

# Resilience of data centre power system: modelling of sustained operation under outage, definition of metrics, and application

Uwe Müller<sup>1,2</sup>, Kai Strunz<sup>2</sup> ✉

<sup>1</sup>InfraOpt GmbH, Puschkinstr. 23, 14943 Luckenwalde, Germany

<sup>2</sup>Department of Electrical Engineering and Computer Science, Technische Universität Berlin, 10587 Berlin, Germany

✉ E-mail: Kai.Strunz@TU-Berlin.de

eISSN 2051-3305

Received on 18th December 2018

Accepted on 1st February 2019

doi: 10.1049/joe.2018.5520

www.ietdl.org

**Abstract:** A novel criterion for quantifying the resilience of power systems supplying data centres is formulated to measure the system's ability to sustain functionality even during an outage. By comparative analysis of two alternative data centre power systems covering apparatus of electrical power supply and environmental control, it is shown that reliability and availability alone are insufficient as metrics to gauge different designs. The gap is bridged by the proposed resilience analysis to further evaluate situations of single and double outages. As a complement to the indicators of single point of failure and double point of failure, respectively,  $N - 1$  and  $N - 2$  security criteria, the novel metrics of a single point of reduced availability and double point of reduced availability are proposed. These criteria identify those single subsystems or subsystem pairs causing system availability to drop below requested levels in periods when they are out of service. The metrics so offer information on the overall system's availability during times of maintenance and failures. Thanks to this understanding, it is shown that a guided reduction of the number of subsystems considering their relative importance can lead to designs offering desirable trade-offs in terms of complexity, reliability, availability, and resilience.

## Nomenclature

$A$	availability
$A_i$	inherent availability
$A_i^0$	$A_i$ of electrical utility supply, single circuit
$A_o$	operational availability
$A_o^0$	$A_o$ of electrical utility supply, single circuit
$a_i, \dots, z_i$	Boolean variables with index $i$
$D_i$	disjoint success path $i$
$DHY$	number of downtime hours per year
$DPoF_m$	set of $\{x_{m_i}, x_{m_j}\}$ leading to double point of failure ( $DPoF$ ) of the $m$ th data centre power supply (DCPS)
$DPoRA_m$	set of $\{x_{m_i}, x_{m_j}\}$ leading to double point of reduced availability ( $DPoRA$ ) of the $m$ th DCPS
$DS(x)$	disjoint sum of system success paths of $x$
$F_k$	number of possible failure states under the condition of $k$ simultaneous failure events
$K_i$	conjunctive term of success path $i$
$MDT$	total maintenance downtime for a given time period
$MTBF$	mean time between failures, reciprocal of $\lambda$
$MTBM$	mean time between maintenance
$MTTR$	mean time to repair or replace a failed component
$MVI$	multi variable inversion
$M$	number of required components or subsystems
$N$	total number of components, systems, subsystems
$R$	reliability over a time span of $t = 8760$ h
$R^0$	$R$ of electrical utility supply, single circuit
$SPoF_m$	set of $x_{m_i}$ leading to a single point of failure ( $SPoF$ ) of the $m$ th DCPS
$SPoRA_m$	set of $x_{m_i}$ leading to a single point of reduced availability ( $SPoRA$ ) of the $m$ th DCPS
$SSP_{x_i}$	set of system success paths containing $x_i$
$SVI$	single variable inversion
$S(x)$	sum of system success paths of $x$
$t$	time span of $1 a = 365 \times 24$ h = 8760 h
$X_m$	set of $x_{m_i}$ of the $m$ th DCPS
$ X $	number of elements of $X$ , cardinality
$\bar{x}_i$	negation of Boolean variable $x_i$

$x_m$	vector of $x_{m_i}$ of the $m$ th DCPS
$x_{m_i}$	Boolean variable giving the status of the $i$ th subsystem of the $m$ th DCPS
$\lambda$	average failure rate per year, reciprocal of $MTBF$
$\cap$	conjunction, logical AND
$\cup$	disjunction, logical OR

## 1 Introduction

Data centre power systems (DCPS) are expected to provide uninterrupted electrical power and continuous environmental control of the critical load points at high levels of availability. With the challenge to minimise the life cycle cost of a data centre, the question of how to design or redesign efficient DCPS with proven reliability, availability, and fault tolerance arises. A valuable source for numerical reliability and availability calculation as well as for component reliability and availability data is IEEE Std 493-2007 [1]. Especially in the field of data centres, the Uptime Institute categorises infrastructure designs into four tier classes with specific availability and failure tolerance attributes [2]. While these quantities were determined empirically, the calculation of DCPS reliabilities was considered in [3].

Regarding general electric power distribution networks, the calculation of reliability and availability is an important part of distribution system engineering [4]. Recent advances in this field offer clear evidence of the continued interest [5–8]. With a particular focus on the electrical power distribution of data centres, methods to analyse the reliability and availability and their relation to optimisation are given in [9–11]. The modelling scope given in the present work is extended to also include the environmental control and affiliated reliability considerations at component and systemic levels. The resulting comprehensive model of the DCPS includes the interdependencies of the electrical power distribution and environmental control. This will allow for calculating the metrics of reliability and availability of the DCPS covering both its electrical power distribution and environmental control system.

Beyond reliability and availability, there has been an emergent need to deal with the issue of resilience. According to [12], in the case of an outage event, a well-designed resilient system is to maintain maximum practicable functionality or enable rapid

restoration with minimum downtime. Further recent suggestions made for electric power distribution focus on measuring resilience in response to unfavourable events affecting the network [13, 14]. In the present work focusing on the DCPS, the need for resilience is recognised, too. The focus laid in this study is on the continued practical operation even under outages.

If a power system is single-failure tolerant, then it is said to be  $N - 1$  secure. In the case of double-failure tolerance, it is  $N - 2$  secure. However, resilience analysis is to look beyond those basic indicators of fault tolerance. For practical operation over a period of outage, the availability needs to reach certain levels, too. Outages could be unforeseen or scheduled, e.g. for maintenance purposes. Is the availability still at the desired level when a subsystem is out of service? Is the availability still meeting expectations in the case of double failures? The ability to answer these questions will give valuable information on the capability of the system to sustain practical functionality in the event of an outage.

By comparing the proposed resilience criteria of different DCPS designs, significant differences in performance are observed. In Section 2, selected fundamentals are reviewed. Mathematical definitions of the metrics of a single point of failure (*SPoF*) and double point of failure (*DPOF*) are proposed in Section 3. The value of reliability and availability for the DCPS design is discussed in Section 4. Section 5 introduces the metrics of resilience for DCPS. The application of the metrics is elaborated upon in Section 6. This section also summarises the results of the analysis of availability, reliability, fault tolerance, and resilience of the DCPS models discussed in this work. Conclusions are drawn in Section 7.

## 2 State-of-the-art and background

IEEE Std 493-2007 [1] including Annex Q is used as a source for all reliability and availability data of this work. This standard defines reliability as a function of time with a timespan  $t$  of 1,  $a = 8760$  h

$$R = e^{-\lambda t}, \quad (1)$$

$$\lambda = 1/MTBF. \quad (2)$$

As also defined in [1], two different availability metrics are applicable. These are the inherent availability  $A_i$  and operational availability  $A_o$

$$A_i = MTBF/(MTBF + MTTR), \quad (3)$$

$$A_o = MTBM/(MTBM + MDT). \quad (4)$$

While  $A_i$  only considers the downtime for repairs of failures,  $A_o$  includes all downtime, including the time needed for scheduled and unscheduled maintenance as well as logistics.

A number of different methods support the systemic analysis of reliability. They can be categorised into inductive and deductive methods. Failure mode and effects analysis [15] is a popular representative of the family of inductive methods, where the contribution of subsystem faults to overall system failures is studied. In the family of deductive methods, however, an overall system failure is the starting point for identifying the contributors to this failure. Fault tree analysis (FTA) [16] is a deductive method. It examines the failure conditions of the overall model to identify the subsystem as a cause of the failure.

While the FTA employs a negative logic because it is oriented towards failures, the reliability block diagram (RBD) [17] is its counterpart of positive logic aimed at dealing with success. In the present study, all representations are made based on the RBD. Thanks to this approach, the physical structure of the entire DCPS is closely mirrored. The RBD covers the electrical power supply and distribution as well as the environmental control system. The obtained diagrams depict the given interdependencies of various success paths and so offer valuable guidance in the process of analysis and design.

For reliability and availability calculations, the RBD lends itself to the formulation of expressions of Boolean algebra. For the use of Boolean algebra, the calculations reviewed hereafter are fundamental [1, 4, 17]. Accordingly, the system success of two series-connected elements is only given if both  $x_1$  and  $x_2$  are true. The operation is known as logical conjunction

$$S_{\text{ser}}(x_1, x_2) = x_1 \cap x_2. \quad (5)$$

Alternatively, it may be written as product  $x_1 x_2$ . The system success of two parallel-connected elements is given if  $x_1$  or  $x_2$  or both are true. The operation is known as logical disjunction

$$S_{\text{par}}(x_1, x_2) = x_1 \cup x_2. \quad (6)$$

In the context of Boolean algebra, it is also common to use the term sum.

System success is expressed through system success paths (*SSPs*). For system success, at least one *SSP* must be true. As shown for the following example, three possible *SSPs* are included as the sum of Boolean product terms

$$S_{\text{ex}}(\mathbf{x}) = x_1 x_2 \cup x_3 x_4 x_6 \cup x_5. \quad (7)$$

The *SSPs* are not mutually exclusive because multiple events may happen together in one or more *SSPs*. In order to address this issue, methods of single variable inversion (*SVI*) [18] and multi variable inversion (*MVI*) [19] were introduced. Applying the *MVI* algorithm by Heidtmann [19] to example (7) produces the sum of disjoint product terms

$$DS_{\text{ex}}(\mathbf{x}) = x_1 x_2 \cup \bar{x}_1 \bar{x}_2 x_3 x_4 x_6 \cup \bar{x}_1 \bar{x}_2 \bar{x}_3 \bar{x}_4 \bar{x}_6 x_5. \quad (8)$$

The sum of product terms (7) and the sum of disjoint product terms (8) are equivalent. This can be proven by a truth table. Optimising *SVI* and *MVI* algorithms to reduce the number of resulting disjoint product terms, for instance by preprocessing the input terms, is discussed in [20–22]. Usually, the *MVI* results in a lower number of terms than the *SVI*. With the representation through disjoint product terms, all Boolean variables can be replaced by subsystem reliability respectively availability values, under the condition of systemic independence at any time. Further limitations are discussed in [17]. For the example using (8)

$$R_{\text{ex}}(x_{\text{ex}}) = R_{x_1} R_{x_2} + (1 - R_{x_1} R_{x_2}) R_{x_3} R_{x_4} R_{x_6} + (1 - R_{x_1} R_{x_2}) (1 - R_{x_3} R_{x_4} R_{x_6}) R_{x_5}. \quad (9)$$

$$A_{\text{ex}} = A_{x_1} A_{x_2} + (1 - A_{x_1} A_{x_2}) A_{x_3} A_{x_4} A_{x_6} + (1 - A_{x_1} A_{x_2}) (1 - A_{x_3} A_{x_4} A_{x_6}) A_{x_5}. \quad (10)$$

Importance analysis to identify the influence of particular subsystems on the total system was introduced in [23]. The so-called H-importance was introduced in [24]. The subsystem  $x_i$  is called more H-important if it is included in a higher number of *SSPs* compared to  $x_j$

$$|SSP_{x_i}| > |SSP_{x_j}|. \quad (11)$$

Applying the H-importance concept, the comments and corrections of [25] have to be considered.

Helpful is also the notation of the number  $F$  of possible failure states of a system with  $N$  subsystems. Under the condition of  $k$  simultaneous failure events, the number of failures is equal to [17]

$$F_k = \binom{N}{k}. \quad (12)$$

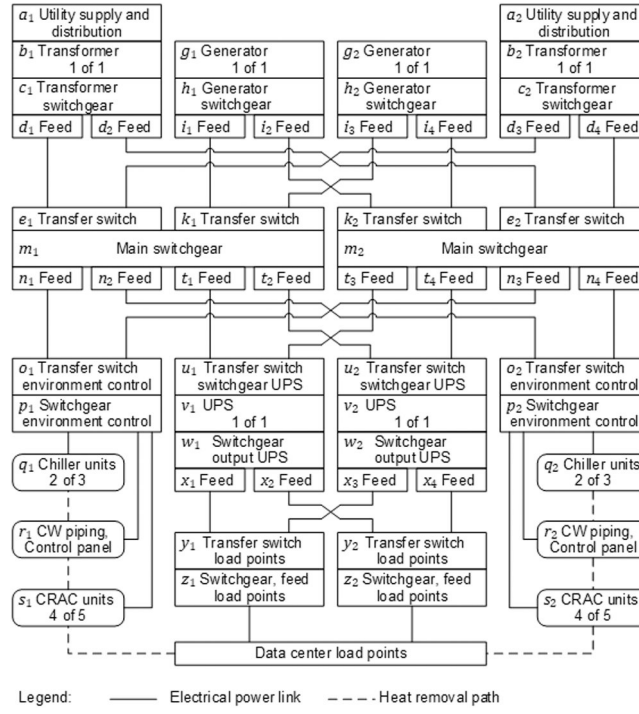


Fig. 1 Model 1 Tier IV DCPS design including all relevant subsystems

### 3 Mathematical definition of SPoF and DPoF

A subsystem  $x_{m_i}$  is a *SPoF* of the  $m$ th DCPS if its failure leads to overall system failure. For the purpose of analysis, a mathematical formulation of *SPoF* is helpful. The following definition of *SPoF<sub>m</sub>* as a subset of the set  $X_m$  of all subsystems of the  $m$ th DCPS is proposed. As such, *SPoF<sub>m</sub>* encompasses all those subsystems  $x_{m_i}$  whose single failure  $x_{m_i} = 0$  causes overall system failure, i.e. results in  $S_m(x_m) = 0$

$$SPoF_m = \left\{ x_{m_i} \in X_m \left| \left( S_m(x_m) = 0 \right) \cap \left( \bar{x}_{m_i} \prod_{l=1, l \neq i}^N x_{m_l} = 1 \right) \right. \right\}. \quad (13)$$

Similarly, the two elements  $\{x_{m_i}, x_{m_j}\}$  belong to the set *DPoF<sub>m</sub>* if the two affiliated subsystems mark a *DPoF*. Thus, if  $(x_{m_i} = 0) \cap (x_{m_j} = 0)$  while all other subsystems are working, then  $S_m(x_m) = 0$  and the two failed components mark a *DPoF*

$$DPoF_m = \left\{ \{x_{m_i}, x_{m_j}\} \subset X_m \left| \left( S_m(x_m) = 0 \right) \cap \left( \bar{x}_{m_i} \bar{x}_{m_j} \prod_{l=1, l \neq i, j}^N x_{m_l} = 1 \right) \right. \right\}. \quad (14)$$

Note that design according to Tier IV [2] or of an availability class 4 [26] does not accept any *SPoF*, but concerning *DPoFs* no statement is made.

### 4 Value of reliability and availability in the design of DCPS

To illustrate the level of information offered by the definitions of reliability (1) and availability (3), (4), two different designs are considered [3]. Model 1 represents a comprehensive design, while model 2 is a lean design. Both are to be compared in terms of  $R$ ,  $A_i$  and  $A_o$ . Model 1 is depicted in Fig. 1, with further subsystem information offered in Appendix. This block diagram shows a symmetric DCPS design, sized to about 500 kW electrical power for the load points. It consists of redundant medium voltage utility supply and distribution  $a_i$ , redundant generators  $g_i$ , redundant main switchgears  $m_i$ , redundant uninterruptible power supplies (UPS)  $v_i$ , and redundant environmental control systems  $q_i$ ,  $r_i$ , and  $s_i$ . The usage of multiple transfer switches denoted by  $e_i$ ,  $k_i$ ,  $o_i$ ,  $u_i$ ,  $y_i$ ,  $z_i$  enhances the number of redundant supply paths.

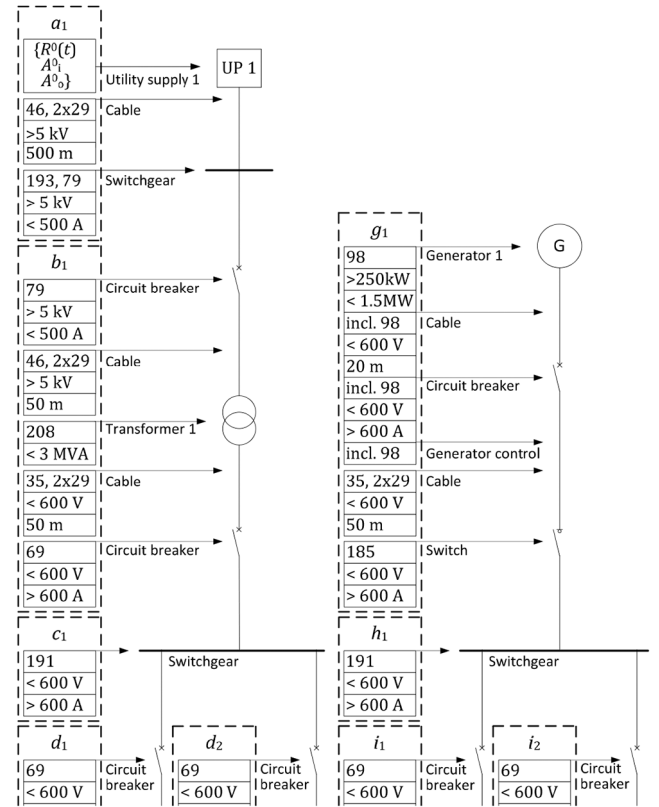
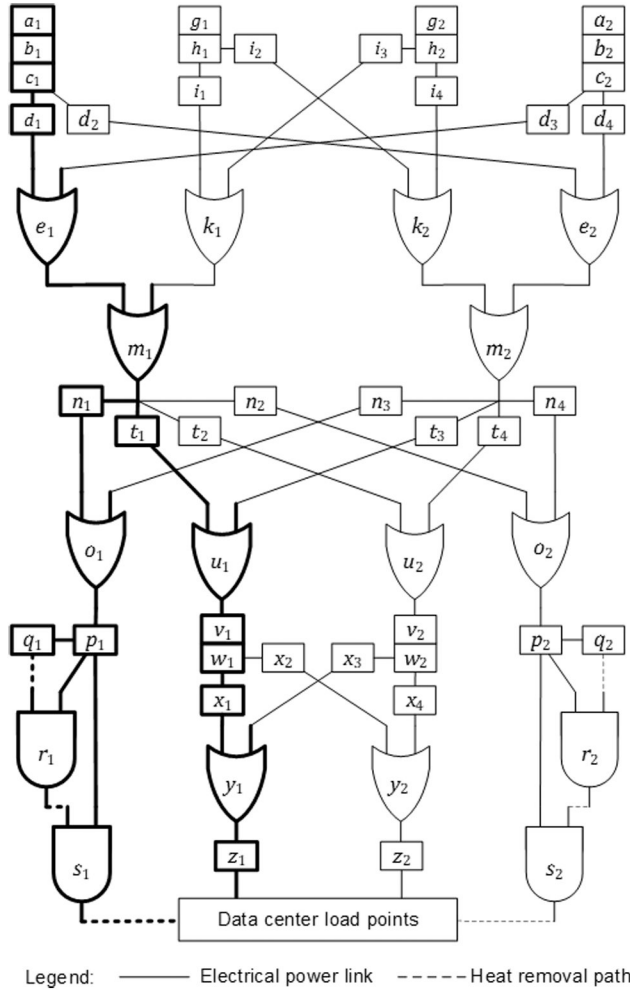


Fig. 2 Model 1 Tier IV DCPS design detail with subsystems and components

The Boolean status indicators  $a_i$ ,  $b_i$ , ...,  $z_i$  shown in Fig. 1 stand for subsystems that consist of one or multiple components. This can be seen by comparing Fig. 1 with the design detail of model 1 shown in Fig. 2. For example, subsystems  $a_i$  consist of utility supply, cable, and switchgear. The grouping of the components with the corresponding item numbers and the resulting reliabilities and availabilities for the subsystem is summarised in the Appendix. The Appendix also gives the reliabilities and availabilities of the environmental control system, which includes redundant chiller units, chilled water (CW) piping and control, and redundant



**Fig. 3** Model 1 DCPS design Boolean circuit

computer room air conditioning (CRAC) units of Fig. 1. All item numbers and dimensions are consistent with IEEE Std 493-2007 [1], Annex Q. Additional calculation details of the applied component and subsystem data are shown in the Appendix.

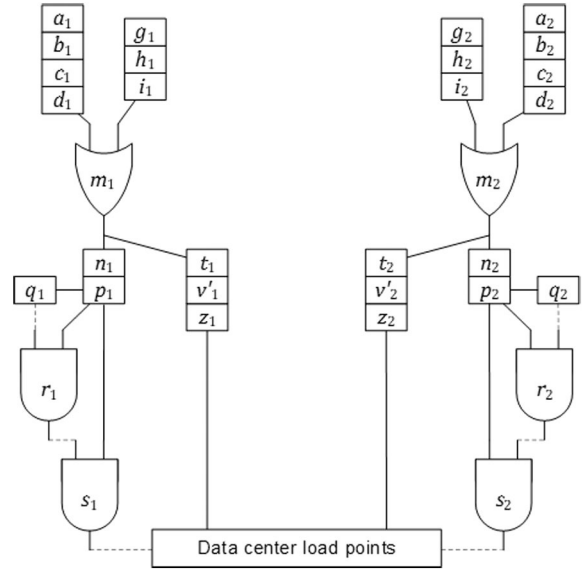
With the structural properties described above, model 1 of Fig. 1 may be seen as a representative example for an elaborate DCPS design. Model 1 was redrawn in Fig. 3 for a more intuitive application of Boolean algebra.

Applying Boolean algebra, the system success of model 1 is determined as a sum of all product terms  $K_i$  denoting SSPs. The bold lines of Fig. 3 illustrate the first SSP called  $K_1$ . It can be seen that  $K_1$  relies not only on the electrical power subsystems but also on the environmental control subsystems  $q_1, r_1, s_1$ , which are connected by heat flow links marked by dashed lines. Model 1 contains 56 subsystems, also summarised in Table 9 of the Appendix. In total, model 1 contains 320 SSPs

$$S_{\text{Model 1}}(\mathbf{x}) = K_1 \cup K_2 \cup \dots \cup K_{320} \\ = a_1 b_1 c_1 d_1 e_1 m_1 n_1 o_1 p_1 q_1 r_1 s_1 t_1 u_1 v_1 w_1 x_1 y_1 z_1 \cup \dots \cup \\ a_2 b_2 c_2 d_2 e_2 m_2 n_2 o_2 p_2 q_2 r_2 s_2 t_2 u_2 v_2 w_2 x_2 y_2 z_2 \quad (15)$$

As opposed to model 1, alternative model 2, introduced in Fig. 4, consists of only 32 subsystems. Model 2 applies no transfer switches, but it is also free of SPoFs. In model 2, the UPS subsystems  $v_i$  were replaced by  $v'_i$ . Owing to not using the transfer switches  $u_i$ , the UPS subsystems  $v'_i$  are now directly connected for supply from  $t_1$ . This difference is also visible from the definitions of  $v_i$  and  $v'_i$  in Fig. 2 and 3.

The success of model 2 depends on 12 SSPs:



**Fig. 4** Model 2 DCPS design Boolean circuit

$$S_{\text{Model 2}}(\mathbf{x}) = K_1 \cup K_2 \cup \dots \cup K_{12} \\ = a_1 b_1 c_1 d_1 m_1 n_1 p_1 q_1 r_1 s_1 t_1 v'_1 z_1 \cup \\ g_1 h_1 i_1 m_1 n_1 p_1 q_1 r_1 s_1 t_1 v'_1 z_1 \cup \\ g_2 h_2 i_2 m_2 n_2 p_2 q_2 r_2 s_2 t_2 v'_2 z_2 \cup \\ a_2 b_2 c_2 d_2 m_2 n_2 p_2 q_2 r_2 s_2 t_2 v'_2 z_2 \cup \\ a_1 b_1 c_1 d_1 m_1 n_1 p_1 q_1 r_1 s_1 g_2 h_2 i_2 m_2 t_2 v'_2 z_2 \cup \\ g_1 h_1 i_1 m_1 n_1 p_1 q_1 r_1 s_1 g_2 h_2 i_2 m_2 t_2 v'_2 z_2 \cup \\ a_1 b_1 c_1 d_1 m_1 n_1 p_1 q_1 r_1 s_1 a_2 b_2 c_2 d_2 m_2 t_2 v'_2 z_2 \cup \\ g_1 h_1 i_1 m_1 n_1 p_1 q_1 r_1 s_1 a_2 b_2 c_2 d_2 m_2 t_2 v'_2 z_2 \cup \\ g_2 h_2 i_2 m_2 n_2 p_2 q_2 r_2 s_2 a_1 b_1 c_1 d_1 m_1 t_1 v'_1 z_1 \cup \\ a_2 b_2 c_2 d_2 m_2 n_2 p_2 q_2 r_2 s_2 a_1 b_1 c_1 d_1 m_1 t_1 v'_1 z_1 \cup \\ g_2 h_2 i_2 m_2 n_2 p_2 q_2 r_2 s_2 g_1 h_1 i_1 m_1 t_1 v'_1 z_1 \cup \\ a_2 b_2 c_2 d_2 m_2 n_2 p_2 q_2 r_2 s_2 g_1 h_1 i_1 m_1 t_1 v'_1 z_1 \quad (16)$$

By applying the *MVI* algorithm of [19] to (16), 14 disjoint product terms of model 2 are obtained in *MVI* form. Term  $K_1$  becomes  $D_{1,1}$ , term  $K_4$  becomes  $D_{4,1} \vee D_{4,2}$  (see (17)). The sum of disjoint product terms of model 2 can now be used to calculate the reliability and availability of the DCPS. With the inherent availability  $A_i$  of (3) and the operational availability  $A_o$  of (4) from [1], two different availability metrics are applicable. The standard [1] explains at 8.6.3: 'A<sub>o</sub> would be the 'real world' – how the system really operates'. The 'resulting end-user availability based on site-caused downtime' of [2] may be seen as an equivalent to the operational availability  $A_o$ . For a Tier IV design, this requires by definition for the entire DCPS

$$A_o \text{ Tier IV} \geq 0.9999. \quad (18)$$

Thus, in this case there is a requested availability  $A_{o \text{ req}} = 0.9999$ . The reliability and availability data of Table 9 of the Appendix were applied to model 1 and model 2. The reliability and availability calculation results of models 1 and 2 are listed in Table 1. Both models are proven to meet the availability requirements (18) of a Tier IV design.

In a direct comparison of model 1 and model 2, the less complex model 2 offers a marginal higher inherent availability because of the significantly lower number of subsystems. Model 1, in turn, offers better reliability and operational availability. The results demonstrate that reliability and availability calculations alone do not offer sufficient criteria to thoroughly compare DCPS designs. This observation supports the need for more expressive metrics.

$$\begin{aligned}
DS_{\text{Model } 2}(\mathbf{x}) &= D_1 \cup D_2 \cup D_{3,1} \cup D_{3,2} \cup D_{4,1} \cup D_{4,2} \cup D_5 \\
&\cup D_6 \cup D_7 \cup D_8 \cup D_9 \cup D_{10} \cup D_{11} \cup D_{12} \\
&= b_1 c_1 d_1 m_1 n_1 p_1 q_1 r_1 s_1 t_1 v'_1 \bar{z}_1 \cup g_1 h_1 i_1 m_1 n_1 p_1 q_1 r_1 s_1 t_1 v'_1 \bar{z}_1 \overline{a_1 b_1 c_1 d_1} \\
&\cup g_2 h_2 i_2 m_2 n_2 p_2 q_2 r_2 s_2 t_2 v'_2 \bar{z}_2 \overline{m_1 n_1 p_1 q_1 r_1 s_1 t_1 v'_1 \bar{z}_1} \\
&\cup g_2 h_2 i_2 m_2 n_2 p_2 q_2 r_2 s_2 t_2 v'_2 \bar{z}_2 \overline{m_1 n_1 p_1 q_1 r_1 s_1 t_1 v'_1 \bar{z}_1} \overline{a_1 b_1 c_1 d_1} \overline{g_1 h_1 i_1} \\
&\cup a_2 b_2 c_2 d_2 m_2 n_2 p_2 q_2 r_2 s_2 t_2 v'_2 \bar{z}_2 \overline{m_1 n_1 p_1 q_1 r_1 s_1 t_1 v'_1 \bar{z}_1} \overline{g_2 h_2 i_2} \\
&\cup a_2 b_2 c_2 d_2 m_2 n_2 p_2 q_2 r_2 s_2 t_2 v'_2 \bar{z}_2 \overline{a_1 b_1 c_1 d_1} \overline{g_1 h_1 i_1} \overline{g_2 h_2 i_2} \\
&\cup a_1 b_1 c_1 d_1 m_1 n_1 p_1 q_1 r_1 s_1 g_2 h_2 i_2 m_2 t_2 v'_2 \bar{z}_2 \overline{t_1 v'_1 \bar{z}_1} \overline{n_2 p_2 q_2 r_2 s_2} \\
&\cup g_1 h_1 i_1 m_1 n_1 p_1 q_1 r_1 s_1 g_2 h_2 i_2 m_2 t_2 v'_2 \bar{z}_2 \overline{t_1 v'_1 \bar{z}_1} \overline{n_2 p_2 q_2 r_2 s_2} \overline{a_1 b_1 c_1 d_1} \\
&\cup a_1 b_1 c_1 d_1 m_1 n_1 p_1 q_1 r_1 s_1 a_2 b_2 c_2 d_2 m_2 t_2 v'_2 \bar{z}_2 \overline{t_1 v'_1 \bar{z}_1} \overline{n_2 p_2 q_2 r_2 s_2} \overline{g_2 h_2 i_2} \\
&\cup g_1 h_1 i_1 m_1 n_1 p_1 q_1 r_1 s_1 a_2 b_2 c_2 d_2 m_2 t_2 v'_2 \bar{z}_2 \overline{t_1 v'_1 \bar{z}_1} \overline{n_2 p_2 q_2 r_2 s_2} \overline{h_2 i_2 a_1 b_1 c_1 d_1} \\
&\cup g_2 h_2 i_2 m_2 n_2 p_2 q_2 r_2 s_2 a_1 b_1 c_1 d_1 m_1 t_1 v'_1 \bar{z}_1 \overline{n_1 p_1 q_1 r_1 s_1 t_2 v'_2 \bar{z}_2} \\
&\cup a_2 b_2 c_2 d_2 m_2 n_2 p_2 q_2 r_2 s_2 a_1 b_1 c_1 d_1 m_1 t_1 v'_1 \bar{z}_1 \overline{n_1 p_1 q_1 r_1 s_1 t_2 v'_2 \bar{z}_2} \overline{g_2 h_2 i_2} \\
&\cup g_2 h_2 i_2 m_2 n_2 p_2 q_2 r_2 s_2 g_1 h_1 i_1 m_1 t_1 v'_1 \bar{z}_1 \overline{n_1 p_1 q_1 r_1 s_1} \overline{t_2 v'_2 \bar{z}_2} \overline{a_1 b_1 c_1 d_1} \\
&\cup a_2 b_2 c_2 d_2 m_2 n_2 p_2 q_2 r_2 s_2 g_1 h_1 i_1 m_1 t_1 v'_1 \bar{z}_1 \overline{n_1 p_1 q_1 r_1 s_1 t_2 v'_2 \bar{z}_2} \overline{a_1 b_1 c_1 d_1} \overline{g_2 h_2 i_2}.
\end{aligned} \tag{17}$$

**Table 1** Reliability and availability analysis results of models 1 and 2

Model	$N$	$R$	$A_i$	$A_o$
1	56	0.944060844	0.999999871	0.999951180
2	32	0.922792721	0.999999875	0.999948819

## 5 Development of resilience analysis metrics

An essential feature of resilience evaluation is the characterisation of the ability of a system to support practical operation under various combinations of outages and to continue operation under outages for a minimum average duration. To reflect these characteristics, a set of resilience metrics is proposed to cover availability during outages.

The metrics of  $SPoF$  and  $DPoF$  discussed in Section 3 are suitable for identifying whether a DCPS can in principle continue to operate under contingencies and so support fault tolerance. The success function is used in the formulation of  $SPoF$  in (13) and of  $DPoF$  in (14) for quantitative analysis of the system success. The metrics  $|SPoF_m|$  and  $|DPoF_m|$  then give the number of  $SPoFs$ , respectively,  $DPoFs$  of the  $m$ th DCPS design. Lower values point to a better level of fault tolerance.

In the power system literature,  $SPoF$  and  $DPoF$  are affiliated with the issues of  $N - 1$  and  $N - 2$  security. These indicators do not quantify the potentially detrimental effects on system availability when one or two subsystems are out of service for maintenance or due to other causes. However, what is the impact on system availability when subsystem  $x_i$  fails? Which pairs of subsystems  $\{x_i, x_j\}$  can be taken out of service while keeping up data centre availability at a high level? Are the availability targets still met if switchgear  $m_i$  and chiller  $q_i$  are out for simultaneous maintenance? Such questions on maintaining practicable functionality under outages relate to the resilience issue in accordance with [12].

In analogy to  $SPoF$  and  $DPoF$ , it is proposed to define the metrics single point of reduced availability ( $SPoRA$ ) and double point of reduced availability ( $DPoRA$ ) in order to offer answers. The definition of  $SPoRA_m$  as a subset of the set  $X_m$  of all subsystems of the  $m$ th DCPS is formulated as follows:  $SPoRA_m$  encompasses all those subsystems  $x_{m_i}$  whose single failure  $x_{m_i} = 0$  results in  $A_o(S_m(\mathbf{x}_m)) < A_o \text{ Tier IV min}$

$$SPoRA_m = \left\{ x_{m_i} \in X_m \left| \left( A_o(S_m(\mathbf{x}_m)) < A_o \text{ Tier IV min} \right) \cap \left( \bar{x}_{m_i} \prod_{l=1, l \neq i}^N x_{m_l} = 1 \right) \right. \right\}. \tag{19}$$

**Table 2** Fault tolerance analysis results of models 1 and 2

Model	$ SPoF_m $ of $F_{k=1}$	$ DPoF_m $ of $F_{k=2}$	$ SPoRA_m $	$ DPoRA_m $
1	0 of 56	23 of 1540	18	856
2	0 of 32	31 of 496	14	448

Likewise, the two subsystems  $\{x_{m_i}, x_{m_j}\}$  belong to the set  $DPoRA_m$  if the double failure  $(x_{m_i} = 0) \cap (x_{m_j} = 0)$  results in  $A_o(S_m(\mathbf{x}_m)) < A_o \text{ Tier IV min}$  while all other subsystems are working:

$$DPoRA_m = \left\{ \{x_{m_i}, x_{m_j}\} \subset X_m \left| \left( A_o(S_m(\mathbf{x}_m)) < A_o \text{ Tier IV min} \right) \cap \left( \bar{x}_{m_i} \bar{x}_{m_j} \prod_{l=1, l \neq i, j}^N x_{m_l} = 1 \right) \right. \right\}. \tag{20}$$

The metrics  $|SPoRA_m|$  and  $|DPoRA_m|$  give the number of elements of the sets  $SPoRA_m$  and  $DPoRA_m$ , respectively. Lower values point to better availability during single and double failures. Better availability, in turn, implies a higher mean time of continued operation.

Table 2 compares the results of the proposed resilience analysis for model 1 and model 2. Both models are free of  $SPoFs$ , as shown in the second column of this table. As shown in the third column, model 1 has only 23  $DPoFs$  because of more inherent redundancies. Model 2 has 31  $DPoFs$  and therefore eight more compared with model 1.

The numbers of  $SPoRA$  and  $DPoRA$  are shown in the fourth and fifth column of Table 2. As opposed to the comparison above, model 2 has 14  $SPoRAs$  and 448  $DPoRAs$  while model 1 has 18  $SPoRAs$  and 856  $DPoRAs$ . The results confirm that more inherent redundancies, offered by a higher number of subsystems, do not necessarily result in a better resilience measured by availability during outages.

As shown in the comparison of model 1 and model 2, resilience analysis makes it possible to value different DCPS designs on additional criteria. The introduced metrics open the capability of improving DCPS designs with respect to availability, reliability, and resilience.

## 6 Application of resilience metrics to design

According to (11), the H-importance of a particular subsystem  $x_i$  is given by the total number of  $SSPs$  in which it appears, here referred to  $|SSP_{x_i}|$ . With knowledge of the Boolean circuit,  $|SSP_{x_i}|$  can be determined by counting. A subsystem with a higher  $|SSP_{x_i}|$  is called more H-important than a subsystem with a lower count. Table 3 shows this analysis for model 1.

Structural model simplification may be achieved through the elimination of subsystems with a small  $|SSP_{x_i}|$ . Consequently, all SSPs containing these subsystems are also eliminated. Based on the H-importance analysis in Table 3, one transformer feed  $d$  and one generator feed  $i$  are eliminated. As model 1 is symmetry, either  $d_2$  and  $i_2$  or  $d_1$  and  $i_1$  may be selected. Consequently, the transfer switches  $e_2$  and  $k_2$  or  $e_1$  and  $k_1$  are not required either. The result of the H-importance analysis of this first modification of model 1 is shown in the two leftmost columns of Table 4.

In the second modification, the feeds  $n_3$  and  $t_3$  are eliminated by example as they are only present in 40 SSPs. Consequently, the transfer switches  $o_1$  and  $u_1$  are also not required. The two rightmost columns of Table 4 show the H-importance analysis following this second modification.

The third modification of model 1 eliminates feed  $x_2$  that is only present in 16 SSPs. Consequently, the transfer switch  $y_2$  is not required either. The two leftmost columns of Table 5 show the H-importance analysis following that modification. It resulted in the DCPS shown in Fig. 5, now labelled as model 3. In model 3,  $v_1$  is replaced by  $v'_1$  because the feed of the uninterrupted power supply (UPS)  $v'_1$  is already realised by  $t_1$ . Details of the component level

of the UPS configurations  $v_1$  and  $v'_1$  are shown in Table 9 of the Appendix.

In the fourth modification, subsystems  $v'_1$ ,  $w_1$ , and  $x_1$  are eliminated, as seen by comparison of the entries of the first row of Table 5. Further elimination of  $t_1$  is not allowed because  $u_2$  would become a *SPoF* in that case. As a consequence of the elimination of UPS  $v'_1$ , an additional modification is required to meet the non-*SPoF* demand regarding short voltage interrupts. The non-redundant UPS  $v_2$  is replaced by a redundant UPS subsystem  $v_{1of2}$ , also listed in Table 9 of the Appendix. Note that  $M$ -of- $N$  redundant subsystems, as for instance  $v_{1of2}$ , are considered to be ' $(N - M)$ -failure tolerant' within the single and double failure simulations. The resulting DCPS model of this fourth modification is shown in Fig. 6, labelled model 4. With model 4, the guided reduction ends here because the examples are sufficient to show the value of resilience analysis in the design of DCPS.

In Table 6, the results of the reliability and availability analysis of Models 1 to 4 are compared. In summary of all models analysed here, model 4 is rated as the design with the highest reliability, inherent availability, and operational availability.

Table 7 shows the results of the fault tolerance and resilience analysis of Models 1–4 following the application of the resilience metrics of availability during outages. According to the second

**Table 3** H-importance analysis of model 1

$ SSP_{x_i} $	Subsystems of Model 1
72	$d_1, d_2, d_3, d_4, i_1, i_2, i_3, i_4$
80	$n_1, n_2, n_3, n_4, t_1, t_2, t_3, t_4, x_1, x_2, x_3, x_4$
128	$a_1, a_2, b_1, b_2, c_1, c_2, g_1, g_2, h_1, h_2$
144	$e_1, e_2, k_1, k_2$
160	$o_1, o_2, p_1, p_2, q_1, q_2, r_1, r_2, s_1, s_2, u_1, u_2, v_1, v_2, w_1, w_2, y_1, y_2, z_1, z_2$
288	$m_1, m_2$

**Table 4** H-importance analysis of first and second modification of model 1

$ SSP_{x_i} $	Subsystems after first modification	$ SSP_{x_i} $	Subsystems after second modification
40	$a_1, b_1, c_1, d_1, d_3, g_1, h_1, i_1, i_3, n_3, n_4, t_3, t_4$	16	$x_1, x_2$
44	$x_1, x_2, x_3, x_4$	24	$a_1, b_1, c_1, d_1, d_3, g_1, h_1, i_1, i_3$
48	$n_1, n_2, t_1, t_2$	32	$n_1, n_2, p_1, q_1, r_1, s_1, t_1, t_2, v_1, w_1$
72	$d_4, i_4$	34	$d_4, i_4, x_3, x_4$
80	$e_1, k_1$	36	$n_4, t_4$
88	$o_1, o_2, p_1, p_2, q_1, q_2, r_1, r_2, s_1, s_2, u_1, u_2, v_1, v_2, w_1, w_2, y_1, y_2, z_1, z_2$	48	$e_1, k_1$
96	$a_2, b_2, c_2, g_2, h_2$	50	$a_2, b_2, c_2, g_2, h_2, y_1, y_2, z_1, z_2$
144	$m_2$	68	$m_2, o_2, p_2, q_2, r_2, s_2, u_2, v_2, w_2$
160	$m_1$	96	$m_1$

**Table 5** H-importance analysis of third and fourth modification of model 1

$ SSP_{x_i} $	Subsystems of model 3	$ SSP_{x_i} $	Subsystems of model 4
16	$t_1, v'_1, w_1, x_1$	16	$t_1$
20	$a_1, b_1, c_1, d_1, d_3, g_1, h_1, i_1, i_3$	20	$a_1, b_1, c_1, d_1, d_3, g_1, h_1, i_1, i_3$
28	$n_1, n_2, n_4, p_1, q_1, r_1, s_1$	28	$n_1, n_2, n_4, p_1, q_1, r_1, s_1$
30	$d_4, i_4$	30	$d_4, i_4$
32	$t_2$	32	$t_2$
34	$x_3, x_4, z_2$	34	$x_3, x_4, z_2$
36	$t_4$	36	$t_4$
40	$e_1, k_1$	40	$e_1, k_1$
43	$a_2, b_2, c_2, g_2, h_2$	43	$a_2, b_2, c_2, g_2, h_2$
50	$y_1, z_1$	50	$y_1, z_1$
56	$o_2, p_2, q_2, r_2, s_2$	56	$o_2, p_2, q_2, r_2, s_2$
60	$m_2$	60	$m_2$
68	$u_2, v_2, w_2$	68	$u_2, v_{1of2}, w_2$
80	$m_1$	80	$m_1$

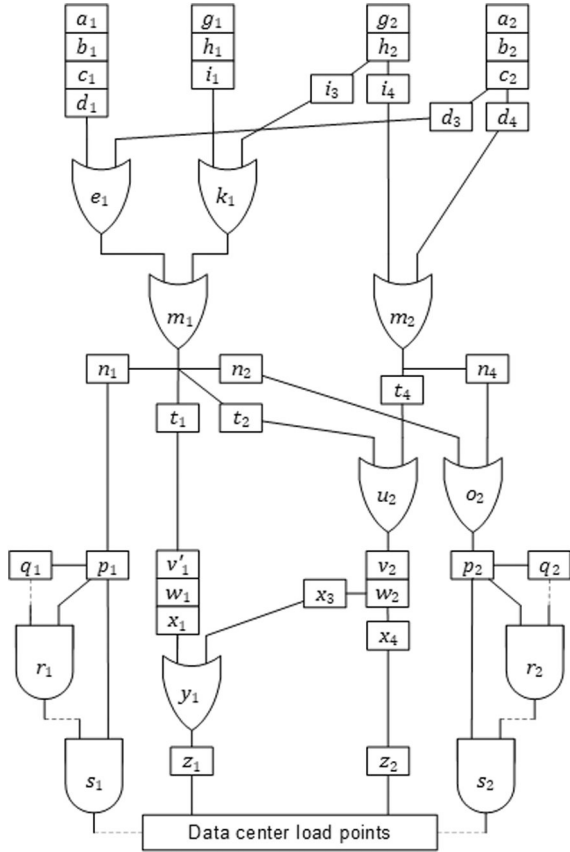


Fig. 5 Model 3 DCPS design Boolean circuit

Table 6 Reliability and availability analysis results summary

Model	N	R	$A_i$	$A_o$
1	56	0.944060844	0.999999871	0.999951180
2	32	0.922792721	0.999999875	0.999948819
3	46	0.936071703	0.999999868	0.999946691
4	43	0.950255588	0.999999999	0.999957825

column of this table, all analysed models here are free of  $SPoFs$ . Referring to the third column of this table, model 1 has the lowest  $DPoF$  number, which is 23. Model 4 is second best with 27  $DPoFs$ . Model 2 follows in the third position with 31  $DPoFs$ .

The fourth column of Table 7 shows model 2 as the design with the lowest  $SPoRA$  number, which is 14. Model 4 follows with 17  $SPoRAs$ . Comparing the  $DPoRA$  number in the last column of this table, a similar order can be seen. Model 2 has the lowest number of 448  $DPoRAs$ , and model 4 follows with 597  $DPoRAs$ .

To better value the results of Tables 6 and 7, Tables 8 shows a ranking of the integrated analysis of availability, reliability, fault tolerance, and resilience. The results of the inherent availabilities are not ranked because the values are equal up to the 6th decimal place. Rank 1 means the best result. The arithmetic average gives the sum of ranks divided by the number of ranked metrics, which is five in this table.

Table 8 shows that model 4 with 43 subsystems has the best reliability and operational availability, and the second-best fault tolerance and resilience compared with all other models considered in this work. Second best in terms of rank average are jointly the comprehensive design of model 1 and the lean design of model 2. Compared to model 1, model 4 counts 13 fewer subsystems, making it more life cycle cost-effective.

The analysis of Table 8 shows how the asymmetric DCPS design of model 4 can offer an appropriate trade-off between availability, reliability, fault tolerance, and resilience compared with all other models. This is true even though other models with a higher number of subsystems can offer higher inherent redundancies. The results are critically affected by the newly proposed resilience metrics of  $SPoRA$  and  $DPoRA$  for

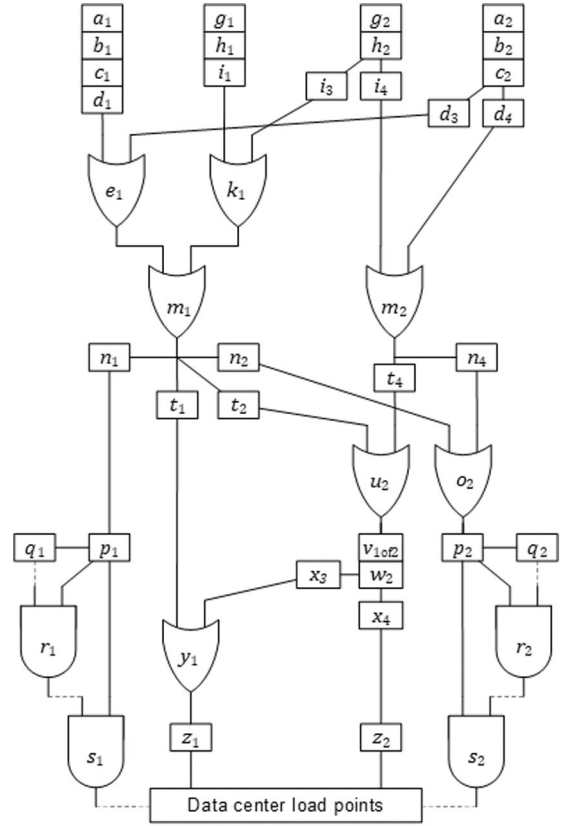


Fig. 6 Model 4 DCPS design Boolean circuit

Table 7 Fault tolerance and resilience analysis results summary

Model	$ SPoF_m $ of $F_{k=1}$	$ DPoF_m $ of $F_{k=2}$	$ SPoRA_m $	$ DPoRA_m $
1	0 of 56	23 of 1540	18	856
2	0 of 32	31 of 496	14	448
3	0 of 46	40 of 1035	21	767
4	0 of 43	27 of 903	17	597

quantification of availability during outages. Without those new metrics, models 1 and 2 would jointly appear as best ranked. Thanks to the novel resilience metrics, new insight was obtained. The discussed model reduction may be seen as an example of the DCPS design process taking into account resilience metrics.

## 7 Conclusions

Availability, reliability, fault tolerance, and resilience are key terms affiliated with the performance of data centres and their supplying power systems and environmental control. While availability, reliability, and fault tolerance are widely used in the analysis, indicators of resilience have been missing. This issue was addressed in this work. First and foremost,  $SPoRA$  and  $DPoRA$  were introduced as novel metrics of resilience. The metrics of  $SPoRA$  gives all those single subsystems that when being out-of-service cause the overall system availability to drop below the level targeted for the overall power system.  $DPoRA$  is the corresponding metric for subsystem pairs that cause the overall system availability to drop below the target level when being out of service. The novel resilience metrics thus quantify how many single and double failure events let the mean time of continued operation to fall below a service level agreement. It is clear that a prolonged operation even under outages can only be expected when reaching a desired level of availability. From these metrics, it is also possible for operators to assess the impact of maintenance schedules on the desired availability levels.

The research performed for this study shows that the proposed resilience metrics are not only useful for operators, they also offer a design aid in the development stage. To substantiate this claim, an

**Table 8** Availability, reliability, fault tolerance, and resilience analysis results

Model	Rank $R_m$	$A_{im} \geq 0.999999$	Rank $A_{om}$	$ SPoF_m  = 0$	Rank $ DPoF_m $	Rank $ SPoRA_m $	Rank $ DPoRA_m $	Rank average
1	2	✓	2	✓	1	3	4	2.4
2	4	✓	3	✓	3	1	1	2.4
3	3	✓	4	✓	4	4	3	3.6
4	1	✓	1	✓	2	2	2	1.6

original DCPS model with a significant number of redundancies was reduced using H-importance analysis. Finally, four alternative designs were obtained; two of the designs were of asymmetric topology. All designs fulfil the requirement of the Tier IV standard: they are free of  $SPoFs$  and so offer  $N - 1$  security, and they are comparable up to the fourth digit in terms of operational availability. When compared with the original model showing the most inherent redundancies, the reduced asymmetric designs can offer a compelling performance based on an integrated analysis of availability, reliability, fault tolerance, and resilience. As these reduced asymmetric designs have a lower number of subsystems, they are more cost-effective. Thanks to the resilience metrics, additional data are available to make informed decisions on complexity-resilience trade-offs.

In sum, the proposed quantification of resilience was shown to offer deeper insight into the assessment of power systems for data centres. It offers guidance in judging trade-offs in the integrated design of power distribution systems covering both electric power supply and environmental control of data centres. A further step in future work could include the transition from a guided reduction of design complexity as presented here to an optimised design based on optimisation criteria also involving resilience metrics.

## 8 Acknowledgments

Support by the German Research Foundation and the Open Access Publication Fund of TU Berlin is gratefully acknowledged.

## 9 References

- [1] IEEE Std 493: 'Design of reliable industrial and commercial power systems', Gold Book, IEEE Institute of Electrical and Electronics Engineers, 2007
- [2] Turner, W.P., Seader, J.H., Renaud, V., et al.: 'Tier classifications define site infrastructure performance' (Uptime Institute Inc., Seattle, 2008)
- [3] Müller, U., Strunz, K.: 'Integrated reliability analysis of data center infrastructures: a case study'. 3rd IEEE PES Innovative Smart Grid Technologies Europe, Berlin, Germany, 2012
- [4] Chowdhury, A.A., Koval, D.O.: 'Power distribution system reliability: practical methods and applications' (IEEE Institute of Electrical and Electronics Engineers, New Jersey, USA, 2009)
- [5] Jiang, K., Singh, C.: 'New models and concepts for power system reliability evaluation including protection system failures', *IEEE Trans. Power Syst.*, 2010, **26**, (4), pp. 1845–1855
- [6] Ziari, I., Ledwich, G., Ghosh, A., et al.: 'Optimal distribution network reinforcement considering load growth, line loss, and reliability', *IEEE Trans. Power Syst.*, 2013, **28**, (2), pp. 587–597
- [7] Al-Muhaini, M., Heydt, G.T.: 'A novel method for evaluating future power distribution system reliability', *IEEE Trans. Power Syst.*, 2013, **28**, (3), pp. 3018–3027
- [8] Benidris, M., Mitra, J.: 'Reliability and sensitivity analysis of composite power systems under emission constraints', *IEEE Trans. Power Syst.*, 2014, **29**, (1), pp. 404–412
- [9] Marmah, M., Maciel, P., Shah, A., et al.: 'Quantifying the sustainability impact of data center availability', *ACM SIGMETRICS Perform. Eval. Rev.*, 2010, **37**, (4), pp. 64–68
- [10] Arno, R., Friedl, A., Gross, P., et al.: 'Reliability of data centers by tier classification', *IEEE Trans. Ind. Appl.*, 2012, **48**, (2), pp. 777–783
- [11] Sankar, S., Gauthier, D., Gurumurthi, S.: 'Power availability provisioning in large data center'. ACM, Proc. 11th ACM Conf. on Computing Frontiers, Cagliari, Italy, 2014
- [12] Dagle, J.: 'Enhancing the resilience of the nation's electricity system' (The National Academies of Sciences, Engineering, Medicine, Washington, DC, 2018)
- [13] Chanda, S., Srivastava, A.K.: 'Defining and enabling resiliency of electric distribution systems with multiple microgrids', *IEEE Trans. Smart Grid*, 2016, **7**, (6), pp. 2859–2868
- [14] Bajpai, P., Chanda, S., Srivastava, A.K.: 'A novel metric to quantify and enable resilient distribution system using graph theory and choquet integral', *IEEE Trans. Smart Grid*, 2018, **9**, (4), pp. 2918–2929
- [15] IEC 60812: 'Analysis techniques for system reliability – procedure for failure mode and effects analysis (FMEA)', 2006

- [16] IEC 61025: 'Fault tree analysis (FTA)', 2006
- [17] IEC 61078: 'Reliability block diagrams', 2006
- [18] Abraham, J.A.: 'An improved algorithm for network reliability', *IEEE Trans. Rel.*, 1979, **28**, (1), pp. 58–61
- [19] Heidtmann, K.D.: 'Smaller sums of disjoint products by subproduct inversion', *IEEE Trans. Rel.*, 1989, **38**, (3), pp. 305–311
- [20] Beichelt, F., Spross, L.: 'An improved Abraham-method for generating disjoint sums', *IEEE Trans. Rel.*, 1987, **36**, (1), pp. 70–74
- [21] Locks, M.O.: 'A minimizing algorithm for Sum of disjoint products', *IEEE Trans. Rel.*, 1987, **36**, (4), pp. 445–453
- [22] Balan, A.O., Traldi, L.: 'Preprocessing MinPaths for sum of disjoint products', *IEEE Trans. Rel.*, 2003, **52**, (3), pp. 289–295
- [23] Birnbaum, Z.W.: 'On the Importance of different Components in a Multicomponent System'. Technical Report, University of Washington, 1968, 54
- [24] Hwang, F.K.: 'A hierarchy of importance indices', *IEEE Trans. Rel.*, 2005, **54**, (1), pp. 169–172
- [25] Zhu, X., Kuo, W.: 'Comments on 'A hierarchy of importance indices'', *IEEE Trans. Rel.*, 2008, **57**, (3), pp. 529–531
- [26] EN 50600-1: 'Information technology - data center facilities and infrastructures', 2019

## 9 Appendix

Source of all item numbers in Table 9 is [1], appendix Q. The failure rate and downtime per failure of 'electric utility power supplies to industrial plants', 'single circuit' is given in Table 3-1 of [1] with  $\lambda = 1.956/a$ ;  $MTTR = 1.32$  h;  $t = 1$  a. The downtime hours per year  $DHY$  [1] is defined as follows:

$$DHY = (1 - A_0) 8760 \text{ h/a}, \quad (21)$$

$$DHY = \lambda MTTR. \quad (22)$$

If no data for  $MTBM$  and  $MDT$  are available,  $A_0$  may be calculated by rearranging of (21) and replacing  $DHY$  by (22)

$$A_0 = 1 - \lambda MTTR / (8760 \text{ h/a}). \quad (23)$$

Application of (1), (3), and (23) gives the result of reliability, inherent availability, and operational availability of the utility supply single circuit

$$R_0 = e^{-\lambda t} = e^{-1.956/a * 1 \text{ a}} = 0.141422983, \quad (24)$$

$$A_i^0 = 1 / (1 + \lambda MTTR / (8760 \text{ h/a})) = 0.999705347, \quad (25)$$

$$A_o^0 = 1 - \lambda MTTR / (8760 \text{ h/a}) = 0.999705267. \quad (26)$$

The results are denoted by the triplet  $\{R_0, A_i^0, A_o^0\}$  in the row for subsystem  $a_i$ .

The reliability calculation of a subsystem in the special case of  $N$  identical, parallel components  $x$  of which  $M$  is required to guarantee the subsystem success, a so-called  $M$ -of- $N$  system, can be simplified [17]

$$R_{M\text{-of-}N} = \sum_{k=0}^{N-M} \binom{N}{k} R_x^{N-k} (1 - R_x)^k. \quad (27)$$

The inherent and operational availability calculation of an  $M$ -of- $N$  system is processed in analogy to (27).



**Table 9** Grouping of components into subsystems

Var.	Subsystem	Item No. [1] (Dimension)	$M$ -of- $N$	$R$	$A_i$	$A_o$
$a_i$	utility supply and distribution	$\{R^0, A_i^0, A_o^0\}$ , 46 (500 m), 29 (2 pcs.), 193, 79	1 of 1	0.134138037	0.999681264	0.998994527
$b_i$	transformer	79, 46 (50 m), 29 (2 pcs.), 208, 35 (50 m), 29 (2 pcs.), 69	1 of 1	0.991153156	0.999997159	0.999879920
$c_i$	transformer switchgear	191	1 of 1	0.990554799	0.999992102	0.999455601
$d_i$	feed from $c_i$ to $e_i$	69, 35 (50 m), 29 (2 pcs.)	1 of 1	0.997390087	0.999999793	0.999954195
$e_i$	transfer switch utility supply	183, 20 (50 m), 29 (2 pcs.), 69, 130	1 of 1	0.947721583	0.999991090	0.997928202
$g_i$	generator	98, 35 (50 m) 29 (2 pcs.) 185	1 of 1	0.882614902	0.999742254	0.997355304
$h_i$	generator switchgear	191	1 of 1	0.990554799	0.999992102	0.999455601
$i_i$	feed from $h_i$	69, 35 (50 m), 29 (2 pcs.)	1 of 1	0.997390087	0.999999793	0.999954195
$k_i$	transfer switch generator	183, 20 (50 m), 29 (2 pcs.), 69, 130	1 of 1	0.947721583	0.999991090	0.997928202
$m_i$	main switchgear	191	1 of 1	0.990554799	0.999992102	0.999455601
$n_i$	feed from $m_i$	69, 20 (20 m), 29 (2 pcs.)	1 of 1	0.997402675	0.999999829	0.999954239
$o_i$	transfer switch environmental control from $n_i$	183, 20 (20 m), 29 (2 pcs.), 185	1 of 1	0.967717971	0.999994045	0.999748157
$p_i$	switchgear environmental control	191	1 of 1	0.990554799	0.999992102	0.999455601
$q_i$	chiller units and feed from $p_i$	69, 20 (50 m), 29 (2 pcs.), 56, 129, 195, 177, 228 (4 pcs.), 235, 199, 163, 237, 229, 124, 237, 229, 163, 156, 176, 228 (4 pcs.)	2 of 3	0.924986820	0.999999814	0.999967038
$r_i$	chilled water piping, control panel and feed from $p_i$	67, 20 (50 m), 29 (2 pcs.), 129, 157, 228 (4 pcs.), 2	1 of 1	0.990233812	0.999998035	0.994760281
$s_i$	computer room air conditioning units and feed from $p_i$	67, 20 (50 m), 29 (2 pcs.), 155, 175, 228 (4 pcs.), 235, 199, 163, 237, 229, 82, 138, 12, 110, 129	4 of 5	0.957867596	0.999999879	0.999995252
$t_i$	feed from $m_i$	69, 20 (20 m), 29 (2 pcs.)	1 of 1	0.997402675	0.999999829	0.999954239
$u_i$	transfer switch, from $t_i$ , switchgear UPS	183, 20 (20 m), 29 (2 pcs.) 185, 191	1 of 1	0.958577680	0.999986147	0.999203895
$v_i$	feed from $u_i$ , UPS, feed to $w_i$	69, 20 (20 m), 29 (2 pcs.), 131, 10, 168, 9, 238, 203, 20 (20 m), 29 (2 pcs.), 69	1 of 1	0.924291516	0.999662672	0.998068330
$v'_i$	UPS,model 2: feed to $z_i$ model 3: feed to $w_i$	131, 10, 168, 9, 238, 203, 20 (20 m), 29 (2 pcs.), 69	1 of 1	0.926698454	0.999662843	0.998114005
$v_{1of2}$	feed from $u_{i2}$ , UPS, Model 4: feed to $w_2$	69, 20 (20 m), 29 (2 pcs.), 131, 10, 168, 9, 238, 203, 20 (20 m), 29 (2 pcs.), 69	1 of 2	0.994268225	0.999999886	0.999996269
$w_i$	switchgear output UPS	191	1 of 1	0.990554799	0.999992102	0.999455601
$x_i$	feed from $w_i$	69, 20 (20 m), 29 (2 pcs.)	1 of 1	0.997402675	0.999999829	0.999954239
$y_i$	transfer switch to $z_i$	183, 20 (20 m), 29 (2 pcs.), 185	1 of 1	0.967717971	0.999994045	0.999748157
$z_i$	feed to a data center load point	191, 67, 20 (20 m), 29 (2 pcs.)	1 of 1	0.989606864	0.999991895	0.999253742