subsequent analysis will only refer to pipeline 1.

B. SIMULATION MODEL AND INPUT PARAMETERS
1) LAYOUT OF SIMULATION MODEL
To facilitate the dc interference study of the pipeline system, due to the potential operation of the HVDC system, we have developed a suitable simulation model (see Fig. 6) using a commercially available software CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis) [22].

In Fig. 6, we show the physical layout of the simulation model. This model is topologically accurate and includes all the necessary electrical and material characteristics of the
HVDC cables, electrodes and pipeline systems (including their earthing systems).

2) APPROPRIATE SOIL AND SEAWATER RESISTIVITY MODELS
Relevant geo-electrical studies that describe the variation of soil resistivity along the length of the enquired pipeline system have been utilised to create appropriately sea/soil resistivity models. The measurements have shown that there is a significant variation of the resistivity along the routing the pipeline (see 1st subplot of Fig. 10). Thus, we have modelled a soil model that is able to capture this variation to a significant extent. Table 6 shows the soil model that has been used as the base scenario for pipeline 1.

3) PIPELINE CHARACTERISTICS
The input parameters of the pipeline system are described in Table 7. The total length of the enquired pipeline system is 82.03 km.

4) ENERGIZATION CONDITIONS
In the subsequent sections the dc interference impact on the pipeline system is confined to the emergency (monopolar) operation of the HVDC link. Thus, Table 8 illustrates the energisation condition used in the simulation process.

C. SIMULATION RESULTS AND ANALYSIS
1) OVERALL APPROACH
The approach followed to evaluate the pipelines’ corrosion rate is shown in Fig. 7. Briefly, the approach relies on four steps. As a conservative-extreme scenario, we assume that the pipeline is not cathodically protected. The steps we follow are:

- **Step 1**: Simulation of the HVDC interference on the pipeline system by omitting the Cathodic Protection (CP) operation.
- **Step 2**: Calculation of pipeline’s leakage current density by assuming the presence of 1 cm² coating defects along its routing.
- **Step 3**: Use of Faraday’s electrolytic law to calculate the corrosion rate along the length of the pipeline.

| TABLE 6. Base soil/seawater model for pipeline system (CDEGS-MALZ). |
| --- |
| **Base soil/sea water model – Pipeline 1** |
| Type: Vertical-multilayer model as per the soil resistivity measurements |
| Notes: |
| • A vertical-multi layer soil structure has been used to accommodate the variation on soil resistivity along the route of pipeline systems as well as the sea section, where the two electrodes are to be located |
| • The sea-water resistivity has been assumed to be equal to 0.25 Ω m (layer-thickness ~310 km). |

| TABLE 7. Characteristics of pipeline 1. |
| --- |
| Pipeline wall resistivity (relative to annealed copper) | 10 |
| Pipeline wall permeability (relative to free space): | 250 |
| Pipeline coating resistivity | 10⁶ Ω m |
| Coating thickness | 0.005 m |
| Pipeline radius | 0.381 m |
| Wall thickness | 10 mm |
| Buried depth (upper edge) | Varies between 1 m – 3 m |
| Length of pipeline | 82.03 km |
| Location of insulating joints | 0 km & 82.03 km |

| TABLE 8. Energization conditions. |
| --- |
| **HVDC operating condition** | **Current value (A) injected in shore-line electrodes** |
| Emergency operating conditions (Monopolar) | 1050 A |
Step 4: Benchmarking of the results against permissible thresholds in standards

2) SIMULATION RESULTS: PIPE TO SOIL POTENTIAL AND LEAKAGE CURRENT DENSITY IN COATING DEFECTS

The readers need to keep in mind that when a pipeline is assessed for its corrosion activity, the leakage current density in coating defects, coating stress voltage, electric field gradient outside the pipeline as well as the time that the coating defect is subjected to the external DC disturbance are important quantities.

The simulation results in the subsequent section are referred to as coating stress voltage and leakage current density in 1 cm² coating defects. Some background information on the physical meaning of these two variables is provided below:

Coating stress voltage: To interpret coating stress voltage, it is first necessary to understand the concept of pipe-to-soil potentials (PSP). The PSP, in principle, mimic the CP readings taken in the field when the CP rectifiers are ON and therefore include $I\cdot R$ drop. This voltage drop is due to the current flow through the earth, which comes in addition to the polarised potential. The polarised potential is the parameter that is important at the interface between coating defects, which expose the metallic wall of the pipeline and the surrounding medium (i.e. soil) [4]. The pipeline’s polarised potential is used to verify whether adequate protection has been achieved on the pipeline. It is, in most of the times, measured immediately after the rectifiers are turned OFF. That is, to remove the $I\cdot R$ drop error. Thus, to minimise the contribution of $I\cdot R$ drop, pipe-to-soil potentials can be instead calculated as coating stress voltages. However, since the CP system operation has been omitted in this study, the pipe-to-soil potentials, can be considered equal to the coating stress voltage of the pipeline. Thus, the calculated coating stress voltage would merely reflect on the disturbance that the pipeline system receives, from the stray currents coming from the HVDC system’s electrode usage.

Leakage Current Density in 1cm² coating defects: The current density in coating defects is the dominant element in evaluating the corrosion rate of a pipeline’s metal. The current through the coating defect can be estimated along the entire length of the pipeline by using the coating stress voltage. The coating defect current is determined as the ratio of the coating stress voltage to the product of the defect’s resistance by the defect’s base area, as shown in Fig. 8. The local soil resistivity $\rho$ is also taken into account. In this study, we assume a cylindrical defect. We further assume that this small defect can occur anywhere along the pipeline.

With the above remarks in mind, Fig. 9 shows the simulated coating stress voltage along the length of pipeline 1 under the monopolar operation of the HVDC system. The profiles in Fig. 9 are displayed under two different scenarios, namely: a) north side electrode operating in anodic mode and b) north side electrode operating in cathodic mode.

A positive voltage in Fig. 9 represents the case where a current leaks out of the pipeline (through a coating defect)
into the earth. For the negative voltage case, the current leaks back into the pipeline (also through a coating defect). The magnitude of the current leaking from the coating defect is determined by the coating stress voltage at any point along the pipeline and the resistance of the coating defect—which depends on the local soil resistivity. Hence, in Fig. 10 we illustrate the calculated current leakage density through the 1 cm$^2$ coating defects, by utilising the coating stress values of Fig. 9 and the soil resistivity along the length of the pipeline (first subplot in Fig. 10), as described in Fig. 8. The results are provided for both the anodic and cathodic operating modes, of the north side electrode.

3) POST PROCESSING OF SIMULATION RESULTS: CORROSION RATE – METAL LOSS

The corrosion rate (i.e. metal loss) along the length of the enquired pipeline under the monopolar (emergency) operation, can be estimated through the application of Faraday’s electrolytic law. The application of this law effectively determines the metal loss consumed in an anodic reaction, provided that the anodic current is known. In Table 9, we show the input parameters and the relevant formulas to calculate the thickness of a corroded metal per year.

The total electrical charge ($Q$) involved in the electrochemical process, is calculated using (15). It is derived from the time integral of the anodic current $I$ through the coating defect over the expected time duration $t$, of this flow.

$$ Q = \int_0^t I \cdot dt$$

With reference to equation (15), the anodic current through the coating defects (1 cm$^2$) of the enquired pipeline has been calculated as shown in the second subplot of Fig. 10. The time duration of this current flow is related to the expected duration of full current electrode usage, as per the method described in sections III and IV of this paper.

Thus, in Table 10 we show the input parameters that are used to calculate the expected annual corrosion rate along the length of the pipeline. As a base scenario we assume that annual duration of full electrode usage relies on a $MTTR$ value equal to 1440 hours. This entails that the expected annual duration of full electrode usage is 326 hours (HVDC system is equipped with MRTBs) and 605 hours (HVDC system is not equipped with MRTBs).

Therefore, in Fig. 11 we illustrate the calculated corrosion rate in $\mu$m/year (over a 1 cm$^2$ coating defect) through the use of the Faraday’s electrolytic law. This has been calculated separately for each coating defect, the location of which has been moved (~in a 20 m step), along the length of the pipeline in each calculation. Thus, the two subplots in Fig. 11 show the superimposed calculations at all considered coating defect locations under the emergency monopolar operating conditions considered in this particular system. In particular, the first subplot in Fig. 11 shows the corrosion rate calculations, under the information that the amount of days per year that the system will be in emergency monopolar operation is 605 hours (HVDC system without MRTBs).

### TABLE 9. Faraday’s law application formulas.

| Description | Equation |
|-------------|----------|
| Thickness $t_m$ of corroded metal per year | $t_m = (Q \cdot M)/(n \cdot d \cdot F \cdot A)$ |
| $t_m$: thickness of corroded metal per year in (m/y) | $Q$: total charge in (C) |
| $M$: atomic mass in (g/mol) | $n$: number of electrons per molecule of the species being reacted |
| $d$: mass density volume in (g/m$^3$) | $F$: Faraday Unit=96485 C/(mol of electrons) |
| $A$: Surface area of metal reacted (m$^2$) |

### TABLE 10. Input parameters for calculating annual corrosion rate.

| Input Parameter | Remarks |
|-----------------|---------|
| Current value injected/collected in/from electrodes (under emergency monopolar conditions) | 1050 A |
| Expected annual duration of full electrode usage if HVDC system is equipped with MRTBs | 326 hours/years (extracted from Table 9) |
| Expected annual duration of full electrode usage if HVDC system is not equipped with MRTBs | 605 hours/years (extracted from Table 9) |
| Length of submarine HVDC link | 330 km |
| MTTR | 1440 hours |
| Ampere-Hours of potentially corrosive charge per annum if HVDC system is equipped with MRTBs | 1050 A \times 326 \text{ h} = 342300 \text{ Ampere-hours} |
| Ampere-Hours of potentially corrosive charge per annum if HVDC system is not equipped with MRTBs | 1050 \text{ A} \times 605 \text{ h} = 635250 \text{ Ampere-hours} |
In the second subplot of Fig. 11, we show the calculation results under 326 hours of full electrode usage (HVDC system with MRTBs). Clearly, the expected annual corrosion rate on the pipeline is higher in the former case. The readers need to keep in mind that corrosion occurs when the leakage current through the coating is positive, i.e. it leaks out of the pipeline. To this extent, the simulation results have shown that a slightly larger corrosion rate occurs when the HVDC electrode in the north side would operate in anodic mode (i.e. injects current into the sea). This is due to the relative topology of the two systems i.e. defined by the pipeline’s routing and the HVDC electrodes’ locations. Depending on the operation mode, the current collection and discharge areas along the pipeline can therefore be changed. However, this is a project’s specific conclusion and it cannot be generalised.

As sensitivity analysis, we calculate the expected corrosion rate on the enquired pipeline system under additional MTTRs values (see Fig. 4 and 5) that essentially reflect on different values for the expected annual electrode usage under the full rated current (i.e. emergency monopolar operation). Thus, in Table 11 we show the input parameters used in this sensitivity analysis, while in Figures 12 and 13 we display the simulated results.

In particular, Fig. 12 shows the corrosion rate calculation on pipeline 1, when the north side electrode operates anodically, while Fig. 13 shows the same calculation by considering that the north side electrode operates cathodically.
Clearly, the simulated annual corrosion rates for the case discussed in this paper (as per Figures 12 and 13) are quite low, if we benchmark these against the limits provided in Table I of the new ISO 21857:2021 standard [4]. We note to this end, that for cathodically protected pipelines, the acceptable corrosion rate is 10 μm/year. Moreover, in [4] it is reported that: “For pipelines that are not cathodically protected, there is no active corrosion mitigation and the acceptable corrosion rate shall be the rate of corrosion used in the pipeline design”.

Nonetheless, both in Figures 12 and 13, the effect of the expected annual electrode usage (through the considered MTR values) on the pipeline corrosion rate is obvious. However, the annual electrode usage depends on a series of factors that may be out of the planners/designers’ control. Thus, at the planning/approval stage of HVDC systems, it may be appropriate to consider not only the expected MTR value (e.g., 1440 h), but also some more conservative values (e.g., 4320 h). This exercise is, of course, subject to the planners/designers’ engineering judgement and risk tolerance.

VI. DISCUSSION AND CONCLUSION

The method presented in this paper has been firstly tailored to quantify the expected duration of the earth return current (and, hence, electrode usage) in point-to-point (P2P) HVDC systems. The method’s general aim is twofold: a) to capture the expected duration of electrode usage from first principles and based on available data, and, b) to exemplify how such results can be further utilized in relevant studies, e.g., corrosion rate calculations, at the planning and approval stages of HVDC projects. In effect, the method provides an informed evidence to planners/consultants, to appropriately account for the expected time of electrode usage.

Finally, to show the completeness of the approach we have demonstrated how to calculate the dc interference impact using realistic data taken from a real system. More specifically, the analysis have shown that the expected annual electrode usage is a decisive factor when performing dc corrosion studies at the planning/approval stage of HVDC systems.

REFERENCES

[1] HVDC Environmental Planning Guidelines, document CIGRE WG B4.44, 2012.
[2] General Guidelines for HVDC Electrode Design, document CIGRE WG B4.61, 2015.
[3] C. A. Charalambous, “Interference activity on pipeline systems from VSC-based HVDC cable networks with earth/sea return: An insightful review,” IEEE Trans. Power Deliv., 2020.
[4] Petroleum, Petrochemical and Natural Gas Industries Prevention of Corrosion on Pipeline Systems Influenced by Stray Currents, document ISO 21857:2021, 2021.
[5] IEEE Guide for Analysis and Definition of DC Side Harmonic Performance of HVDC Transmission Systems, Standard 1124-2003, IEEE Power Engineering Society, New York, NY, USA, 2003.
[6] S. R. Mohammed, J. Teh, and M. K. M. Jamil, “Reliability and power density increase in a novel four-pole system for line-commutated converter HVDC transmission,” IEEE Access, vol. 7, pp. 10057–10076, 2019, doi: 10.1109/ACCESS.2019.2919780.
[7] Technical Requirements and Specifications of State-of-the-Art HVDC Switching Equipment, document I. W. G. A3/B4.34, 2017.
[8] Z. Hafizlah, Reliability Modelling of a Multi-Terminal High Voltage Direct Current (HVDC) System Based on Half-Bridge Modular Multilevel Converter (MMC) Technology. Delft, The Netherlands: TU Delft, 2017.
[9] Components Testing of VSC System for HVDC Applications, CIGRE, Paris, France, 2011, vol. 447, no. 447.
[10] R. Billinton and R. Allan, Reliability Evaluation of Power Systems, 2nd ed. New York, NY, USA: Plenum Press, 1984.
[11] A. Beddard and M. Barnes, “Availability analysis of VSC-HVDC schemes for offshore windfarms,” in Proc. 6th IET Int. Conf. Power Electron., Mach. Drives (PEMD), Mar. 2012, pp. 1–6.
[12] C. K. Kim, V. K. Sood, G. S. Jang, S. J. Lim, and S. J. Lee, HVDC Transmission: Power Conversion Applications in Power Systems. Singapore: Wiley, 2009.
[13] K. R. Padiyar, HVDC Power Transmission Systems: Technology and System Interactions. New York, NY, USA: Wiley, 1990.
[14] A. Courts, J. Vithayathil, N. Hingorani, J. Porter, J. Gorman, and C. Kimblin, “A new DC breaker used as metallic return transfer breaker,” IEEE Trans. Power App. Syst., vol. PAS-101, no. 10, pp. 4112–4121, Oct. 1982.
[15] C. MacIver, K. R. W. Bell, and D. P. Nedić, “A reliability evaluation of offshore HVDC grid configuration options,” IEEE Trans. Power Del., vol. 31, no. 2, pp. 810–819, Apr. 2016.
[16] Calculating Target Availability Figures for HVDC Interconnectors, OFGEM, London, U.K., 2012.
[17] Designing HVDC Grids for Optimal Reliability and Availability Performance, document CIGRE WG B4.60, 2018, no. 296.
[18] An Introduction to High Voltage Direct Current (HVDC) Underground Cables, Europacable, Brussels, Belgium, 2012.
[19] High Voltage Direct Current Electricity Technical Information, National Grid, London, U.K., 2013.
[20] C. MacIver, A Reliability Evaluation of Offshore HVDC Transmission Network Options. Glasgow, Scotland: Univ. Strathclyde Glasgow, 2015.
[21] C. A. Charalambous, N. D. Dimitriou, I. F. Gonos, and T. A. Papadopoulos, “Modeling and assessment of short-term electromagnetic interference on a railway system from pole-to-ground faults on VSC-HVDC cable networks with sea electrodes,” IEEE Trans. Ind. Appl., vol. 57, no. 1, pp. 121–129, Jan. 2021.
[22] CDEGS Software. Accessed: Nov. 28, 2022. [Online]. Available: https://www.sestech.com/Product/Package/CDEGS

CHARALAMBOS A. CHARALAMBOUS (Member, IEEE) received the B.Eng. and Ph.D. degrees (Hons.) in electrical power engineering from The University of Manchester Institute of Science and Technology (UMIST), in 2002 and 2006, respectively. He is currently a Tenured Associate Professor and the Director of the Power System Modeling (PSM) Laboratory, Department of Electrical and Computer Engineering, University of Cyprus (UCY). He is a fellow of IET and a registered Chartered Engineer (C.Eng.) in U.K. He acted as an Expert Member in the standardization committee ISO/TC 67/SC 2/WG 24 prevention of corrosion on pipeline systems with sea electrodes.

ALEXANDROS I. NIKOLAIDIS was born in Ptolemaida, Greece, in 1986. He received the M.Eng. degree in electrical and computer engineering from the Democritus University of Thrace, Greece, in 2010, and the M.Sc. degree in energy technologies and sustainable design and the Ph.D. degree in electrical engineering from the University of Cyprus, in 2012 and 2017, respectively. Since 2012, he has been working as a Research Associate with the Power System Modeling (PSM) Laboratory, University of Cyprus. He is currently a System Studies Engineer at the Transmission System Operator-Cyprus. His main research interests include interconnected power system analysis and system requirements identification.