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Dependability Evaluation of Data Center Power Infrastructures Considering Substation Switching Operations

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Abstract: Electrical power systems (EPS) are systems that include energy generation, transmission and distribution. One of the most important components of EPS corresponds to the electrical substation, which is utilized to control, modify, distribute and direct the electricity flow. The quality level of these systems is regulated by using Service Level Agreements (SLAs) which specify, for instance, maximum downtime per year. Penalties may apply if the quality level is not satisfied. On the other hand, fault tolerance techniques employ redundant equipment to increase the availability level of general systems, and the use of spare devices may incur additional infrastructure costs. Thus, to meet the SLA requirements, electrical system designers need to evaluate the dependability level of these systems. It is important to state that the use of software tools is suitable for dependability metrics evaluation, since it is not trivial to simulate or analyze complex systems. Modeling techniques with a strong mathematical background such as Stochastic Petri Nets (SPN) and Reliability Block Diagrams (RBD) can be adopted to assess dependability in power systems. This work proposes a methodology, which includes a hierarchical heterogeneous modeling technique that considers the advantages of both stochastic Petri nets (SPN) and reliability block diagrams (RBD) to evaluate data center power infrastructures considering substation switching operations. A case study is provided to demonstrates the feasibility of the proposed methodology.

Keywords: Data center, power system, dependability, substation switching operations, reliability block diagrams, stochastic Petri nets.

1. INTRODUCTION

Cloud computing has driven the new wave of Internet-based applications by providing computing as a service [1]. Nowadays, usual business applications (e.g., spreadsheets, text editors) are provided as cloud computing services, in the sense that they are often accessed using a web browser, and, their respective software/data reside on remote servers. Such paradigm is attractive for a number of reasons: (i) it frees users from installing, configuring and updating the software applications; (ii) it offers advantages in terms of mobility as well as collaboration; and (iii) updates and bug fixes can be deployed in minutes, simultaneously affecting all users around the globe [2]. Over the last years, there has been a significant concern about the availability of services in general. For instance, in companies that heavily depend on the Internet for their operations, service outages can be very expensive, easily running into millions of dollars per hour [3]. In context of data centers, there has been an increase in the number and size of data centers, mainly because of the adoption of cloud computing as the platform for new web-based applications. Moreover, the big success of social networking and e-commerce websites has resulted in a high demand for Internet infrastructures. For prominent cloud system providers, the quality level is regulated by adopting a Service Level Agreement (SLA), which specifies, for instance, the maximum downtime per year. Penalties may be applied if the defined quality level is not satisfied. To meet the requirements of high availability for such services, substantial investments must be applied, including new equipment to provide redundancy [3]. An essential component of the data center infrastructure corresponds to the power system which is responsible for providing energy to

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cooling and Information Technology (IT) devices. In order to improve the power system availability level, a widely adopted approach consists of the utilization of redundant subsystems in the electrical substation that can be used through switch operations [4]. However, it is not easy to decide which component setup should be adopted to apply redundancy or what the most appropriate configuration is to be utilized.

In order to cope with these issues, modeling techniques with a strong mathematical foundation, such as Stochastic Petri Nets (SPN) [5] and Reliability Block Diagrams (RBD) [6] can be adopted to assess dependability in such infrastructures. Thus, an analysis of dependability is necessary to determine high reliable data center architectures, also taking into account the power system configuration. This work presents a methodology to support the dependability evaluation of data center infrastructures considering switching operations in electrical substations. The proposed approach adopts a hierarchical heterogeneous modelling that considers the advantages of both SPN and RBD to evaluate dependability metrics. To demonstrate the feasibility of the proposed methodology a case study is provided considering a data center with different electrical substation configurations. The paper is organized as follows. Section 2 highlights the related works. Section 3 describes data center power systems. The methodology and the proposed models are presented in Section 4. Afterwards, Section 5 presents an applied example of the methodology. Then, Section 6 presents a case study. Finally, Section 7 concludes this paper and introduces future works.

2. RELATED WORKS

Uninterrupted energy supply is of utmost importance to provide highly available computing services. Currently, many works have been developed in order to enhance the quality of power systems. An approach to analyze reliability include time-dependent effects in a model of the high-voltage network in Switzerland is proposed in [7]. The assessment technique utilizes classical modeling combined with object-oriented hybrid approaches, describing transmission lines, generators and network operators. In [8], the authors present a methodology for modeling operation sequences of protections in systems electrical power. Stochastic Petri nets were used to analyze the interaction of the main and redundant power subsystems. The proposed approach presents a quantitative method to assess the impact of failures in the system, taking into account possible existence of unnecessary operations and hidden faults in the power system.

Callou et al. [9] suggested a methodology which includes a hybrid modeling technique that considers the advantages of SPNs and RBDs to evaluate power systems in data centers taking into account different maintenance policies. In addition, a cost model is proposed based on the system operation and SLA contracts. In [10], the author evaluates diverse substation configurations showing how different power systems can be compared. It shows that the reliability of a substation is highly affected by the switching schemes. Other works, such as [11] and [12], evaluate substation systems considering operating conditions and failure types on system reliability. Different from previous work, this paper presents a methodology to perform dependability evaluation in data center power systems taking into account switching operations on its electrical substations. The proposed method combines the advantages of SPN and RBD models and utilizes the most suitable modelling technique depending on the subsystem complexity.

3. DATA CENTER POWER SYSTEMS

This work considers a generic data center system, which essentially consists of the following subsystems, in addition to the building facility: (i) IT infrastructure; (ii) cooling infrastructure; and (iii) power infrastructure. The power infrastructure [13] is responsible for providing uninterrupted, conditioned power at the correct voltage and frequency to the IT equipment hosted in data center racks. From the electric utility, the power typically, goes through step down transformers, transfer switches, Uninterruptible Power Supplies (UPS), Power Distribution Units (PDU), and finally to rack power strips. A substation is one of the most important components of the power system and can be defined as a set of devices responsible for transmitting, switching or modifying the electrical energy flow. In this work, four substation configurations are considered and shown as follows. It is important to stress that the proposed methodology is generic enough to evaluate other substation configurations. Additionally, this paper focuses on the study of substation switching operations and other safety components (e.g., current transformer, transformer for measurement of electric voltage) are not considered so far. In the configurations considered in this work, the system needs an operational bus, a input circuit breaker and a output circuit breaker to be considered available. The reader is referred to [14] for further details about electrical substation arrangements.

Single Bus. This configuration is the simplest and has the lowest cost [15]. It consists of a unique bus, two circuit breakers (CB), four disconnect switches and a transformer (Figure 1). As this arrangement provides no redundancy, the failure of any component causes the substation shutdown. In addition to this, maintenance tasks are just possible if the entire substation is de-energized.

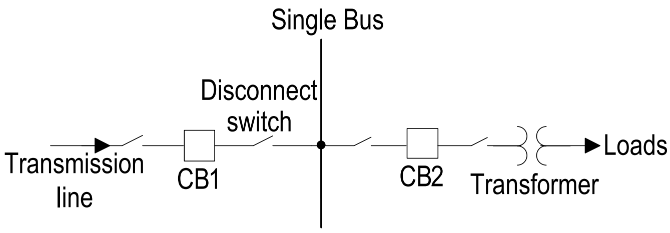

Figure 1: Single Bus Configuration

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Main and Transfer Bus. The main and transfer bus configuration is shown in Figure 2. In normal operation conditions, the energy flows from the transmission line passing through input circuit breaker (CB1), main bus (MB), output circuit breaker (CB2) and transformer. In this arrangement, there is an additional CB, namely Transfer CB, that is utilized whenever a maintenance in CB1 or CB2 is required. If CB1 fails, it is disconnected and Bypass SW is switched on. Then, the energy flow passes through transfer bus (TB), Transfer CB and MB to the rest of the circuit. The analogous process happens whenever CB2 fails. It is important to state that TB is adopted only to perform maintenance tasks on CBs (CB1 or CB2). Therefore, if MB fails the substation becomes unavailable.

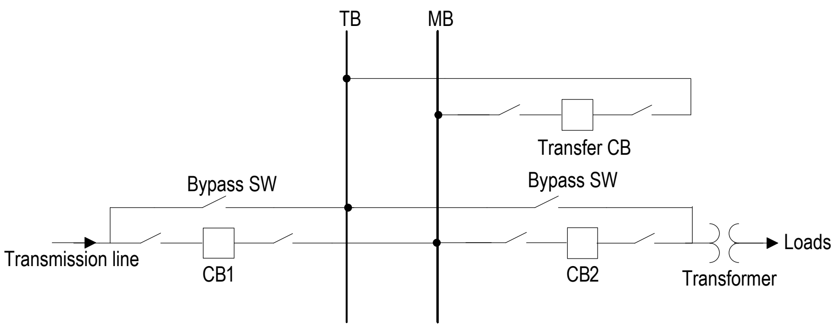

Figure 2: Main and Transfer Bus Configuration.

Double Bus and Four Switches. Figure 3 presents the double bus and four switches arrangement. Different from previous architecture, by using the selection bus switches (Sel BUS), both buses (BUS1 and BUS2) can be used as the main bus. Accordingly, whenever one of the buses fails, the other one can be utilized avoiding an overall system failure. In standard operation, energy flows from the transmission line passing through input circuit breaker (CB1), BUS1 or BUS2, output circuit breaker (CB2) and transformer. Similarly to main and transfer bus arrangement, this configuration also provides redundancy to CBs (CB1 or CB2). Whenever CB1 or CB2 fails, BUS1 is used main bus, BUS2 as transfer bus, the respective Bypass SW is switched on and Coupler CB substitutes the failed CB.

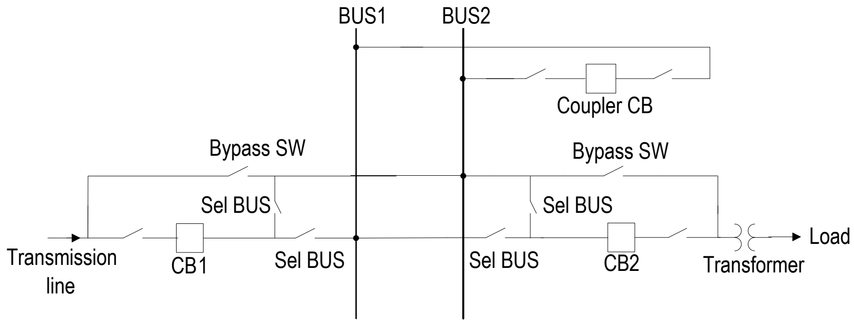

Figure 3: Double Bus and Four Switches Configuration.

Double Bus and Five Switches. The presented configuration (c.f. Figure 4) is similar to the previous arrangement, adding a switch on the input and output bus circuits. The additional switch enables more flexibility to select which bar will be used as main and transfer bus in case of failure in CB1 or CB2.

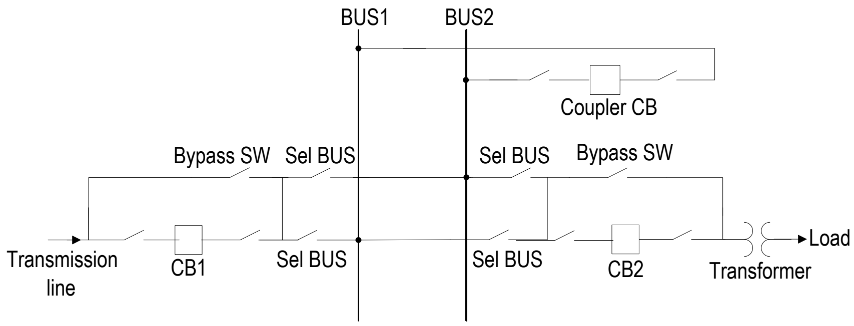

Figure 4: Double Bus and Five Switches

4. METHODOLGY

This section presents the adopted hierarchical modeling to evaluate system dependability. The proposed approach (Figure 5) adopts a heterogeneous modeling strategy, which combines combinatorial and state-based models for estimating dependability metrics. For lack of space the reader is referred to other publications for an introduction to dependability concepts as well as SPN and RBD basic definitions [16, 5]. The methodology's first step concerns understanding the conceived system, its components and their interactions, as well as the definition of dependability metrics. This step also breaks the whole system into smaller subsystems, which are considered to mitigate the complexity of evaluating the final system model. Next, the subsystems are combined in a high level (e.g., RBD) model containing all subsystems. After that, for each subsystem it is necessary to choose the most suitable modeling technique, such as SPN or RBD (to mention only the models adopted in this work). Next, models are created for each subsystem. Afterwards, the subsystem models are evaluated, and the results are adopted to compose the final dependability model. Such a model is then adopted to obtain the metrics of interest, which may or may not meet design requirements. Once satisfying the requirements, the process is finished; otherwise, adjustments on the architectures should be performed in order to increase, for instance, the availability of the system.

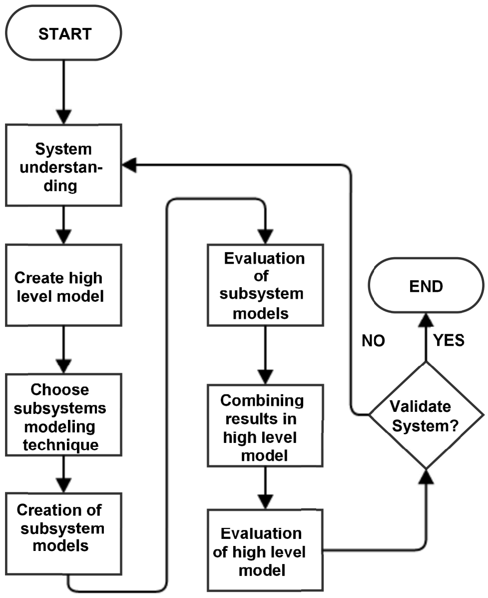

Figure 5: Methodology

5. METHODOLOGY'S APPLIED EXAMPLE

This section presents an applied example for demonstrating the methodology utilization. For this purpose, we adopted a data center power system with 200 racks detailed as follows.

5.1. System understanding

The adopted data center power infrastructure is depicted in Figure 6. From the substation, the power goes through uninterruptible power supplies (UPS), power distribution units (composed of a step down transformer and one subpanel), junction boxes (each with 10 output terminals), and, finally, to rack PDUs (rack power distribution units). It is important to emphasise that each data center IT device (enclosure) receives energy from two independent power sources. The reader should assume a *rack PDU* as a special power strip (Figure 7), which considers a circuit breaker attached to 2 output terminals (electrical sockets). Additionally, this power infrastructure provides energy to 200 IT racks. Although Figure 7 is similar to a RBD model, it shows the power components that are required to provide energy to it devices.

It is worth stating that a rack is composed of 4 enclosures (Figure 7), in which every enclosure is fed by output terminals from two different rack PDUs. The reader should assume an enclosure as a set of IT equipment. Moreover, an enclosure fails if the two connected terminals are unavailable, and an IT rack has been considered inaccessible if one of its enclosures is at the failure state. Whenever one rack is failed, the whole system stays in a failure state until a repair activity (maintenance) is performed.

5.2. Create power system high level model and choose subsystems models

The power system high level model is presented in Figure 8. The model presents the substation switching components (SubsScheme), substation transformer (SubsTransf), UPS, data center transformer (DCTransf), subpanel input (SubpanelInput) and the RacksSet, which represents the junction boxes

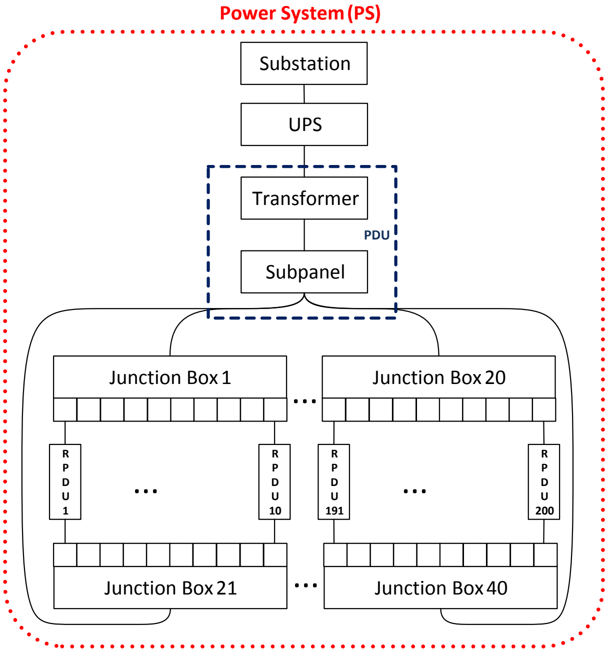

Figure 6: Power Infrastructure with 200 Racks

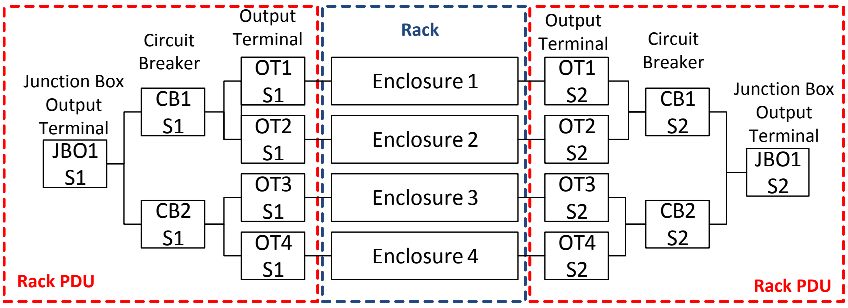

Figure 7: IT Rack Infrastructure

and the rack PDUs presented in Figure 6. For this data center power infrastructure, most of the subsystems were represented utilizing RBD models. For this example, separated submodels were created only for SubsScheme and RackSet as the other components presented in Figure 8 can be modeled using simple RBD blocks. SPN modeling was adopted only to represent SubsScheme (Figure 8) in some configurations that present complex interactions between components (e.g., main and transfer bus).

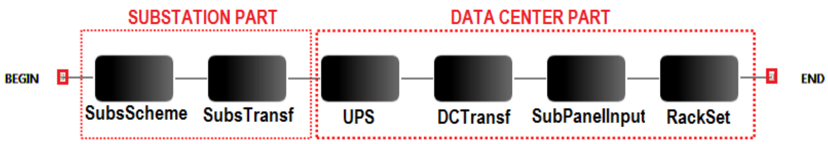

Figure 8: Power Infrastructure with 200 Racks

5.3. Creation of submodels: SubsScheme

This section provides details about the electrical substation models adopted in this work. Henceforth, the following operators are adopted for assessing dependability metrics: $P\{exp\}$ estimates the probability of the inner expression (*exp*); and #*p* denotes the number of tokens in place *p*. Additionally, *AND*, *OR* and *NOT* corresponds respectively to logical conjunction, disjunction and complement.

SPN block: generic component. The generic component (e.g., MB in Figure 10) is adopted to represent components that have no redundancy and might be in two states, either functioning or failed. In order to compute its availability, mean time to failure (*MTTF*) and mean time to repair (*MTTR*) are the only parameters needed for computing its availability. Places *X_ON* and *X_OFF* are the model component's activity and inactivity states, respectively. Label "X" is instantiated according to the component name, for instance, *MB_ON* and *MB_OFF* (Figure 10). A component is operational only if the number of tokens in place *X_ON* is greater than 0.

RBD Model: single bus. Due to its simplicity, the single bus configuration (Section 3) is represented by a simple RBD model (Figure 9). The components represented in the model are: four disconnect switches (DSW1 to DSW4), two circuit breakers (CB1 and CB2) and a bus. The RBD model is arranged in a series configuration and if any component fails the entire system stops working.

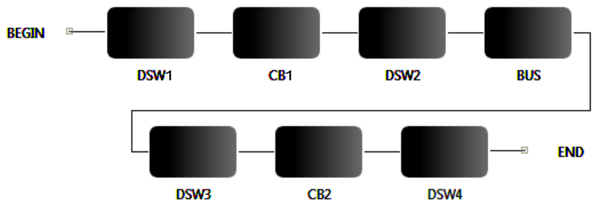

Figure 9: RBD Model: Single Bus configuration

SPN Model: main and transfer bus. As the main and transfer bus configuration presents complex interactions between components, it is easier to represent the arrangement by using an SPN model (Figure 10). This model utilizes six generic SPN components for representing the arrangement (see Figure 2). CB1 and CB2 symbolize the circuit breakers, MB models the main bus. The bypass switches for CB1 and CB2 are represented as BYP1 and BYP2, respectively. TBSys describes the whole subsystem containing transfer bus and transfer CB. The transition SWT1 models the CB1 failure detection and the activation of transfer bus. Whenever CB1 fails, SWT1 is fired and TBSys is utilized while the maintenance in CB1 is performed. Once the circuit breaker is recovered, T1 is fired and the substation returns to normal operation. SPR1 is adopted to represent the utilization of transfer bus subsystem as a backup device. If SPR1 contains no tokens, it means that TBSys is being used. Otherwise (#SPR1 = 1), TBSys is free and any CB can use the subsystem as a spare to perform maintenance activities. The analogous behavior is represented considering the CB2 failure. In order to evaluate its availability, we adopt the following expression P{(#CB1_ON=1 OR (#BYP1_ON=1 AND #TBSys_ON=1)) AND (#MB_ON=1) AND (#CB2_ON=1 OR (#BYP2_ON=1 AND #TBSys_ON=1))}. In this expression, we compute the probability of having the main bus and two circuit breakers working (using the redundancy mechanisms or not).

SPN Model: double bus and four switches. The double bus and four switches configuration is depicted in Figure 11. There are five generic components: two for representing the circuit breakers (CB1 and CB2), two for modeling the bypass switches (BYP1 and BYP2) and a component that symbolizes the coupler circuit breaker (COUPCB). The relation between the buses is represented in BUS1 and BUS2 part of Figure 11.

BUS1Sys and BUS2Sys are adopted to model the bus subsystem of BUS1 and BUS2. Each subsystem represents the bus itself and the two switches associated with each bus (Sel BUS). In this model, a few

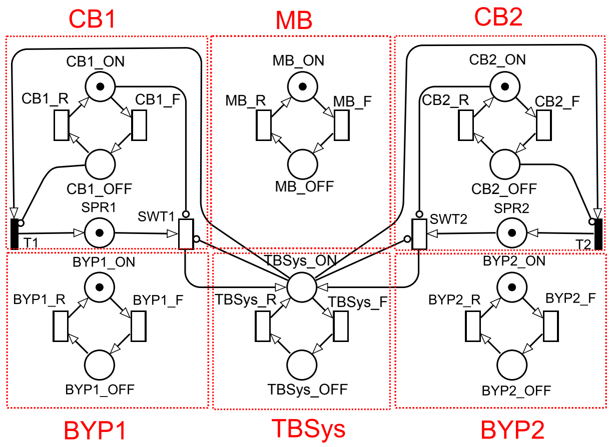

Figure 10: SPN Model: main and transfer bus configuration

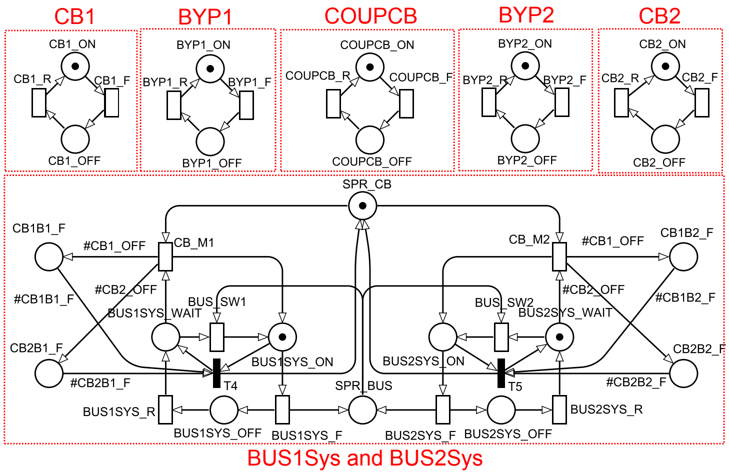

Figure 11: SPN Model: double bus and four switches configuration

assumptions have been considered. Firstly, if no CB has failed, only one bus can be used at a time. Both buses must be operational to perform maintenance tasks in a CB. BUS1Sys and BUS1Sys have the same properties. Finally, just one CB can be repaired at a time. Considering BUS1Sys, places BUS1SYS_ON, BUS1SYS_OFF and BUS1SYS_WAIT represent the states energized, failed and ready to be used. The transitions BUS1SYS_F, BUS1SYS_R and BUS_SW1 represent the failure, repair and activation tasks related to BUS1Sys. When BUS1Sys fails, SPR_BUS receives a token and if the other bus system is ready to be used it is activated. After the maintenance task of BUS1Sys, it becomes ready to be used again. BUS2Sys has the same behavior considering the analogous places and transitions. In this model, SPR_CB is used to mark the utilization of a bus system as a backup for a broken CB. If SPR_CB has no tokens, it is not possible to use a spare bus system to perform maintenance activities in CBs. The utilization of BUS1Sys as a backup for performing corrective maintenance in one CB is represented using places CB1B1_F and CB2B1_F and transitions CB_M1 and T4. If BUS1Sys is free (#BUS1SYS_WAIT=1) and a CB is failed (#CB1_ON=0 or #CB2_ON=0), CB_M1 will fire and CB1B1_F or CB2B1_F will receive a token depending where the failure happened. If CB1 have failed, CB1B1_F will receive a token. Otherwise, CB2B1_F will obtain a new token. Once the failed circuit breaker is repaired, T4 fires and return the token to SPR_CB. The same process happens to BUS2Sys. In order to evaluate its availability, we adopt the expression P{((#CB1_ON=1)OR(#BYP2_ON=1 AND #COUPCB_ON=1 AND #BUS1SYS_ON=1 AND #BUS2SYS_ON=1)) AND(#BUS1SYS_ON=1 OR #BUS2SYS_ON=1)

AND ((#CB2_ON=1)OR(#BYP1_ON=1 AND #COUPCB_ON=1 AND #BUS1SYS_ON=1 AND #BUS2SYS_ON=1))}. This metric is similar to the previous availability expression, however in this case it is possible to use both buses as main bus. The guard transitions adopted in this model are presented in Table 1. The transitions represent the conditions to activate the circuit breakers redundancies and to return to normal operation.

Table 1: Guard Expressions for double bus and four switches model.

Transition	Condition	Description
CB_M1 and CB_M2	(#CB1_ON=0)OR(#CB2_ON=0) AND(#BUS2SYS_ON=0)	Failure of CB1 or CB2
T4 and T5	(#BUS2SYS_ON=1 AND #BUS1SYS_ON=1) AND((#CB1B2_F=1 AND #CB1_ON=1) OR(#CB2B2_F=1 AND #CB2_ON=1))	CB1 or CB2 recovery

SPN Model: double bus five switches. This configuration is similar to the previous one, but with an additional switch for the input and output bus circuits (Figure 4). In this arrangement, the extra switch is adopted to select which bus system will act as main and transfer bus in case of CB maintenance. However, in terms of dependability evaluation, it is necessary to have two operational bus systems to perform a CB maintenance. Then, the SPN model utilized to represent the double for five switches is the same as the previous one (Figure 11). The only difference is related to the MTTF and MTTR of the CB that will consider one less switch.

5.4. Creation of submodels: RackSet Submodel

In order to simplify the RacksSet representation, it is evaluated by using a separated model (Figure 12). As stated before, the data center is available if all enclosures are operational. Then, RackSet is modeled as a series composition of all enclosures. In order to consider a enclosure available, it must receive energy from one of its power outlets (Figure 7). As some components provide energy for multiple output terminal, RackSet is modelled using a RBD with repeated components. For instance, JBO1_S1 (Figure 7) provides energy to four enclosures, then it is represented four times in the RBD model (enclosures 1 to 4).

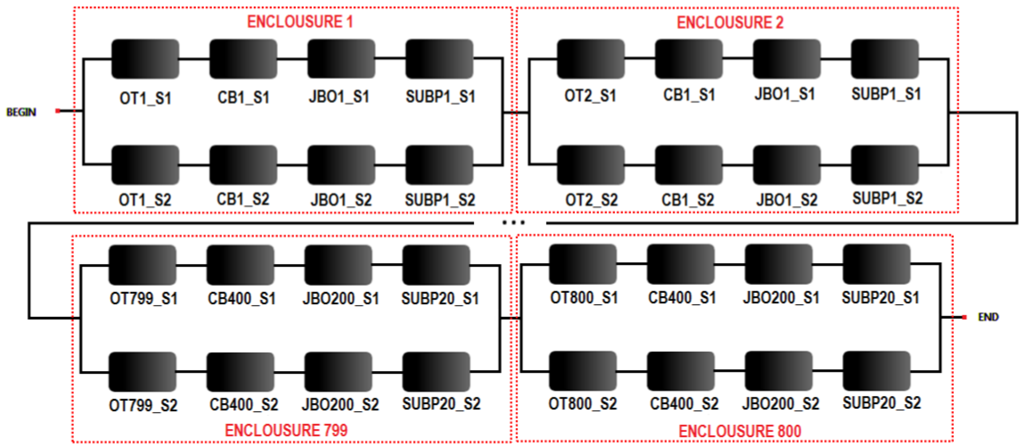

Figure 12: RacksSet Submodel

The algorithm for RBD generation considering this particular power system is shown in Figure 13. The algorithm parameters are: n_{enc} which represents the number of enclosures; e_{cb} , e_{jbOut} and e_{subOut} that respectively denotes the number of enclosures per circuit breaker, junction box output, and subpanel output. Some internal variables are created in line 3 to update the index of the created blocks considering each enclosure. c_i is adopted for updating the circuit breaker index, j_i for junction box output and s_i for subpanel output. In line 4, a series block (E_{set}) is created to represent the series block of all enclosures.

```
01 generateModel(n_enc, e_cb, e_jbOut, e_subOut) {
02   c_i = 0; j_i = 0; s_i = 0;
03   E_set = createSeriesBlock();
04   for(o_i = 0;o_i < n_enc;o_i++){
05     P_s1 = createSeriesBlock();
06     P_s1.addSeries(OT(o_i, s1), CB(c_i, s1),
07                 JBO(j_i, s1), SUBP(s_i, s1))
08     P_s2 = createSeriesBlock();
09     P_s2.addSeries(OT(o_i, s2), CB(c_i, s2),
10                 JBO(j_i, s2), SUBP(s_i, s2))
11     E_p = createParallelBlock();
12     E_p.addParallel(P_s1, P_s2)
13     if(o_i mod e_cb == 0) c_i++;
14     if(o_i mod e_jbOut == 0) j_i++;
15     if(o_i mod e_subOut == 0) s_i++;
16     E_set.addSeries(E_p);}
17   return createRBD(E_set);
   }
```

Figure 13: RBDGeneration

In lines 6 to 8, a series block (P_{s1}) is created to represent the components that must be working to provide energy to the given enclosure taking into account one of its power supplies (side 1). For instance, the components OT1_S1, CB1_S1, JBO1_S1 and SUBP1_S1 are created in these lines considering Enclosure 1 (Figure 12). The analogous steps are performed in lines 9 to 11 for the other enclosure's power supply (P_{s2}). In lines 12 and 13, a parallel block (E_p) is created to consider the two energy paths of the enclosure (P_{s1} and (P_{s2})). The indexes created in line 3 are updated in lines 15 to 17 taking into account the number of enclosures that each element provides energy. Then, the parallel block is added to E_{set} in line 18. Finally, the result model is returned in line 20. In this case study (Figure 12), the algorithm was executed with parameters n_{enc} = 800, e_{cb} = 2, e_{jbOut} = 4, e_{subOut} = 40 and the result model is created to Mercury Tool [17].

5.5. Evaluation and combination of submodels

Mercury-ASTRO [17] and TimeNET [18] tools have been used to perform the evaluation of models considered in this work. Afterwards, depedendability results for each submodels were considered in the high-level model. Finally, the high level model could be evaluated using the RBD series equation [17] to estimate the overall dependability metrics.

6. CASE STUDY

In order to demonstrating the feasibility of the proposed methodology, a case study is presented using the infrastructure presented in Section 5. It is important to stress that the dependability parameters of the basic equipment have been adopted based on [19, 20]. The results of the model are presented in Figure 14. The evaluation takes into account diverse substation arrangements and switching times to assess the impact of the substation type on the overall data center availability. The switching times considered were 0, 0.5, 5, 15 and 30 minutes.

The results are presented in terms of number of nines, which is calculated by expression $nines =$

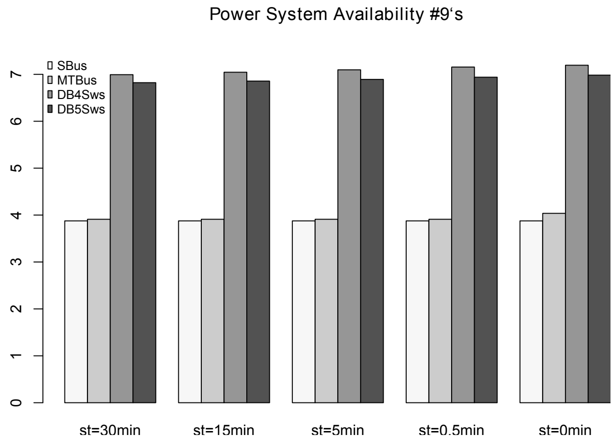

Figure 14: Results of data center evaluation taking into account the substation configuration.

$-log[1-A]$ (A corresponds to availability). SBus represents a data center with substation in a single bus configuration, MTBus with main and transfer bus, DB4Sws and DB5Sws considering double bus four and five switches configurations. In this graph, it is possible to observe that the availability improvement when comparing SBus and MTBus is not significant. However, the double bus configurations present a higher number of nines when compared to SBus. It is also possible to observe that, considering this particular case study, the switching time is not as significant as the configuration type. Finally, although DB5Sws presents a more flexible configuration, the availability of DB4Sws presents a higher availability level as it presents one less switch.

7. CONCLUSION

This work presented models for dependability evaluation of data centers considering switching operations in their power system substation. The proposed technique allows the impact assessment of substation configuration and switching time and considers the advantages of RBD and SPN models for performing the evaluation. Additionally, a case study is provided considering a set of substation configurations for demonstrating the feasibility of the proposed work. The results demonstrated the influence of switching times and substation configuration on data center dependability metrics. As future research, we intend to evaluate costs and environmental impacts considering the proposed infrastructure. Additionally, a software tool will be created to enable non-specialized users to adopt this approach.

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