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

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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
$a_i, \ldots, z_i$	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 mth 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 mth DCPS
$DS(\boldsymbol{x})$	disjoint sum of system success paths of $\boldsymbol{x}$
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 λ
$MTBM$	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 $t = 8760\,\mathrm{h}$
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 mth DCPS
$SPoRA_m$	set of x_{m_i} leading to a single point of reduced availability ($SPoRA$) of the mth DCPS
SSP_{x_i}	set of system success paths containing x_i
SVI	single variable inversion
$S(\boldsymbol{x})$	sum of system success paths of $\boldsymbol{x}$
t	time span of $1\,a = 365 \times 24\,\mathrm{h} = 8760\,\mathrm{h}$
X_m	set of x_{m_i} of the mth DCPS
$\lvert X \rvert$	number of elements of X, cardinality
$\bar{x}_i$	negation of Boolean variable x_i
$\boldsymbol{x}_m$	vector of x_{m_i} of the mth DCPS
x_{m_i}	Boolean variable giving the status of the ith subsystem of the mth DCPS
λ	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

$$R = \mathrm{e}^{-\lambda t}, \tag{1}$$

$$\lambda = 1/MTBF\,. \tag{2}$$

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

$$A_\mathrm{i} = MTBF/(MTBF + MTTR), \tag{3}$$

$$A_\mathrm{o} = MTBM/(MTBM + MDT)\,. \tag{4}$$

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

$$S_\mathrm{ser}(x_1, x_2) = x_1 \cap x_2\,. \tag{5}$$

Alternatively, it may be written as product x_1x_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

$$S_\mathrm{par}(x_1, x_2) = x_1 \cup x_2\,. \tag{6}$$

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

$$S_\mathrm{ex}(\boldsymbol{x}) = x_1\, x_2 \cup x_3\, x_4\, x_6 \cup x_5\,. \tag{7}$$

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

$$DS_\mathrm{ex}(\boldsymbol{x}) = x_1\, x_2 \cup \overline{x_1\, x_2}\, x_3\, x_4\, x_6 \cup \overline{x_1\, x_2}\; \overline{x_3\, x_4\, x_6}\, x_5\,. \tag{8}$$

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)

$$\begin{aligned} R_\mathrm{ex}(x_\mathrm{ex}) = {} & R_{x_1}R_{x_2} + \left(1 - R_{x_1}R_{x_2}\right) R_{x_3}R_{x_4}R_{x_6} \\ & + (1 - R_{x_1}R_{x_2})(1 - R_{x_3}R_{x_4}R_{x_6})R_{x_5}\,. \end{aligned} \tag{9}$$

$$\begin{aligned} A_\mathrm{ex} = {} & A_{x_1}A_{x_2} + \left(1 - A_{x_1}A_{x_2}\right) A_{x_3}A_{x_4}A_{x_6} \\ & + \left(1 - A_{x_1}A_{x_2}\right) \left(1 - A_{x_3}A_{x_4}A_{x_6}\right)A_{x_5}\,. \end{aligned} \tag{10}$$

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

$$\left|SSP_{x_i}\right| > \left|SSP_{x_j}\right|. \tag{11}$$

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]

$$F_k = \binom{N}{k}. \tag{12}$$

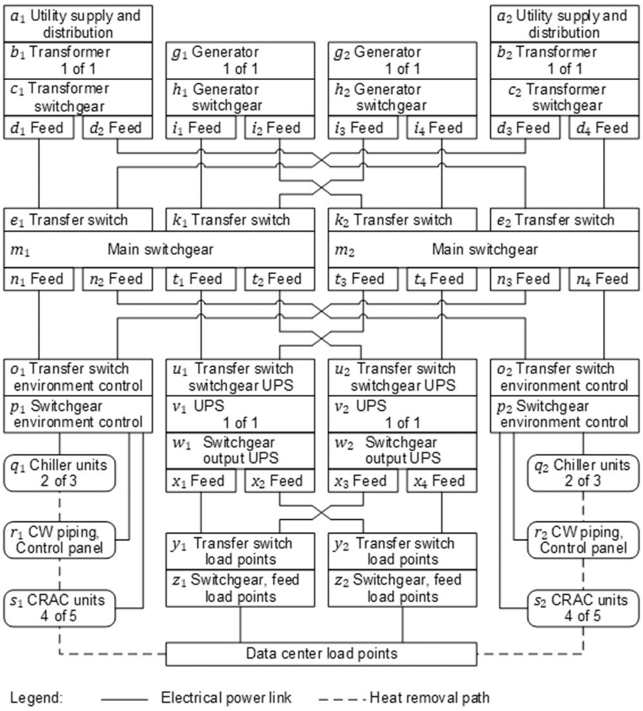

Fig. 1 *Model 1 Tier IV DCPS design including all relevant subsystems*

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 $SPoF_m$ as a subset of the set X_m of all subsystems of the *m*th DCPS is proposed. As such, $SPoF_m$ encompasses all those subsystems x_{m_i} whose single failure $x_{m_i} = 0$ causes overall system failure, i.e. results in $S_m(\boldsymbol{x}_m) = 0$

$$SPoF_m = \left\{ x_{m_i} \in X_m \middle| \begin{array}{l} (S_m(\boldsymbol{x}_m) = 0) \cap \\ \left(\bar{x}_{m_i} \prod_{l=1,\, l \neq i}^{N} x_{m_l} = 1\right) \end{array} \right\}. \tag{13}$$

Similarly, the two elements $\{x_{m_i}, x_{m_j}\}$ belong to the set $DPoF_m$ if the two affiliated subsystems mark a *DPoF*. Thus, if $\left(x_{m_i} = 0\right) \cap \left(x_{m_j} = 0\right)$ while all other subsystems are working, then $S_m(\boldsymbol{x}_m) = 0$ and the two failed components mark a *DPoF*

$$DPoF_m = \left\{ \{x_{m_i}, x_{m_j}\} \subset X_m \middle| \begin{array}{l} (S_m(\boldsymbol{x}_m) = 0) \cap \\ \left(\bar{x}_{m_i} \bar{x}_{m_j} \prod_{l=1,\, l \neq i,\, j}^{N} x_{m_l} = 1\right) \end{array} \right\}. \tag{14}$$

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 uninterrupted 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 enhances the number of redundant supply paths.

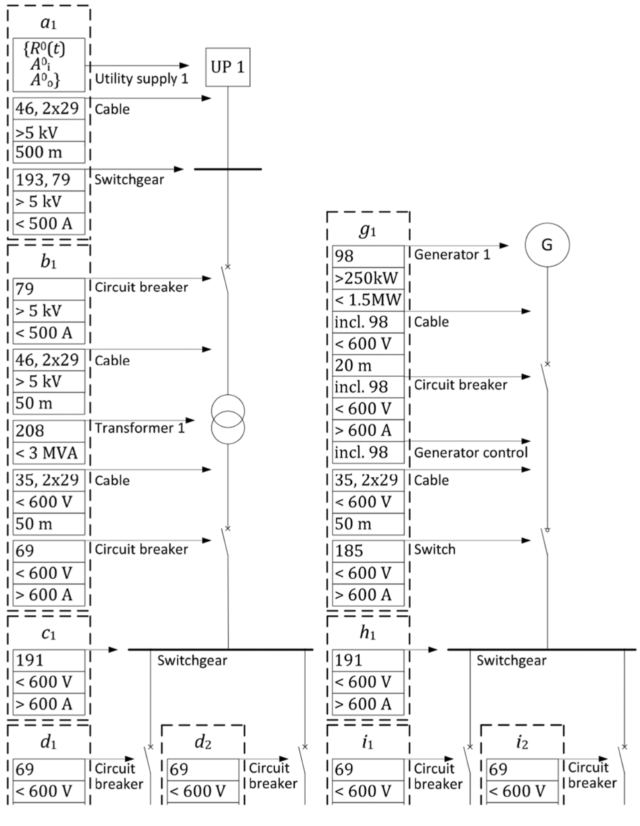

Fig. 2 *Model 1 Tier IV DCPS design detail with subsystems and components*

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

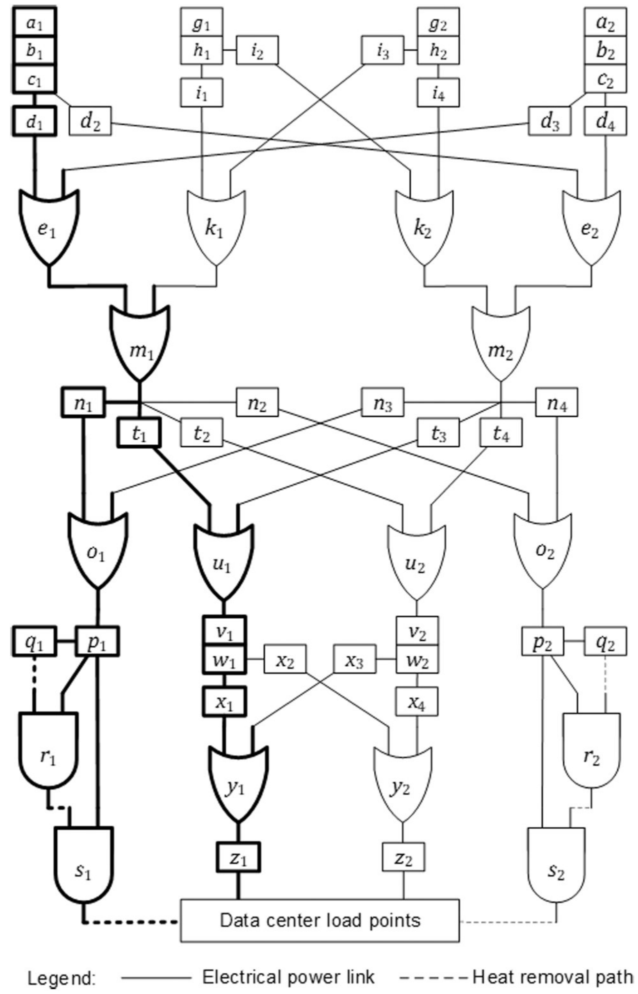

Fig. 3 *Model 1 DCPS design Boolean circuit*

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*

$$\begin{aligned} S_{\text{Model 1}}(\boldsymbol{x}) &= K_1 \cup K_2 \cup \ldots \cup K_{320} \\ &= a_1b_1c_1d_1e_1m_1n_1o_1p_1q_1r_1s_1t_1u_1v_1w_1x_1y_1z_1 \cup \ldots \cup \\ &\quad a_2b_2c_2d_4e_2m_2n_4o_2p_2q_2r_2s_2d_3e_1m_1t_2u_2v_2w_2x_4y_2z_2\,. \end{aligned} \tag{15}$$

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*:

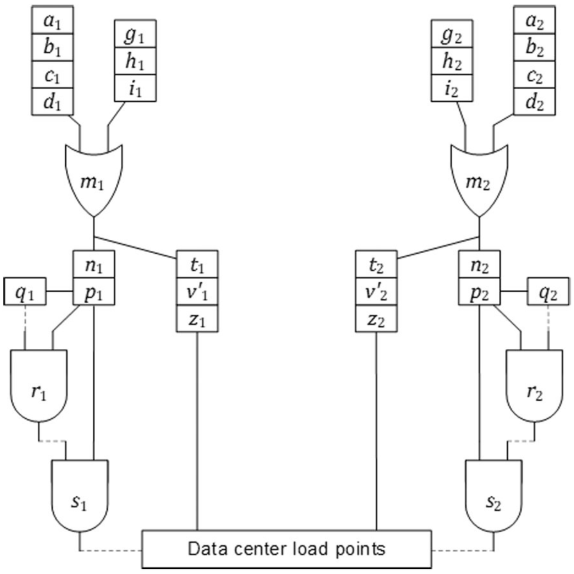

Fig. 4 *Model 2 DCPS design Boolean circuit*

$$\begin{aligned} S_{\text{Model 2}}(\boldsymbol{x}) &= K_1 \cup K_2 \cup \ldots \cup K_{12} \\ &= a_1b_1c_1d_1m_1n_1p_1q_1r_1s_1t_1v'_1z_1 \cup \\ &\quad g_1h_1i_1m_1n_1p_1q_1r_1s_1t_1v'_1z_1 \cup \\ &\quad g_2h_2i_2m_2n_2p_2q_2r_2s_2t_2v'_2z_2 \cup \\ &\quad a_2b_2c_2d_2m_2n_2p_2q_2r_2s_2t_2v'_2z_2 \cup \\ &\quad a_1b_1c_1d_1m_1n_1p_1q_1r_1s_1g_2h_2i_2m_2t_2v'_2z_2 \cup \\ &\quad g_1h_1i_1m_1n_1p_1q_1r_1s_1g_2h_2i_2m_2t_2v'_2z_2 \cup \\ &\quad a_1b_1c_1d_1m_1n_1p_1q_1r_1s_1a_2b_2c_2d_2m_2t_2v'_2z_2 \cup \\ &\quad g_1h_1i_1m_1n_1p_1q_1r_1s_1a_2b_2c_2d_2m_2t_2v'_2z_2 \cup \\ &\quad g_2h_2i_2m_2n_2p_2q_2r_2s_2a_1b_1c_1d_1m_1t_1v'_1z_1 \cup \\ &\quad a_2b_2c_2d_2m_2n_2p_2q_2r_2s_2a_1b_1c_1d_1m_1t_1v'_1z_1 \cup \\ &\quad g_2h_2i_2m_2n_2p_2q_2r_2s_2g_1h_1i_1m_1t_1v'_1z_1 \cup \\ &\quad a_2b_2c_2d_2m_2n_2p_2q_2r_2s_2g_1h_1i_1m_1t_1v'_1z_1\,. \end{aligned} \tag{16}$$

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, 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_o 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

$$A_{\text{o Tier IV}} \geq 0.9999. \tag{18}$$

Thus, in this case there is a requested availability $A_{\text{o req}}$ of $A_{\text{o req}} = 0.9999$. 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.

$$
\begin{aligned}
DS_{\text{Model }2}(\boldsymbol{x}) = {} & D_1 \cup D_2 \cup D_{3,1} \cup D_{3,2} \cup D_{4,1} \cup D_{4,2} \cup D_5 \\
& \cup D_6 \cup D_7 \cup D_8 \cup D_9 \cup D_{10} \cup D_{11} \cup D_{12} \\
& = b_1c_1d_1m_1n_1p_1q_1r_1s_1t_1v'_1z_1 \cup g_1h_1i_1m_1n_1p_1q_1r_1s_1t_1v'_1z_1\,\overline{a_1b_1c_1d_1} \\
& \cup g_2h_2i_2m_2n_2p_2q_2r_2s_2t_2v'_2z_2\,\overline{m_1n_1p_1q_1r_1s_1t_1v'_1z_1} \\
& \cup g_2h_2i_2m_2n_2p_2q_2r_2s_2t_2v'_2z_2m_1n_1p_1q_1r_1s_1t_1v'_1z_1\overline{a_1b_1c_1d_1}\,\overline{g_1h_1i_1} \\
& \cup a_2b_2c_2d_2m_2n_2p_2q_2r_2s_2t_2v'_2z_2\overline{m_1n_1p_1q_1r_1s_1t_1v'_1z_1}\,\overline{g_2h_2i_2} \\
& \cup a_2b_2c_2d_2m_2n_2p_2q_2r_2s_2t_2v'_2z_2\,\overline{a_1b_1c_1d_1}\,\overline{g_1h_1i_1}\,\overline{g_2h_2i_2} \\
& \cup a_1b_1c_1i_1m_1n_1p_1q_1r_1s_1g_2h_2i_2m_2t_2v'_2z_2\,\overline{t_1v'_1z_1}\,\overline{n_2p_2q_2r_2s_2} \\
& \cup g_1h_1i_1m_1n_1p_1q_1r_1s_1g_2h_2i_2m_2t_2v'_2z_2\,\overline{t_1v'_1z_1}\,\overline{n_2p_2q_2r_2s_2}\overline{a_1b_1c_1d_1} \\
& \cup a_1b_1c_1d_1m_1n_1p_1q_1r_1s_1a_2b_2c_2d_2m_2t_2v'_2z_2\overline{t_1v'_1z_1}\overline{n_2p_2q_2r_2s_2}\,\overline{g_2h_2i_2} \\
& \cup g_1h_1i_1m_1n_1p_1q_1r_1s_1a_2b_2c_2d_2m_2t_2v'_2z_2\,\overline{t_1v'_1z_1}\overline{n_2p_2q_2r_2s_2}\overline{g_2h_2i_2a_1b_1c_1d_1} \\
& \cup g_2h_2i_2m_2n_2p_2q_2r_2s_2a_1b_1c_1d_1m_1t_1v'_1z_1\,\overline{n_1p_1q_1r_1s_1}\overline{t_2v'_2z_2} \\
& \cup a_2b_2c_2d_2m_2n_2p_2q_2r_2s_2a_1b_1c_1d_1m_1t_1v'_1z_1\overline{n_1p_1q_1r_1s_1}\overline{t_2v'_2z_2}\,\overline{g_2h_2i_2} \\
& \cup g_2h_2i_2m_2n_2p_2q_2r_2s_2g_1h_1i_1m_1t_1v'_1z_1\overline{n_1p_1q_1r_1s_1}\,\overline{t_2v'_2z_2a_1b_1c_1d_1} \\
& \cup a_2b_2c_2d_2m_2n_2p_2q_2r_2s_2g_1h_1i_1m_1t_1v'_1z_1\overline{n_1p_1q_1r_1s_1}\overline{t_2v'_2z_2}\,\overline{a_1b_1c_1d_1g_2h_2i_2}\,.
\end{aligned}
\tag{17}
$$

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

Table 2 Fault tolerance analysis results of models 1 and 2

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

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_1 and chiller q_1 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 $A_\text{o}(S_m(\boldsymbol{x}_m)) < A_{\text{o Tier IV min}}$

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

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

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

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 $\left|SSP_{x_i}\right|$. With knowledge of the Boolean circuit, $\left|SSP_{x_i}\right|$ can be determined by counting. A subsystem with a higher $\left|SSP_{x_i}\right|$ 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 $v_{1\text{of}2}$, also listed in Table 9 of the Appendix. Note that *M*-of-*N* redundant subsystems, as for instance $v_{1\text{of}2}$, 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

$\lvert SSP_{x_i}\rvert$	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

$\lvert SSP_{x_i}\rvert$	Subsystems after first modification	$\lvert SSP_{x_i}\rvert$	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

$\lvert SSP_{x_i}\rvert$	Subsystems of model 3	$\lvert SSP_{x_i}\rvert$	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

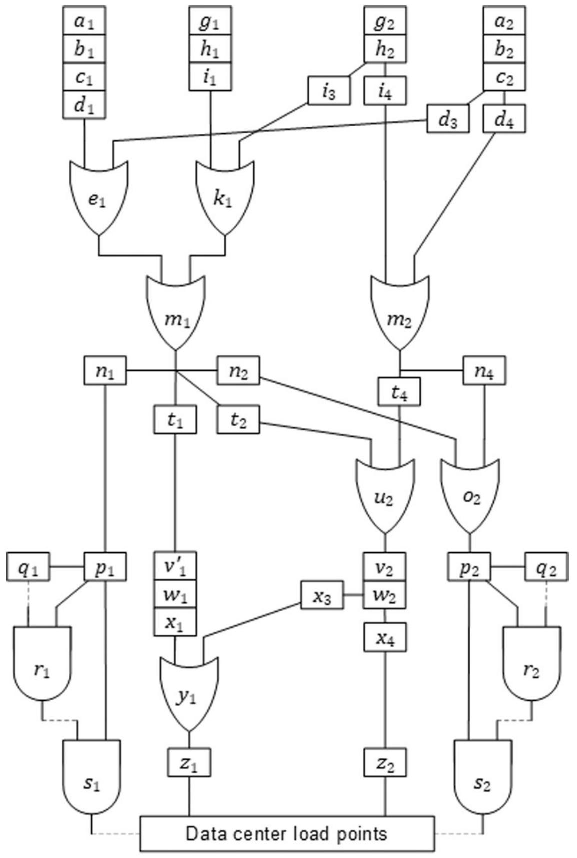

Fig. 5 *Model 3 DCPS design Boolean circuit*

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

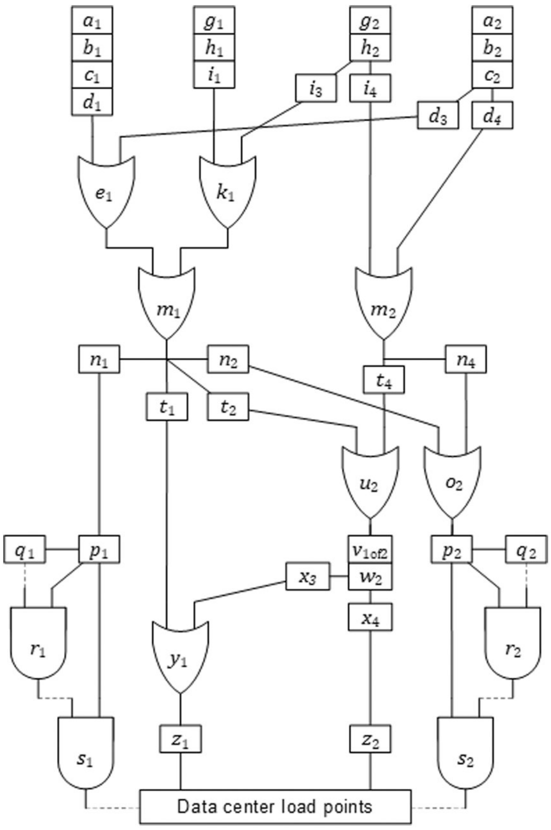

Fig. 6 *Model 4 DCPS design Boolean circuit*

Table 7 Fault tolerance and resilience analysis results summary

Model	$\lvert SPoF_m\rvert$ of $F_{k=1}$	$\lvert DPoF_m\rvert$ of $F_{k=2}$	$\lvert SPoRA_m\rvert$	$\lvert DPoRA_m\rvert$
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

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 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}	$\lvert SPoF_m \rvert = 0$	Rank $\lvert DPoF_m \rvert$	Rank $\lvert SPoRA_m \rvert$	Rank $\lvert DPoRA_m \rvert$	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.

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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 $\lambda = 1.956/\mathrm{a}$; $MTTR = 1.32\,\mathrm{h}$; $t = 1\,\mathrm{a}$. The downtime hours per year DHY [1] is defined as follows:

$$DHY = (1 - A_{\rm o})\,8760\,\mathrm{h/a}, \tag{21}$$

$$DHY = \lambda\, MTTR\,. \tag{22}$$

If no data for $MTBM$ and MDT are available, $A_{\rm o}$ may be calculated by rearranging of (21) and replacing DHY by (22)

$$A_{\rm o} = 1 - \lambda\, MTTR/(8760\,\mathrm{h/a})\,. \tag{23}$$

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

$$R_0 = \mathrm{e}^{-\lambda t} \; = \; \mathrm{e}^{-1.956/a\,*\,1\,a} = 0.141422983, \tag{24}$$

$$A_{\rm i}^0 = 1/(1 + \lambda\, MTTR/(8760\,\mathrm{h/a})) = 0.999705347, \tag{25}$$

$$A_{\rm o}^0 = 1 - \;\lambda\, MTTR/(8760\,\mathrm{h/a}) = 0.999705267. \tag{26}$$

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]

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

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	$\{R^0, A_\mathrm{i}^0, A_\mathrm{o}^0\}$, 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_1	131, 10, 168, 9, 238, 203, 20 (20 m), 29 (2 pcs.), 69	1 of 1	0.926698454	0.999662843	0.998114005
$v_{1\mathrm{of}2}$	feed from u_2, 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