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RESEARCH ARTICLE

Synchrophasor-Based DTR and SIPS Cyber-Physical Network Reliability Effects Considering Communication Network Topology and Total Network Ageing

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ABSTRACT The lifespan of overhead transmission conductors is influenced by various factors, including design, maintenance, and operating conditions. Prolonged exposure to high temperatures, particularly near maximum design values, can significantly age transmission lines (TLs). The dynamic thermal rating (DTR) system, an advanced technology that increases TL capacities, can contribute to these stringent conditions. DTR overlays a cyber layer with communication and control systems onto the physical network, transforming it into a cyber-physical network. Currently, the increased risk of TL ageing associated with DTR, and the cyber layer's functionality lack a unified framework for quantification. This study introduces a novel framework that considers the cyber layer's network topology and its impact on TL ageing due to DTR implementation. It also proposes the implementation of system integrity protection schemes (SIPS) within the framework. SIPS detects abnormal conditions from DTR deployment, like excessive line loading, and takes corrective actions to optimize DTR system's performance. The study employs a Sequential Monte Carlo Simulation (SMCS) technique on a modified cyber-physical IEEE RTS-79. The study reveals that topologies like double ring and mesh, cause higher line ageing indices compared to line and star topologies. ETNA values remain relatively stable across the network topologies within a year, suggesting minimal short-term impact on transmission line ageing. However, cumulative effects over several years can potentially reduce lifespan. SIPS can slow network ageing by up to 5hr/yr, but their contingencies can cause the opposite effect. Nonetheless, a reliable SIPS can maintain an ETNA value of 101hr/yr without increasing load curtailment.

INDEX TERMS Cyber-physical systems, dynamic thermal rating systems, generator rejection scheme, power system reliability, phasor measurement units, system integrity protection schemes, transmission line ageing.

NOMENCLATURE

A. SETS

AB Set of all adjacent buses.
AL Set of all adjoining lines.

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B Set of all buses.
GB Set of all generation buses.
L Set of all transmission lines.
LB Set of all Load buses.
OL Set of all observable lines.
UL Set of all Unobservable lines.

B. PARAMETERS

A_{bl}	Network incidence matrix element.
A_s	Availability of a component or system.
AB_{PMU}	Adjacent buses to PMU buses.
AL_{PMU}	Adjacent lines to PMU buses.
B_{PMU}	PMU bus.
$BrObs(L)$	Branch observability.
$BusObs(B)$	Bus observability.
$MTTF_s/MTTR_s$	Mean time to failure/ repair.
PF_l	Power flow capacity of line l.
PF_l^{max}	Maximum power flow capacity of line l.
PF_l^{STR}/PF_l^{DTR}	STR / DTR of line power flow capacity.
S^c	State of component c.
X_l	Reactance of line l.
ϵ_c	Creep of conductor c.
RS	Remaining strength of conductor/.
RS_{al}	Remaining strength of aluminium strands.
STR_{al}/STR_{st}	Initial strength aluminium/steel strands.
STR_T	Initial strength total.
η_{al}/η_{st}	Number of aluminium/steel strands.
$\bar{S}_{al}/\bar{S}_{st}^{1\%}$	Average breaking stress of aluminium/steel strand at 1% extension (MPa).
d_{al}/d_{st}	Diameter aluminium/steel strands (mm).
k_{al}/k_{st}	Reduction factors aluminium/steel strand.
T_c	Conductor temperature.
T_{age}	Ageing temperature.
ϑ_b	Voltage phase angle of bus b.

I. INTRODUCTION AND BACKGROUND

Cyber-physical power systems combine cyber and physical layers, incorporating communication and control systems with power generation, transmission, and distribution systems [1], [2]. This integration enables more efficient operation and adoption of advanced technologies [3]. Intelligent electronic devices (IEDs), such as smart meters, smart sensors, and phasor measurement units (PMUs), are utilized to implement these advanced technologies on the network. These devices are responsible for calculating and transmitting synchrophasor estimates, including single-phase and positive sequence measurements, to phasor data concentrators (PDCs) [3], [4], [5], [6]. However, adding the cyber layer also introduces challenges in terms of reliability and security [7], [8]. Dynamic thermal rating (DTR) systems are an example of advanced technology for implementation on cyber-physical systems that use real-time data to calculate conductor temperature, increasing TL capacity and improving system reliability [9], [10], [11]. Successful implementation of DTR depends on reliable communication networks, especially wireless communication systems, in transmitting line rating information back to the utility company so that an appropriate line flow control can be executed [12]. DTR systems have the potential to enhance power system reliability and mitigate TL risks [13], [14]. System Integrity Protection Schemes (SIPS)

is another technology for cyber-physical networks that utilize protective measures which detect abnormal conditions and take corrective actions to enhance system reliability and prevent cascading failures [15], [16]. Common SIPS include load shedding and remedial action schemes. Their implementation ensures prompt detection and response to abnormalities, preventing widespread blackouts and maintaining power system integrity [8], [12]. Following the successful implementation of DTR, the transmission lines (TLs) will operate at higher temperatures. Thus, conductor thermal ageing refers to the gradual deterioration of transmission conductors due to prolonged exposure to high temperatures, which could occur due to DTR implementation [17], [18]. Monitoring temperature and load capacity in real-time is crucial to assess operational risks and mitigate the effects of thermal ageing. One such mitigation approach is through the implementation of SIPS. SIPS has the potential to detect abnormalities that could arise from DTR implementation, such as TLs becoming overloaded and approaching thermal limits, and takes corrective actions like tripping of generating units to shed some load to reduce line loading, which then reduces the line temperatures, thus restoring the operation to normal.

Ensuring power network resilience in the face of disruptions caused by overloaded lines is a critical concern for modern power systems. Therefore, assessing the influence of these technologies on TL ageing is vital for network operators to proactively address potential challenges and maintain network reliability.

A. REVIEW OF RELATED WORK AND IDENTIFICATION OF GAPS

Several research efforts have investigated the application of various technologies to improve network reliability. The assessment of reliability in cyber-physical power networks, explicitly given the function of the cyber layer communication networks and their effects on total reliability, currently needs more comprehensive studies. This is key, especially considering the necessity of an adequate communication infrastructure for deploying DTR and any other type of advanced technology. Additionally, introducing DTR implies that the TLs will function at greater temperatures, requiring careful monitoring to slow ageing.

To the best of the authors' knowledge, Table 1 compares studies related to the present study. This table is populated to show the research gaps in existing related studies. Essential aspects such as the type of technology, utilization of PMUs, cable type, cyber layer topology and network ageing assessment are considered. In [19] and [20], DTR assessment is carried out without synchrophasors. These studies do not consider the cyber layer topologies in the DTR assessment, but the ageing of the lines is quantified. The former assesses underground conductors, whereas the latter assesses all allow aluminum conductors (AAAC). In [12], [18], and [21], DTR assessment is carried out together with SIPS while considering the Aluminum Conductors Steel Reinforced (ACSR)

TABLE 1. Related work and research gaps.

Source	Tech	PMU	Cable type	Cyber layer topology	Network ageing assessment
This study		✓	✓	✓	✓
[19]	DTR	-	Underground	-	✓
[20]	DTR	-	AAAC	-	✓
[12]	DTR+SIPS	✓	ACSR	✓	-
[18]	DTR+SIPS	✓	ACSR	-	✓
[22]	DTR+BESS	-	ACSR	-	✓
[9]	DTR+DR+BESS	-	ACSR	-	-
[21]	DTR+SIPS	✓	-	-	-
[23]	DTR	-	ACSR	-	✓
[24]	DTR+DR	-	ACSR	-	✓
[25]	-	-	-	-	✓

conductors. The cyber layer topology is considered in [12] and ignored in [18], while the network ageing assessment is considered in [18] and ignored in [12]. In [21], both the cyber layer topology and network ageing assessment are ignored in the reliability study. In studies [22] and [23], DTR assessment is carried out while considering ACSR conductor types and network ageing assessment. However, the cyber layer assessment is ignored. Studies [9] and [24] are also quite similar; however, [9] includes a battery energy storage system (BESS) technology in its assessment and ignores both the cyber layer and network ageing assessment.

On the other hand, [24] considers the network's ageing but ignores the cyber layer in its evaluation. Lastly, in [25], line ageing is studied in detail while considering the topology of the physical grid. However, cyber layer topology is not considered in this study. Based on the above studies, although several papers discuss network ageing, studies considering the cyber layer as a factor still need to be included. In [20], the paper considers the cyber additions but not the reliability of the communication network topology. Studies that utilize synchrophasor technology for DTR assessment are also relatively few. Notwithstanding the abovementioned studies, this study considers all factors in Table 1.

B. KEY CONTRIBUTIONS

Although numerous studies have investigated the effects of varying line ratings on the ageing of overhead TLs as depicted in Table 1, however, to the best of our knowledge, no study quantifies the impacts of various communication network topologies on the ageing of synchrophasor-based cyber-physical power networks. Notwithstanding the studies highlighted above, this article has the following contributions:

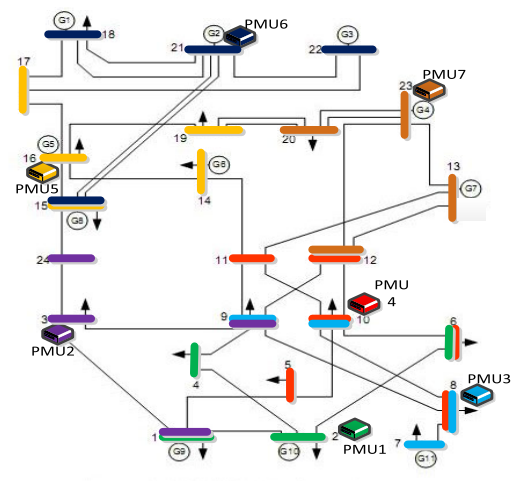
1. Synchrophasor-based advanced functions for implementing DTR and SIPS are established through developing a cyber layer, particularly considering different communication network topologies.
2. Investigation of the effects of cyber layer communication network contingencies on the ageing

of a synchrophasor-based cyber-physical network enhanced with DTR and SIPS functionality.

3. Finally, the positive and negative effects of SIPS implementation together with DTR on the ageing of the cyber-physical network are quantified.

C. ORGANIZATION OF THE PAPER

The rest of the paper is organized as follows. Section II describes the cyber-physical network reliability evaluation framework in detail. Section III presents the implementation of the proposed framework highlighting the details of the modelled cases. Section IV discusses the numerical analysis and results from the study in detail, and Section V concludes the study.

**FIGURE 1.** PMU placement on IEEE RTS-79 cyber-physical test network.

II. CYBER-PHYSICAL NETWORK RELIABILITY EVALUATION FRAMEWORK

As previously mentioned, the network consists of 2 layers: the physical layer and the cyber layer. The physical layer consists of all the physical components directly involved in delivering electrical power within the wider network. Therefore, the physical layer comprises the TLs and the generating units. On the other hand, the cyber layer includes all communication network components placed on the network to enhance the network with monitoring, protection, and control features such as the DTR and SIPS function. The IEEE reliability test network (IEEE RTS-79) is employed to evaluate reliability in this study. The modelling of both layers is discussed in detail in the following sub-sections.

A. PHYSICAL LAYER

In the physical layer, the TL conductors are modelled, and, in this study, Aluminum Conductors Steel Reinforced (ACSR) conductors are employed to model the TLs. ACSR conductors have lightweight, high strength, corrosion resistance, and excellent conductivity. They are widely used as TLs for transmission and distribution purposes and are well

TABLE 2. Transmission line properties.

Conductor code name	Stranding number	Stranding diameter al/st (mm)	Conductor Diameter (mm)	Cross-sectional area al/st (mm ²)	Resistance at 25°C (Ω/m)	Resistance at 75°C (Ω/m)	Static rating (MVA)	Voltage level (V)
Drake	26/7	4.78/3.18	28.1	807.5/55.6	7.283e-5	8.688e-5	175	138
Lapwing	45/7	4.44/3.45	38.2	402.6/65.4	3.6673e-5	4.4406e-5	500	230

known for their economic and reliability benefits [26], [27]. The IEEE RTS-79 is divided into two sections. There are 38 TLs in this network. In the upper section, which is the 230 kV segment, the 1590 kcmil ACSR “Lapwing” conductor properties are used to model the TLs, while in the lower section, which is the 138 kV section, the 795 kcmil ACSR “Drake” conductor properties are utilized. Some of the properties of these two conductors are shown in Table 2. These values are obtained from [26], [27], [28], and [29]. Furthermore, the TL characteristics can be found in the data for the IEEE RTS-79 [30].

B. CYBER LAYER

1) PMU PLACEMENT AND NETWORK OBSERVABILITY MODEL

The number of PMUs required for this network has been estimated in earlier research [31], [32]. It has been determined that installing seven PMUs at buses 2, 3, 8, 10, 16, 21, and 23 will enable complete network observability with some redundant measurements available. When a PMU is installed at a particular bus, it permits the observation of that bus, the neighbouring buses, and the adjoining TLs following the observability rules [4]. The PMU placement is shown in Fig. 1. Each PMU is colour coded and observes the buses corresponding to each PMU colour, as seen in Fig. 1. Two PMUs can examine a few buses in the current design; hence, they have redundant measurements. If one of the PMUs malfunctions, the redundancy ensures that backup measurements are available. Thus, the rules for observability are defined as equations (1) and (2) below. Equation (1) states that a bus can be observed if the corresponding PMU on that bus is operational. This rule applies to all PMU buses. Adjacent buses can be observed if the PMU connected to that bus is operational, and the TL between the two buses is also operational. The bus is only observable if either of these conditions is met. Equation (2) states that a branch (TL) can be observed if the buses at both ends of the line are observable. If either of the buses is not observable, the branch is not observable.

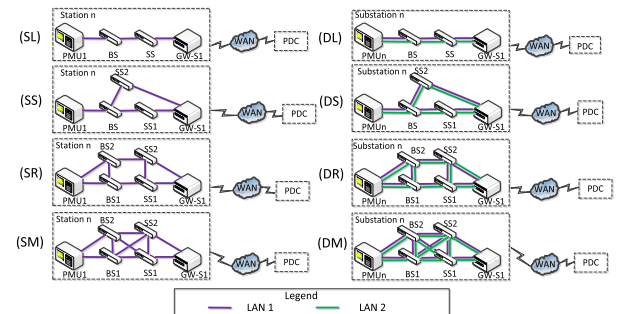
$$BusObs(B) = \begin{cases} 1, & \text{if } A_{PMU}^B = 1 \\ & \text{if } A_{PMU}^{AB} * A_L^{AL} = 1 \\ 0, & \text{otherwise} \end{cases} \quad \begin{matrix} B \in B_{PMU} \\ AB \in AB_{PMU} \\ \forall B \end{matrix} \quad (1)$$

$$BusObs(L) = \begin{cases} 1, & \text{if } BusObs(B) * BusObs(AB) = 1 \\ 0, & \text{otherwise} \end{cases} \quad \forall L \quad (2)$$

2) CYBER LAYER COMMUNICATION MODEL

The PMUs and the communication network form the cyber layer of the cyber-physical power network. These communication components include the WAN, LAN (through its gateway), station switch (SS), bay switch (BS) and ethernet media that connects all components. These physical components, called nodes, are connected in a specific architecture and determine how the synchrophasors are passed from the PMUs to the PDC within the cyber-physical network. The PMU communicates with the BS; next, the synchrophasors are passed to the SS, then to the LAN gateway across to the WAN, which directs the synchrophasors to the PDC for processing. This architecture is referred to as network topology, and there are several types, including line, star, ring, and mesh topologies [33], [34], [35], [36]. In this study, these four topologies are employed in the reliability evaluation. In line topology, one node connects to the next in series to form a line. A designated central source node connects to several destination nodes in star topology. In this case, a single BS is the source node, and it connects to two SS as the destination nodes. In the case of ring topology, the nodes are connected in the form of a loop, whereas in the mesh type, all nodes can connect simultaneously.

Here, there are two BS and SS, each creating redundancy in the topology. These topologies are referred to as single line (SL), star (SS), ring (SR) and mesh (SM) because of the utilization of a single LAN connection. In addition, the topologies are also explored with the additional redundancy of a second LAN. These topologies are then referred to as double line (DL), double star (DS), double ring (DR) and double mesh (DM) topologies. These 8 topologies are illustrated in Fig. 2.

**FIGURE 2.** Cyber layer topologies.

In reliability studies, the availabilities of components are computed using the component's mean time to failure (MTTF) and mean time to repair (MTTR). This is formulated

TABLE 3. Reliability data of cyber layer components.

ICT Component	MTTF (Years)	MTTR (Hours)
PMU	220	23
BS	300	22
SS	250	22
Ethernet	800	22
LAN	63.8	22
WAN	50	22

as (3)(9). The MTTF and MTTR of all cyber layer components are populated in Table 3 [4], [37], [38], [39], [40].

$$A_s = \frac{MTTF_s}{MTTF_s + MTTR_s} \quad (3)$$

Thus, the availabilities of the described topologies are computed based on each component's dependence on other components together with their reliability data and formulated as (4) – (11).

$$A_{SL} = A_{BS} \times A_{SS} \times A_{LAN} \times A_{WAN} \quad (4)$$

$$A_{SS} = A_{BS} \times (1 - (1 - A_{SS})^2) \times A_{LAN} \times A_{WAN} \quad (5)$$

$$A_{SR} = (1 - (1 - (A_{SS} \times A_{BS}))^2) \times A_{LAN} \times A_{WAN} \quad (6)$$

$$A_{SM} = (1 - (1 - A_{BS})^2) \times (1 - (1 - A_{SS})^2) \times A_{LAN} \times A_{WAN} \quad (7)$$

$$A_{DL} = A_{BS} \times A_{SS} \times (1 - (1 - A_{LAN})^2) \times A_{WAN} \quad (8)$$

$$A_{DS} = A_{BS} \times (1 - (1 - A_{SS})^2) \times (1 - (1 - A_{LAN})^2) \times A_{WAN} \quad (9)$$

$$A_{DR} = (1 - (1 - (A_{SS} \times A_{BS}))^2) \times (1 - (1 - A_{LAN})^2) \times A_{WAN} \quad (10)$$

$$A_{DM} = (1 - (1 - A_{BS})^2) \times (1 - (1 - A_{SS})^2) \times (1 - (1 - A_{LAN})^2) \times A_{WAN} \quad (11)$$

3) SYNCHROPHASOR-BASED DTR MODEL

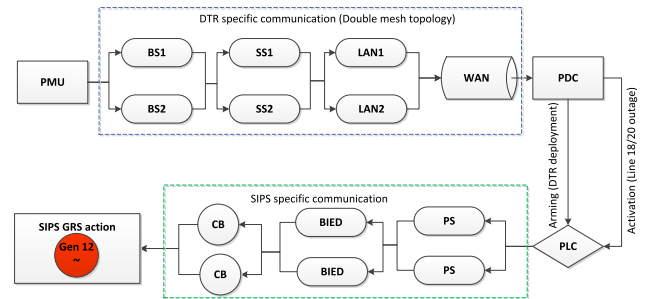
In synchrophasor-based DTR implementation, data is collected from the lines and sent to the PMUs to calculate the 3-phase synchrophasors. Subsequently, the PMUs send the synchrophasors to the PDC, which is the control centre, through the cyber layer communication network described in subsection II) above. When the synchrophasors arrive at the PDC, the data is used to estimate the network state for the implementation of DTR. Thus, when the PMUs and the communication network are operational, the values of the computed synchrophasors are regarded as being available, and the network is considered observable. Hence the DTR values can be calculated based on the state estimation of the network and implemented on the TLs. Otherwise, when the PMUs and communication network become unavailable, the synchrophasors are lost, making it impossible to observe the buses and adjacent TLs and leading to a lack of DTR implementation. DTR availability is thus formulated

as (12) below.

$$A_{DTR} = \left(\prod_{b=1}^7 A_{PMU}^b \right) \cdot \left(\prod_{b=1}^7 A_{comm}^b \right) \cdot A_{PDC} \quad b \in B_{PMU} \quad (12)$$

$$A_{comm}^b = \{A_{SL}, A_{SS}, A_{SR}, A_{SM}, A_{DL}, A_{DS}, A_{DR}, A_{DM}\} \quad (13)$$

where A_{DTR} represents the DTR system availability, A_{PMU} is the PMU's availability, computed from its reliability data in Table 3, A_{comm} is the communication network's availability which is equal to the availability of any selected topology as in (13) and based on (4) – (11) and A_{PDC} is the PDC availability, which is assumed fully reliable in this assessment.

**FIGURE 3.** SIPS GRS implementation.

Based on the IEEE 738 standard for indirect DTR calculation, meteorological data from the Centre for Environmental Data Analysis (CEDA) archive, and the physical layer characteristics discussed in section II-A, the DTR values of the lines are computed. The relationship is described in the following way:

$$I^2 R(\theta) = q_s - q_c(\theta, T_a, V_w, \varphi) + q_r(\theta, T_a) \quad (14)$$

where joule heat gain = $I^2 R(\theta)$, solar radiation heat gain = q_s , convection heat loss = q_c , and radiative heat loss = q_r . The variable I is the ampacity, while $R(\theta)$ is the resistance of the conductor.

4) SYNCHROPHASOR-BASED SIPS MODEL

A generator rejection scheme (GRS) is a commonly used type of SIPS which is implemented by rejecting surplus generation [16], [37]. This can relieve line overload and prevent the TLs from operating above Maximum Designed Temperatures (MDT) for extended hours. This study gives particular attention to the SIPS communication infrastructure to determine its effects on the ageing of TLs. SIPS GRS is implemented on bus 13 of the IEEE-RTS and monitors adjoining lines L18 and L20. PMUs transmit synchrophasors to the PDCs through the cyber layer communication network. The arrival of synchrophasors at the PDC indicates the successful implementation of DTR, indicating that the monitored lines are observable. This information triggers the arming logic of the SIPS. Synchrophasors also serve as indicators for network operators, providing information on the status of the monitored lines and acting as an activation signal when

one of the lines is tripped. Subsequently, the PLC sends an implementation signal to a circuit breaker (CB) to disconnect the generator, carrying out the GRS. This process is shown in Fig. 3. This describes a centralized SIPS system with centralized arming and activation logic. It is important to note that the SIPS is unnecessary if the line thermal ratings are not increased, meaning synchrophasors are not received. In such cases, the lines operate under STR and cannot become overloaded. Despite the potential benefits, SIPS can fail in two ways: dependability-based mis-operation, in which the scheme fails to operate when a triggering condition exists, and security-based mis-operation, in which the scheme would have been deployed in the absence of a triggering condition [16], [37].

Consequently, in addition to the cyber layer communication model discussed in 2) above, additional components are employed for SIPS implementation. This includes programmable logic control (PLC), process switch (PS), breaker Intelligent Electronic Device (BIED) and circuit breaker (CB). This is indicated in Fig. 3. In this study, these components are considered to have redundancies i.e., each component as a redundant spare to boost the SIPS reliability further. The following formulations are employed to compute the availability of the SIPS system:

$$A_{SIPS\ COMM} = A_{PLC} \times (1 - (1 - A_{PS})^2) \times (- (1 - A_{BIED})^2) \times (- (1 - A_{CB})^2) \quad (15)$$

$$A_{SIPS} = A_{Arming} \times A_{Activation} \times A_{Implementation} \quad (16)$$

$$A_{Arming} \times A_{Activation} = A_{DTR} \quad (17)$$

$$A_{Implementation} = A_{SIPS\ COMM} \quad (18)$$

$$A_{SIPS} = A_{DTR} \times A_{SIPS\ COMM} \quad (19)$$

C. TRANSMISSION LINE AGEING MODEL

The utilization capabilities of a network can be significantly enhanced by deploying DTR, which allows the TLs to operate at higher temperatures than their MDT. Therefore, elevated temperature creep in overhead TL refers to the phenomenon where the conductors of the TLs deform gradually when they operate at temperatures beyond their intended design limits and are stressed beyond their specified yield strength for an extended period [27]. When a TL is subjected to elevated temperatures, the conductors may experience a change in their physical properties, leading to a slow, time-dependent elongation or deformation known as creep. Thus, creep can affect the structural integrity and performance of the TL over time [41], [42]. The specific temperature at which the lines start to age, known as the ageing temperature T_{age} , varies depending on the type of conductors used. The calculation of elevated temperature creep is performed according to IEEE 1283 standard. In this study, only the ACSR conductor is taken into consideration. For the ACSR conductor, T_{age} is determined to be 95°, meaning that the conductor will start to creep once the operating temperature exceeds 95° [22], [24].

The creep rate can be determined using the equation provided in [43] and [44] and formulated as follows:

$$\varepsilon_c = 0.24 (\%RS)^{1.3} T_C^{1.4} t^{0.16} \quad (20)$$

where T_C is the operating temperature of the line, t is the number of hours the conductor has been working at T_C , and $\%RS$ represents the percentage of the ACSR conductor's remaining strength. The remaining strength (RS) is calculated as follows [45]:

$$RS = RS_{al} (STR_{al} / STR_T) + 109 (STR_{st} / STR_T) \quad (21)$$

$$RS_{al} = \begin{cases} \delta t^\rho & \text{if } \delta < 100 \\ 100 t^\rho & \text{otherwise} \end{cases} \quad (21a)$$

$$\delta = 134 - 0.24 T_C \quad (21b)$$

$$\rho = (0.241 - 0.00254 T_C) / d_{al} \quad (21c)$$

$$STR_{al} = \pi \eta_{al} \bar{S}_{al} d_{al} k_{al} / 4 \quad (21d)$$

$$STR_{st} = \pi \eta_{st} S_{st}^{1\%} d_{st} k_{st} / 4 \quad (21e)$$

$$STR_T = STR_{al} + STR_{st} \quad (21f)$$

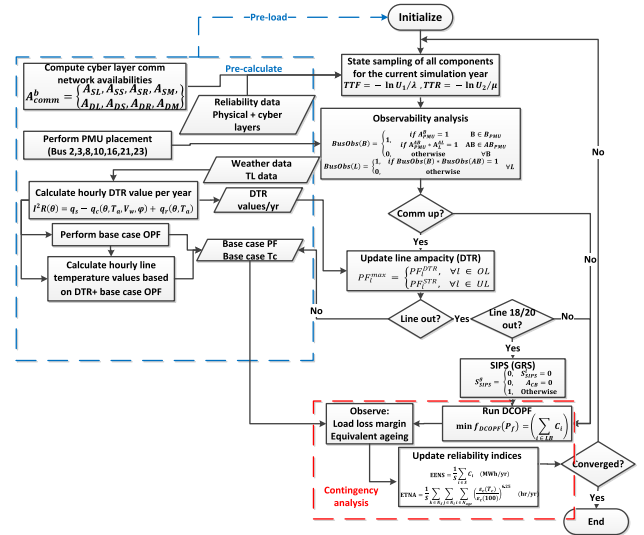


FIGURE 4. SMCS algorithm.

The variable RS represents the remaining percentage of the conductor's strength. The variable RS_{al} denotes the percentage of remaining strength specifically for the aluminum strands. The variable $STR_{al, st, T}$ represents the initial strength of the aluminum strands or steel core in MPa, and it represents the total initial strength of the conductor. The variable $\eta_{al/st}$ refers to the number of aluminium or steel strands present and $d_{al, st}$ represent the diameter of the aluminium or steel strands in mm. The values used for $\eta_{al/st}$ and $d_{al, st}$ in this study can be found in Table 2. $k_{al, st}$ represents the reduction factors for the aluminium or steel strands. Finally, the variables $\bar{S}_{al}$ and $S_{st}^{1\%}$ represents the average breaking stress of the aluminum or steel strand at 1% extension, of which the values 165 MPa and 1100 MPa are used respectively.

D. SEQUENTIAL MONTE CARLO SIMULATION COMPUTATION

In this section the SMCS used is described in detail. Although other methods such as the Non Sequential Monte Carlo Simulation and analytical methods can be used to carry out reliability studies, however, SMCS is employed in this study because it enables the simulation of actual system performance and random behaviour in chronological order and permits a high level of modelling complexity, which is fit for the complexity level of the cyber-physical network examined in this study.

Step 1: First, base case calculations are performed to assess the cyber-physical system under the assumption that both layers' components remain operational throughout the year. In this step, the cyber layer topology availability values, DTR values for the year, base case optimal power flow (OPF) values and base case line temperatures are all calculated.

Step 2: The simulation selects a cyber layer topology in this step. The states of all components of both layers are sampled hourly and each component's TTF and TTR are calculated.

Step 3: The system state is estimated by observing the buses and TLs and conducting an observability analysis based on PMU and communication network availabilities.

- a. If the cyber layer is functional, i.e., the network is observable, the following scenarios can occur:
 - i. All lines are up: DTR is assumed to be successfully implemented in this scenario. Thus, the simulation chooses the corresponding pre-calculated base case values of power flows and line temperatures and proceeds to step 5.
 - ii. A line outage is present: new DTR values are calculated, and the lines are uprated, then the simulation proceeds to step 4.
 - iii. SIPS monitored lines L18/L20 are on the outage: in this case, GRS is deployed subject to the availability of the SIPS system and proceeds to step 4.
- b. Otherwise, the network is unobservable; the lines are operated on STR values and the simulation proceeds to step 4.

Step 4: Contingency analysis is carried out by executing DCOPF to determine the line power flows and to calculate the line temperatures.

Step 5: Reliability indices are calculated and updated at every iteration until convergence. The proposed algorithm is shown in Fig. 4.

1) OPTIMAL POWER FLOW FORMULATION

In this study, the OPF problem is solved using MATPOWER open-source power simulation package and used within the MatLab environment. Both AC and DC-OPF are possible in the MATPOWER package. ACOPT for the network in consideration converges in about 0.2s whereas DCOPF converges in about 0.05s which makes it about 4 times faster. Thus, DC-OPF is used due to its linearity and quicker solving time.

The OPF problem in step 4 is formulated as equation (22) below and is subject to (22a) - (22h).

$$\min_{DCOPF} (P_f) = \left(\sum_{i \in LB} C_i \right) \quad (22)$$

subject to

$$\sum_{g \in G} S^g (PG_g) + \sum_{i \in LB} C_i = \sum_{i \in LB} PD_i \quad (22a)$$

$$PG_g^{min} \leq PG_g \leq PG_g^{max}, \quad \forall g \in G \quad (22b)$$

$$0 \leq C_d \leq PD_d, \quad \forall d \in LB \quad (22c)$$

$$PF_l = \frac{S^l}{X_l} \sum_{b \in B} A_{bl} \vartheta_b, \quad \forall l \in L; \forall b \in B \quad (22d)$$

$$A_{bl} = \begin{cases} 1, & b = fb \\ -1, & b = tb \\ 0, & \text{otherwise} \end{cases} \quad (22e)$$

$$|PF_l| \leq PF_l^{max}, \quad \forall l \in L \quad (22f)$$

$$PF_l^{max} = \begin{cases} PF_l^{DTR}, & \forall l \in OL \\ PF_l^{STR}, & \forall l \in UL \end{cases} \quad (22g)$$

$$S_{SIPS}^g = \begin{cases} \left[S_{SIPS}^l \mid l = 18, 20 \right] = 0, \\ 0, & \text{s.t.} \\ BusObs(b = 13) = 1 \& A_{SIPS} = 1 \\ 0, & A_{CB} = 0 \\ 1, & \text{Otherwise} \end{cases} \quad (22h)$$

In (22a), the power balance equation for each bus is denoted where S^g denotes the state of the generator. This value is 1 if the generator is online or 0 otherwise. The constraints for generation aspect PG_g are considered in (22b), where the value is between the minimum and maximum specified value. The load curtailments aspect C_d are considered in (22c), where the value is between 0 when there is no load curtailment or PD_d when the total load demand on the bus is curtailed. In (22d), line power flows are calculated, and S^l indicates the state of each line. If the line is unavailable (state 0), the power flow calculation is skipped; otherwise, it is performed. X_l represents the reactance of the line and ϑ_b denotes the voltage phase angle of the bus. The network incidence matrix element used to determine power flow is represented in (22e), where the value is 1 when bus b is sending bus of line l , -1 when it is receiving and 0 otherwise. The power flow constraint for each line is described in (22f), and (22g) restricts the line flow limits to the DTR value when the lines are observable or the STR value otherwise. Finally, S_{SIPS}^g in (22h) represents the state of the designated SIPS generator that will be deactivated during GRS implementation or when the CB spuriously trips. S_{SIPS}^l represents the state of the monitored SIPS lines (L18 and L20), where the value is 1 if the line is up or 0 otherwise. Consequently, the value of S_{SIPS}^g is 0 if S_{SIPS}^l is 0, indicating a line outage. This is

also subject to the availability of the SIPS communication network ($A_{SIPSCOMM}$) and the observability of SIPS bus 13 ($BusObs(b)$). Furthermore, S_{SIPS}^g is also 0 if there is a spurious CB trip ($A_{CB} = 0$), and its value is 1 otherwise.

2) CYBER-PHYSICAL NETWORK PERFORMANCE INDICES

The reliability indices in step 5 above are calculated to determine the impacts of the cyber layer enhancements on the modified cyber-physical network's reliability. Expected Number of Load Curtailments (ENLC), Expected Duration of Load Curtailments (EDLC), and Expected Energy Not Supplied (EENS) indices which are calculated as (23)- (25), respectively, are quantified to check the performance of the network in terms of load curtailment [46]. Another load curtailment index ($EENS_{COMM}$) is also quantified to assess the contribution of cyber layer outage only to the total load curtailment value and is calculated as (26). Furthermore, the Expected Duration of Communication Network Outage (EDCO) calculates the average number of hours the communication network cannot provide synchrophasor data to the PDC in a simulation year. This is calculated as (27). Lastly, Expected Total Network Ageing (ETNA) indicates the network ageing risk posed by the TLs' operation at higher temperatures close to their MDTs. The ETNA represents the total number of individual ageing occurrences across all TLs in a simulation year.

$$ENLC = \sum_{i \in S} \left(P_i \sum_{k \in N} \lambda_k \right) (\text{occ./yr}) \quad (23)$$

$$EDLC = \sum_{i \in S} p_i \times 8760 (\text{hr/yr}) \quad (24)$$

$$EENS = \frac{1}{S} \sum_{i \in S} C_i (\text{MWh/yr}) \quad (25)$$

$$EENS_{COMM} = \frac{1}{S_c} \sum_{c \in S_c} C_c (\text{MWh/yr}) \quad (26)$$

$$EDCO = \sum_{c \in S_c} P_c \times 8760 (\text{hr/yr}) \quad (27)$$

$$ETNA = \frac{1}{S} \sum_{k \in N_S} \sum_{j \in N_l} \sum_{i \in N_{age}} \left(\frac{\varepsilon_c(T_c)}{\varepsilon_c(100)} \right)^{6.25} (\text{hr/yr}) \quad (28)$$

where P_i represents the probability of system state i , λ_k is the departure rate of a system component regarding system state i , and N is the set of all potential departure rates in that system state, p_i represents the system state probability of load curtailment, and S is a collection of all power system states. C_i denotes the load curtailment of system state i , while C_c is the load curtailment caused by cyber layer outage only. S_c is a collection of all cyber layer system states, and P_c is the system state probability of a cyber layer outage. The terms $\varepsilon_c(T_c)$ and $\varepsilon_c(100)$ stand for the creep at T_c and 100°C , respectively. Because creep can happen at different temperatures, this ratio can be used to compare values across all creeping temperatures. The sets of all ageing events, TLs, and sampling years are denoted by N_{age} , N_l , and N_S , respectively.

TABLE 4. Case numbers, nodes and communication paths for each topology.

Case no.	Topology	Number of nodes	Number of communication paths
1	SL	4	1
2	SS	5	2
3	SR	6	4
4	SM	6	6
5	DL	4	2
6	DS	5	4
7	DR	6	8
8-10	DM	6	12

III. IMPLEMENTATION OF THE PROPOSED FRAMEWORK

A. CYBER-PHYSICAL RELIABILITY TEST NETWORK PROPERTIES

This study employs a composite reliability assessment on a modified version of the IEEE RTS-79 to evaluate how synchrophasor-based DTR and SIPS systems affect the reliability of cyber-physical systems. The original network is altered to increase the generation and load demand capacities to approximately 90% of their original values. This modification intentionally stresses the network by operating the lines close to their maximum capacity, showcasing the advantages of DTR implementation. The load demand on bus 13 is disconnected, and the generation capacities are boosted to make the bus contribute around 28% of the total generation capacity of the network. This setup is designed to strain the adjacent lines on that bus and emphasize the influence of the GRS SIPS protection scheme on network reliability. The generating units are assumed to be completely reliable to avoid overshadowing the effects of the cyber layer, which can influence the failures of generating units. Consequently, this study focuses solely on failures in the physical layer i.e., TLs and the cyber layer components.

In addition, the cyber layer components are called nodes, i.e., the PMU, bay switch, station switch and LAN gateway. The synchrophasors are passed from the PMUs to the gateway and from the WAN to the PDC. This channel of information flow is represented as the communication path. Each topology has a different number of nodes and communication paths. The line topology has 4 nodes, the star has 5, while the ring and mesh have 6 nodes each. This information is itemized in Table 4.

The physical layer is characterized by modeling ACSR conductor properties as detailed in Section II-A. The cyber layer model encompasses the placement and observation of the network by Phasor Measurement Units (PMUs), detailed in Section II-B 1). Additionally, in the cyber layer, the communication infrastructure of the PMUs, which facilitates the transmission of synchrophasor measurements from the physical layer through the PMUs to the control center, is elaborated on in Section II-B 2). Subsequently, the calculation of Dynamic Thermal Rating (DTR) values for each line is carried out using the model outlined in Section II-B 3), and the implementation of System Integrity Protection Schemes

TABLE 5. Numerical results.

Case	Topology	ETNA (hr/yr)	EENS				
			EENS Total (MWh/yr)	EENS COMM (MWh/yr)	EDCO (hr/yr)	EDLC (hr/yr)	ENLC
Base	-	44	0.00	0.00	-	-	-
0	-	107	87.05	0.00	-	3.58	1.92
1	SL	101	923.31	480.62 (52.05%)	1440.60	20.13	3.07
2	SS	101	684.96	325.98 (47.59%)	1156.40	15.25	2.68
3	SR	102	570.69	234.06 (41.01%)	981.37	12.55	2.44
4	SM	102	556.59	231.17 (41.53%)	970.24	12.36	2.47
5	DL	100	314.32	94.33 (30.01%)	574.09	7.57	2.09
6	DS	100	179.56	25.93 (14.44%)	253.96	4.87	1.85
7	DR	104	114.07	2.20 (1.93%)	44.19	3.70	1.77
8	DM	104	115.81	3.13 (2.71%)	41.61	3.71	1.76

(SIPS) is executed based on the model described in Section II-B 4). All these models are integrated into the Sequential Monte Carlo Simulation (SMCS) framework detailed in Section II-D, where the performance of the cyber network is evaluated through the measurement of indices specified in Section II-D 2).

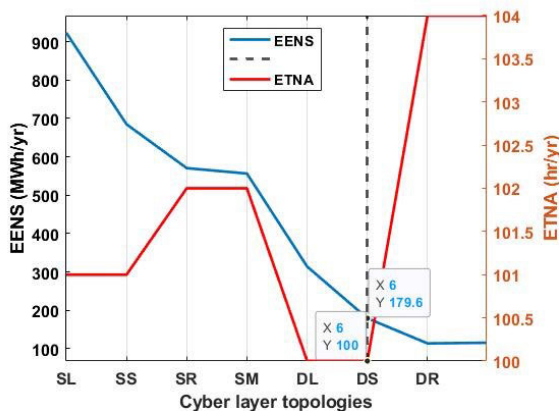


FIGURE 5. EENS vs ETNA for all topologies.

B. MODELLED CASES

The primary purpose of this study is to investigate the effects of the communication network unavailability based on the network topology on the availability of the DTR system and, ultimately, on the ageing of PMU-based cyber-physical power networks. The study also considers the impacts of SIPS communication network availability on total network ageing. The following 12 cases are explored to carry out this assessment.

Base case: This case considers a perfectly reliable network irrespective of the topology.

Case 0: This case considers a perfectly reliable cyber layer irrespective of the topology. In this case, DTR is assumed to be deployed every hour of the year. However, the physical layer contingencies are considered: the TLs.

Case 1-8: In these cases, contingencies from the cyber layer communication network are considered for DTR implementation together with the TL contingencies of the

physical layer. Each case considers one topology at a time, i.e., case 1 considers the SL topology, case 2 considers the SS likewise case 8 considers the DM topology, respectively. SIPS implementation is disregarded in these cases.

Case 9: The double mesh topology for DTR is examined in this case together with SIPS. Here, contingencies from SIPS implementation are considered.

Case 10: Double mesh topology is re-examined in this case with SIPS; this time, SIPS is assumed fully reliable.

IV. NUMERICAL ANALYSIS

The discussion is divided into five parts and listed below.

1. The first discussion highlights the effects of each network topology on network ageing from DTR implementation.
2. The second discusses the impacts of the network topologies on load curtailment with a focus on load curtailment caused solely by the contingencies from the cyber layer during DTR implementation.
3. In the third part, the impacts of the cyber layer topology on the cyber layer outage duration are explained.
4. The inadequacies of the weather on DTR deployment are highlighted concerning its impact on network ageing in the fourth part.
5. Finally, the effects of SIPS implementation in addition to the DTR system are quantified considering network ageing and load curtailment.

The general numerical results are presented in Table 5.

A. CYBER LAYER TOPOLOGY IMPACTS ON TOTAL NETWORK AGEING

In Table 5, the base case shows that ETNA is at a value of 44 hr/yr when the network is fully reliable. This case is performed to check the impacts of the DTR implementation in this synchrophasor-based cyber-physical network on the ageing of the TLs when all lines are fully functional. The effects are relatively minimal in this scenario. However, this is not a realistic case, as the complete reliability of the TL is practically impossible. In case 0, where the contingencies of the TLs are considered, the ETNA value increases by more than a double fold to 107 hr/yr. This is because when lines are on outage, adjacent lines are forced to carry higher capacities

to accommodate the demand. This implies that these adjacent lines will operate at higher temperatures, possibly above their specified MDT causing the lines to age further. Operation of the network on the SL topology in case 1 gives an ETNA value of 101 hr/yr, which is over 5% lower than in case 0. This indicates that the contingencies from this cyber layer topology cause the lines to operate less above MDTs than when the cyber layer is assumed fully reliable in the previous case. It is important to note that for the SL topology with 4 nodes and only a single communication path, all components are singular; they do not have a redundant spare. This implies that once any of the nodes are down, then there is a loss of synchrophasor measurement which then implies that the DTR values cannot be implemented on the lines, and consequently, the lines cannot be operated above their maximum specified value even if the lines are up. When this scenario occurs, the lines are operated on STR values, positively affecting the TLs' ageing. There is an extra node, a redundant station switch, for the SS topology, which provides an extra communication path compared to the SL topology. However, the ETNA of this topology remains at 101 hr/yr. This is majorly because only a single bay switch is present in this topology. This implies that if that single bay switch is down, the synchrophasors are lost, forcing the lines to be operated on STR, thereby not contributing to network ageing. Thus, the additional node does not cause any contribution to the ageing of the lines. In cases 3 and 4, the ETNA values are the same. This is because the SR and SM topologies in cases 3 and 4 have the same number of nodes. Though, the number of communication paths is more in the SM topology, which is provided by the communication of all switches with one another compared to the ring counterpart in which bay switch 1 can only communicate with station switch 1 and bay switch 2 can only communicate with station switch 2, still, the ETNA value remained unchanged. Comparing these results to cases 1 and 2, ETNA only increased slightly by 1 hr. Therefore, the increase in the number of nodes has a minimal impact on the ageing of the TLs in a year.

In the results for cases 5 and 6, the ETNA value was reduced by 1 hr to 100 hr/yr compared to cases 1 and 2 despite the increased availability of the cyber layer. This reduction is because, similarly to cases 1 and 2, these cases utilize only 4 and 5 nodes, respectively, which is less than in cases 3 and 4. This means that the additional communication paths did not contribute to the ageing of the TLs; instead, the number of nodes played a role in reducing the time the lines operate above MDT, albeit only minimally. Cases 7 and 8 also have the same ETNA values and show the most increment to this value. This is because the number of nodes and the communication paths are increased. This implies that the cyber layer has better reliability than all other topologies regarding its availability to deploy the DTR function. The increased availability thus implies an increase in the number of hours the lines will operate at maximum capacity, thereby contributing to the speed of line ageing, as depicted in Table 5. The average lifespan of an ACSR conductor can vary

between 46 to 77 years depending on several conditions [47], [48]. Generally, the ETNA values are minimally affected. However, when the lines are operated continuously over several years, the accumulated thermal and mechanical stresses may significantly impact the conductor's insulation and other components, leading to degradation and reduced lifespan. On the other hand, EENS which is another very important index is significantly reduced when comparing the SL to other topologies going down Table 5 with the DM topology having the least value of EENS. Since both the ETNA and EENS indices are important, it is necessary to consider a tradeoff between them to determine the optimum operating condition for the network. Considering both indices, the DS topology shows the best conditions as can be observed from Fig. 5. DS has the least value of ETNA and a relatively low value of EENS compared to other topologies.

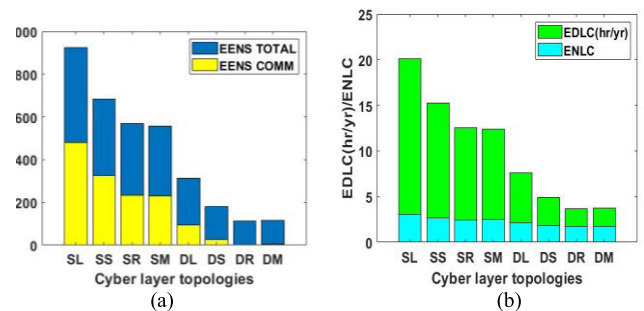


FIGURE 6. Cyber layer topology impacts on load curtailment.

B. CYBER LAYER TOPOLOGY IMPACTS ON LOAD CURTAILMENT

With case 1 being the most unavailable and case 8 being the most available of all the studied topologies, EENS values from cases 1 to 8 indicate a considerable improvement going down Table 5 compared to the preceding topology value. This is expected because an increase in the cyber layer availability implies an improved deployment of DTR; thus, a lower load value is expected to be curtailed.

The connection between the PMUs and the physical network can be described as an Indirect Cyber-physical interdependence. This classification arises because the failure of a PMU does not directly result in a failure of the physical network. Instead, it results in an impaired situational awareness of the network's status due to insufficient information, making it challenging to assess the TLs' optimal capacity accurately. This implies that at certain hours of the year when there is no TL outage in the physical network, PMU or any other cyber layer component outages may occur, which means that DTR values will not be calculated, and hence the lines will be operated on the conservative STR value. Due to this, the study also quantified the impacts of communication network outage alone to determine its impacts on total network reliability. This quantity is the EENS_{COMM} index described in section II(e) above. As shown in Fig. 6(a),

the decreasing trend of $EENS_{COMM}$ can be observed across Table 5, corresponding to the increasing availability of different topologies. This decline aligns with the overall reduction in total EENS values, as described earlier. Such a pattern is anticipated based on the previous explanation.

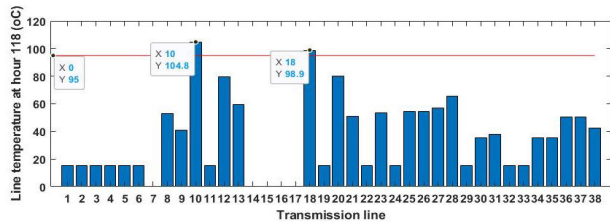


FIGURE 7. Line temperatures at hour 118 of the simulation year.

Furthermore, the percentage of $EENS_{COMM}$ contributing to the total value of EENS also reduces significantly going down the table due to the increased communication network availability, which causes a smaller number of outages. In the SL topology, $EENS_{COMM}$ contributes 52.05%, which is the least available topology, whereas, in the DM topology, the value is 2.71%. It can also be observed that the duration and number of load curtailment (EDLC and ENLC) follows a similar trend. EDLC and ENLC values decrease as the communication network becomes more available as shown in Fig. 6(b). The SR and SM results are similar to that of the DR and DM topologies. These topologies have an equal number of nodes with additional communication paths. If the outage is from the node, then the impact on reliability will be similar. However, the additional communication path has a slightly positive impact on these values as regards an improvement in load curtailment.

Another contributing factor to load curtailment from the cyber layer is that PMUs depend on the availability of lines to observe adjacent buses. This follows the first observability rule in (1). In Fig. 1, PMU1 observes buses 1, 2, 4 and 6, but it is placed on bus 2, so only that bus has primary observability. The other three buses are being observed secondarily through adjoining TLs. Buses 1 and 6 are also being observed by other PMUs. Hence, they have redundant measurements from those PMUs in case their adjoining lines to bus 2 go on an outage. However, it can be observed that bus 4 is only observed by PMU1, which implies that if L2-4 goes down, then bus 4 loses observability, and hence, the other adjoining L4-5 is operated on STR values. This will contribute to the load curtailment value.

C. CYBER LAYER TOPOLOGY IMPACTS ON COMMUNICATION NETWORK OUTAGE DURATION

The EDCO, which is the expected duration of outage in the cyber layer, shows an improvement trend from the least to most available topologies, as shown in Table 5. The single-line topology is vulnerable to single-point failures, which means that any disruption from a node leads to a complete loss of communication. When evaluating the available

communication paths, SS and DL have an equal number of paths, but SS has a more significant impact on EDCO due to the lack of a redundant substation LAN. This implies that if the single LAN fails in SS topology, there is a total loss of communication between the PMU and the PDC. On the other hand, the redundant LAN in the DL topology effectively handles a similar situation, significantly reducing communication network outage time. SR and DS have a similar relationship to DL and SS, but an even greater outage duration is saved between them.

TABLE 6. SIPS impact on network ageing.

Case	Topology	EENS (MWh/yr)	EENS COMM (MWh/yr)	ETNA (hr/yr)	EDCO (hr/yr)
8	DM DTR	115.81	3.13	104	41.61
9	DM DTR + SIPS	6186.80	77.31	106	42.21
10	DM DTR + SIPS	115.81	57.01	101	41.61

Furthermore, the results of SR and SM are similar, like DR and DM. This is because both topologies have the same number of nodes. However, the double topologies have additional communication paths, as explained above. In this vein, a similar impact will occur on the duration of the expected outage, as the EENS explained above. These findings indicate that having a redundant LAN significantly reduces EDCO. As a result, a shorter duration of communication network outage leads to less load curtailment, resulting in improved reliability.

D. WEATHER PROFILE IMPACTS ON TOTAL NETWORK AGEING

When all the components in both cyber and physical layers are functional in the current network configuration, two lines, namely L10 and L18, are operated above MDT for a few hours in the simulation year. This occurs due to the weather profile and loading conditions applied in this study. This condition implies that the wind speeds are low for some hours in the simulation year, forcing those two lines to operate above MDT, thereby causing them to creep for a cumulative number of 44 hr in the simulation year. An example of one of such hours is hour 118, where the wind speed is 1.03 m/s leading to a DTR value of 678 MW. In this hour, L10 is operated at 104.8 °C and L18 at 98.9 °C, as seen in Fig. 7. Thus, the low wind speed is a contributing factor to increased ETNA values. Generally, DTR values and TL temperatures are highly dependent on weather values. If the wind speed is higher, then the DTR value is higher; thus, the lines can accommodate more power to match the increased demand capacities at a particular loading condition. Whereas, at lower wind speeds, the lines may be forced to operate at higher temperatures as seen in Fig. 7 since the DTR value is lower.

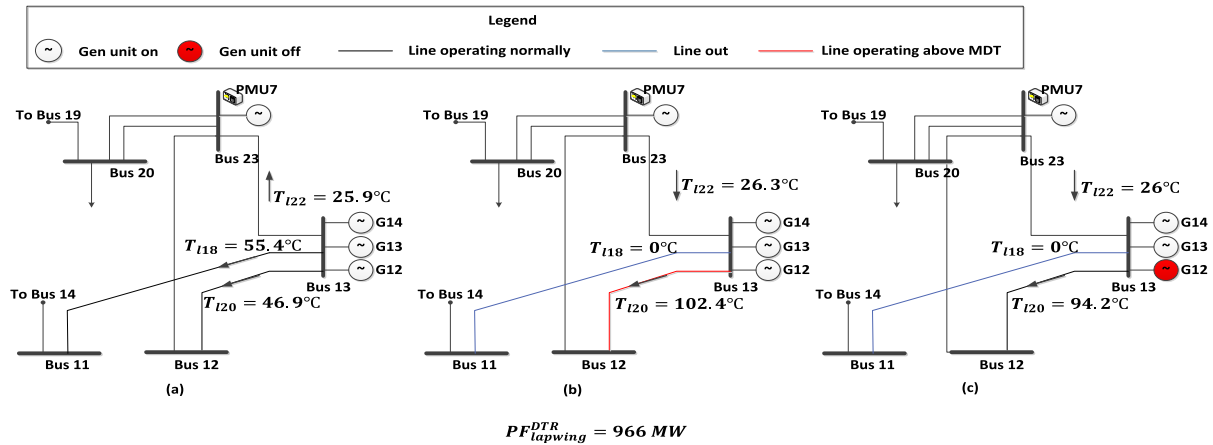


FIGURE 8. Impacts of SIPS GRS action.

E. IMPACTS OF SIPS IMPLEMENTATION ON TOTAL NETWORK AGEING AND LOAD CURTAILMENT

In Table 6, the results show that if DTR only is implemented with the DM topology, i.e., case 8, the TLs will be operated above MDT for 104 hr/yr. It is important to note that SIPS is not implemented on the network in this case. Meanwhile, if SIPS is deployed alongside the DTR feature on the network, as shown in case 9, ETNA increases to 106 hr/yr, indicating fast ageing. This is because, in this case, the contingencies of the SIPS communication network have been considered. Although SIPS deployment is supposed to improve overall reliability, the reverse can occur. This is because the SIPS GRS helps to relieve overloaded lines after DTR has been deployed by switching off a single generator on bus 13, thereby relieving lines 18 or 20. This action will ensure that those lines are not operated beyond acceptable temperatures, thereby preventing accelerated ageing. However, when the contingencies of SIPS are considered, SIPS may fail in two ways, i.e., Dependability based misoperation (DBM) or security based misoperation (SBM). In the first instance, when the lines have been upgraded to DTR, and either of lines 18/20 is down, the other line becomes overloaded, causing its temperature to increase and contributing to its ageing speed. It is then required for SIPS to take action by activating GRS. If SIPS is not functional in this instant, the line remains overloaded for extended periods which is observed in the increased ETNA value of case 9. This action could also cause cascading line outage until bus 13 becomes wholly isolated from the network, contributing significantly to the load curtailment value as observed in Table 6. On the other hand, if SIPS SBM occurs, a generator unit is taken off when this action is not needed causing the lines to be underutilized but contributing to the load curtailment. Both SIPS DBM and SBM contingencies could impact the overall reliability as seen in the results.

Notwithstanding, if SIPS is reliable, it is observed that load curtailment value is maintained at 115.81MWh/yr; meanwhile, the TLs will be operated at 101 hr/yr above MDT,

which is lower than if DM topology for DTR is deployed alone, indicating an improvement in general reliability. At the 128th hour of the simulation year, for example, the DTR value for the lapwing 230 kV lines is calculated to be 966 MW based on the DTR model and weather data employed, in which case line 20 is operated at 46.9° with the current system conditions when all lines are up. This scenario is demonstrated in Fig. 8(a). If, at this hour, line 18 goes down, then adjacent line 20 temperature increases by over 118% to 102.4°, which is above the MDT of 95°, thereby contributing to the line's ageing. This is shown in Fig. 8(b). However, if SIPS is reliably activated at this hour with the current conditions maintained, then the temperature of L20 reduces by 8% to 94.2°. This value is below the T_{age} of 95°, as seen in Fig. 8(c). Subsequently, this implies that the SIPS action has saved that line from creeping in that hour, thereby improving system reliability.

The ETNA value reduction from a reliable SIPS implementation of 5 hr/yr may have an insignificant impact on a year of service. However, continuous operation of the lines above MDT for such hours in a year for a prolonged number of years will significantly slow down the network's ageing in the long run and ultimately improve the network's reliability.

It can be observed that the EDCO is similar in all three cases 8-10 as compared in Table 6. This is simply because the DTR communication network topology in all three cases is the same, i.e., double mesh topology. However, this value is slightly higher in case 9 than in case 10 because the contingencies from SIPS implementation will contribute to the duration of the communication network outage.

In reference [19], the study introduced Time-Varying Line Rating (TVLR) applications utilising Flexible AC Transmission Systems (FACTS). The SMCS method was employed and enhanced line modeling to assess the impact of ICT failures on the IEEE-RTS 96 network under conditions similar to this study. Their results revealed ETNA and EENS values of 1247 hr/yr and 2352 MWh/yr, respectively. Comparatively,

the present study achieved a 91% reduction in ETNA and a 95% decrease in EENS values. In another study [22], DTR was assessed with a focus on network ageing, but the cyber layer assessment was omitted. Their findings showed a lower ETNA value of 70 hr/yr compared to the current study, but a notably higher EENS value of 68300 MWh/yr. However, unlike both [19] and [22], the current study integrated PMUs to enable a hybrid DTR and SIPS deployment while considering diverse communication topologies. Overall, this study achieved enhanced reliability and underscored the advantages of a hybrid framework, taking the communication infrastructure into account.

V. CONCLUSION

TL operation at extended periods of high temperatures, especially when approaching the maximum design values, can lead to a notable ageing effect on TLs. Advanced technologies like the dynamic thermal rating (DTR) system, which increases TL capacities and boosts network reliability, can contribute to these stringent conditions. Despite previous research examining the influence of different line ratings on the deterioration of overhead TLs, there appears to be a lack of studies that precisely measure the effects of different communication network topologies on the ageing process of synchrophasor-based cyber-physical power networks. This study proposes a framework that evaluates the reliability of a cyber-physical network by considering the impacts of the cyber layer on TL ageing caused by DTR implementation to address this gap. The proposed framework employs a Sequential Monte Carlo Simulation technique that incorporates important properties of 8 cyber layer topologies for DTR and SIPS while considering the ageing of TLs. The study is performed on a modified cyber-physical version of the IEEE RTS-79 network. When the failures of the topologies are considered rather than assuming they are fully reliable, it has a positive effect on the ageing of the TLs but has a negative effect on the load curtailment. This is because the contingencies from the cyber layer outages mean that DTR will be deployed less, and hence the lines will operate less at higher temperatures. ETNA values from all topologies change marginally between the least available single-line topology and the most available double-mesh topology. This implies that irrespective of the topology type, the cyber layer in the present configurations is insufficient to affect the line ageing negatively in a single year significantly. However, over 40 years, the accumulated thermal and mechanical stresses may significantly impact the conductor's insulation and other components, leading to degradation and reduced lifespan. The implementation of SIPS is proposed to forestall this condition. Although SIPS is meant to forestall line ageing, the reverse can occur when the contingencies from the SIPS itself are considered. Nonetheless, a reliable SIPS can slow down network ageing by 5 hours a year without increasing the load curtailment value, as observed from the results, thereby indicating reliability improvement. This method can be applied to larger cyber-physical power networks; however,

the computational time is expected to increase as the size of the network increases.

A limitation of the current study is that the framework only considers network observability with the least possible number of PMUs. Subsequently, reliability could be improved if the network has better observability by having redundant PMUs that could provide spare measurements. Consequently, additional PMUs may have their contribution to the ageing of TLs and overall reliability.

REFERENCES

- [1] R. V. Yohanandhan, R. M. Elavarasan, R. Pugazhendhi, M. Premkumar, L. Mihet-Popa, J. Zhao, and V. Terzija, "A specialized review on outlook of future cyber-physical power system (CPPS) testbeds for securing electric power grid," *Int. J. Electr. Power Energy Syst.*, vol. 136, Mar. 2022, Art. no. 107720.
- [2] R. V. Yohanandhan, R. M. Elavarasan, R. Pugazhendhi, M. Premkumar, L. Mihet-Popa, and V. Terzija, "A holistic review on cyber-physical power system (CPPS) testbeds for secure and sustainable electric power grid—Part—I: Background on CPPS and necessity of CPPS testbeds," *Int. J. Electr. Power Energy Syst.*, vol. 136, Mar. 2022, Art. no. 107718.
- [3] B. Jimada-Ojuolape, J. Teh, and M. O. Arowolo, "Synchrophasor-based dynamic thermal rating system for sustainable cyber-physical power systems," in *Cyber-Physical Systems for Industrial Transformation Fundamentals, Standards, and Protocols*, 1st ed., G. Manogaran, N. E. M. Khalifa, M. Loey, and M. H. N. Taha, Eds. Boca Raton, FL, USA: CRC Press, 2023, pp. 177–191.
- [4] F. Aminifar, M. Fotuhi-Firuzabad, M. Shahidehpour, and A. Safdarian, "Impact of WAMS malfunction on power system reliability assessment," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1302–1309, Sep. 2012.
- [5] B. Jimada-Ojuolape and J. Teh, "Reliability impacts of ICT failures on synchrophasor based dynamic thermal rating system," in *Proc. 11th Int. Conf. Robot., Vis., Signal Process. Power Appl.*, 2022, pp. 337–343.
- [6] Z. Soltani and M. Khorsand, "Real-time topology detection and state estimation in distribution systems using micro-PMU and smart meter data," *IEEE Syst. J.*, vol. 16, no. 3, pp. 3554–3565, Sep. 2022.
- [7] B. Jimada-Ojuolape and J. Teh, "Impact of the integration of information and communication technology on power system reliability: A review," *IEEE Access*, vol. 8, pp. 24600–24615, 2020.
- [8] B. Jimada-Ojuolape and J. Teh, "Surveys on the reliability impacts of power system cyber-physical layers," *Sustain. Cities Soc.*, vol. 62, Nov. 2020, Art. no. 102384.
- [9] M. K. Metwaly and J. Teh, "Probabilistic peak demand matching by battery energy storage alongside dynamic thermal ratings and demand response for enhanced network reliability," *IEEE Access*, vol. 8, pp. 181547–181559, 2020.
- [10] S. Talpur, T. T. Lie, and R. Zamora, "Application of dynamic thermal rating: Overhead line critical spans identification under weather dependent optimized sensor placement," *Electric Power Syst. Res.*, vol. 180, Mar. 2020, Art. no. 106125.
- [11] C.-M. Lai and J. Teh, "Comprehensive review of the dynamic thermal rating system for sustainable electrical power systems," *Energy Rep.*, vol. 8, pp. 3263–3288, Nov. 2022.
- [12] B. Jimada-Ojuolape and J. Teh, "Impacts of communication network availability on synchrophasor-based DTR and SIPS reliability," *IEEE Syst. J.*, vol. 16, no. 4, pp. 6231–6242, Dec. 2022.
- [13] J. Teh and C.-M. Lai, "Reliability impacts of the dynamic thermal rating system on smart grids considering wireless communications," *IEEE Access*, vol. 7, pp. 41625–41635, 2019.
- [14] J. Teh, C.-M. Lai, N. A. Muhamad, C. A. Ooi, Y.-H. Cheng, M. A. A. M. Zainuri, and M. K. Ishak, "Prospects of using the dynamic thermal rating system for reliable electrical networks: A review," *IEEE Access*, vol. 6, pp. 26765–26778, 2018.
- [15] N. Liu and P. Crossley, "Risk assessment of a generator rejection scheme implemented in a wind farm," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2016, pp. 1–5.
- [16] M. Panteli, P. A. Crossley, and J. Fitch, "Design of dependable and secure system integrity protection schemes," *Int. J. Electr. Power Energy Syst.*, vol. 68, pp. 15–25, Jun. 2015.
- [17] Y. Yaqoob, A. Marzuki, C.-M. Lai, and J. Teh, "Fuzzy dynamic thermal rating system-based thermal aging model for transmission lines," *Energies*, vol. 15, no. 12, p. 4395, Jun. 2022.

- [18] B. Jimada-Ojuolape and J. Teh, "Composite reliability impacts of synchrophasor-based DTR and SIPS cyber-physical systems," *IEEE Syst. J.*, vol. 16, no. 3, pp. 3927–3938, Sep. 2022.
- [19] K. Kopsidas and S. Liu, "Power network reliability framework for integrating cable design and ageing," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1521–1532, Mar. 2018.
- [20] C. Cruzat and K. Kopsidas, "Modelling of network reliability of OHL networks using information and communication technologies," in *Proc. IEEE Manchester PowerTech*, Jun. 2017, pp. 1–6.
- [21] M. K. Metwaly and J. Teh, "Fuzzy dynamic thermal rating system-based SIPS for enhancing transmission line security," *IEEE Access*, vol. 9, pp. 83628–83641, 2021.
- [22] M. K. Metwaly and J. Teh, "Optimum network ageing and battery sizing for improved wind penetration and reliability," *IEEE Access*, vol. 8, pp. 118603–118611, 2020.
- [23] K. Kopsidas, C. Tumelo-Chakonta, and C. Cruzat, "Power network reliability evaluation framework considering OHL electro-thermal design," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 2463–2471, May 2016.
- [24] W. C. Khoo, J. Teh, and C.-M. Lai, "Demand response and dynamic line ratings for optimum power network reliability and ageing," *IEEE Access*, vol. 8, pp. 175319–175328, 2020.
- [25] Z. Wu, H. Long, and C. Chen, "Line aging assessment in distribution network based on topology verification and parameter estimation," *J. Modern Power Syst. Clean Energy*, vol. 10, no. 6, pp. 1658–1668, Nov. 2022.
- [26] *Aluminium Rods Bare Conductors and Cables*, Universal Cable (M) Berhad, Johor Bahru, Malaysia, 2019.
- [27] *Aluminum Electrical Conductor Handbook*, 3rd ed. The Aluminum Assoc., Arlington County, VA, USA, 1989.
- [28] *Standard Specification for Zinc-Coated (Galvanized) Steel Core Wire for Aluminum Conductors, Steel Reinforced (ACSR)*, ASTM, West Conshohocken, PA, USA, 2002.
- [29] J. Teh and C.-M. Lai, "Risk-based management of transmission lines enhanced with the dynamic thermal rating system," *IEEE Access*, vol. 7, pp. 76562–76572, 2019.
- [30] C. Grigg et al., "The IEEE reliability test system-1996. A report prepared by the reliability test system task force of the application of probability methods subcommittee," *IEEE Trans. Power Syst.*, vol. 14, no. 3, pp. 1010–1020, Aug. 1999, doi: [10.1109/59.780914](https://doi.org/10.1109/59.780914).
- [31] X.-C. Guo, C.-S. Liao, and C.-C. Chu, "Probabilistic optimal PMU placements under limited observability propagations," *IEEE Syst. J.*, vol. 16, no. 1, pp. 767–776, Mar. 2022.
- [32] X. Chen, F. Wei, S. Cao, C. B. Soh, and K. J. Tseng, "PMU placement for measurement redundancy distribution considering zero injection bus and contingencies," *IEEE Syst. J.*, vol. 14, no. 4, pp. 5396–5406, Dec. 2020.
- [33] A. Hassani Ahangar, B. Vahidi, and H. Askarian Abyaneh, "Evaluating smart grid reliability based on impacts of cyber (control, monitoring and protection) network and its different topologies," *Int. J. Syst. Assurance Eng. Manage.*, vol. 9, no. 5, pp. 1047–1056, Oct. 2018.
- [34] J. Espina, T. Falck, and O. Mühlens, "Network topologies, communication protocols, and standards," in *Body Sensor Networks*, vol. 2014, G. Z. Yang, Ed. London, U.K.: Springer, 2006, doi: [10.1007/1-84628-484-8_5](https://doi.org/10.1007/1-84628-484-8_5).
- [35] Y. Liu, Q. Zhang, and L. Ni, "Opportunity-based topology control in wireless sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 21, no. 3, pp. 405–416, Mar. 2010.
- [36] A. Grami, "Chapter 11—Communication networks," in *Introduction to Digital Communicatio*. Academic, 2016, pp. 457–491. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/B9780124076822000119> and <https://doi.org/10.1016/B978-0-12-407682-2.00011-9>
- [37] N. Liu and P. Crossley, "Assessing the risk of implementing system integrity protection schemes in a power system with significant wind integration," *IEEE Trans. Power Del.*, vol. 33, no. 2, pp. 810–820, Apr. 2018.
- [38] N. Liu, M. Panteli, and P. A. Crossley, "Reliability evaluation of a substation automation system communication network based on IEC 61850," in *Proc. 12th IET Int. Conf. Develop. Power Syst. Protection (DPSP)*, Mar. 2014, pp. 1–6.
- [39] F. Aminifar, S. Bagheri-Shouraki, M. Fotuhi-Firuzabad, and M. Shahidepour, "Reliability modeling of PMUs using fuzzy sets," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2384–2391, Oct. 2010.
- [40] M. Panteli, P. A. Crossley, and J. Fitch, "Quantifying the reliability level of system integrity protection schemes," *IET Gener., Transmiss. Distribution*, vol. 8, no. 4, pp. 753–764, Apr. 2014.
- [41] G. Chen, X. Wang, J. Wang, J. Liu, T. Zhang, and W. Tang, "Damage investigation of the aged aluminium cable steel reinforced (ACSR) conductors in a high-voltage transmission line," *Eng. Failure Anal.*, vol. 19, pp. 13–21, Jan. 2012.
- [42] F. Lequien, Q. Auzoux, G. Moine, M. Rousseau, S. Pasquier-Tilliette, A. Holande, S. Ammi, S. Heurtault, and P. Prieur, "Characterization of an aluminum conductor steel reinforced (ACSR) after 60 years of operation," *Eng. Failure Anal.*, vol. 120, Feb. 2021, Art. no. 105039.
- [43] *IEEE Guide for Determining the Effects of High-Temperature Operation on Conductors, Connectors, and Accessories*, IPE Society, IEEE Standard 1283-2004, Mar. 2005.
- [44] *IEEE Guide for Determining the Effects of High-Temperature Operation on Conductors, Connectors, and Accessories*, IPE Society, IEEE Standard 1283-2013, 2013.
- [45] J. R. Harvey, "On the strength of aluminum conductors," *IEEE Trans. Power App. Syst.*, vol. PAS-91, no. 5, pp. 1769–1772, Sep. 1972, doi: [10.1109/TPAS.1972.293498](https://doi.org/10.1109/TPAS.1972.293498).
- [46] R. Billinton and L. Wenyuan, *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods*. New York, NY, USA: Springer, 1994.
- [47] W. Naim, K. Morozovska, and P. Hilber, "Effects of dynamic line rating on the durability and mechanical strength of aluminum cable steel reinforced (ACSR) conductors," in *Proc. 10th Int. Conf. Appl. Energy (ICAE)*, Hong Kong, vol. 2019, Aug. 2018, pp. 3164–3169.
- [48] D. G. Havard, M. K. Bissada, C. G. Fajardo, D. J. Horrocks, J. R. Meale, J. Y. Motlis, M. Tabatabai, and K. S. Yoshiki-Gravelsins, "Aged ACSR conductors. II. Prediction of remaining life," *IEEE Trans. Power Deliv.*, vol. 7, no. 2, pp. 588–595, Apr. 1992.



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