Reducing Data Center Power Losses through UPS Serial Consolidation

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***Abstract*—Reducing data center (DC) power consumption is one of green Information and Communication Technology (ICT) challenges, which can be realised through improvement of DC energy-efficiency. To accomplish this improvement, each component of DC including those of power supply system such as uninterruptible power supplies (UPSs), has to operate at its maximum power efficiency. Since the broadly accepted concept based on server consolidation approach demonstrates significant DC power saving at the level of server racks, the contribution of constantly active UPSs to the overall DC power inefficiency become non-negligible. It is shown that a possible technique for reducing UPS power inefficiency in DCs can be based on dynamic merging of UPS activity state with server consolidation, where the neighbouring connectivity between one UPSs and two neighbour server racks have been established on the backup power supply paths. In this paper enhancement of neighbouring connectivity concept based on a new approach for establishing connectivity between UPSs and server racks on DC backup power delivery paths are introduced. More specifically, the algorithm which enables serial connectivity of active UPSs with DC server racks during merged UPS and server consolidation process is proposed. Through the extensive simulations of real DC having a large number of rack servers and UPSs, the proposed concept based on serial connectivity has been tested. Results show that proposed concept improves the energy-efficiency of DC when compared with neighbouring connectivity approach or existing legacy DC power supply approach lacking any UPS consolidation. Proposed concept can be used in practice as a solution which can reduce the impact of power consumption inefficiency of UPSs as main DC power supply elements.**

***Index Terms*—Data Center, Power Delivery Path, Management, Virtual machine, Server, UPS, Energy-efficiency, Consolidation**

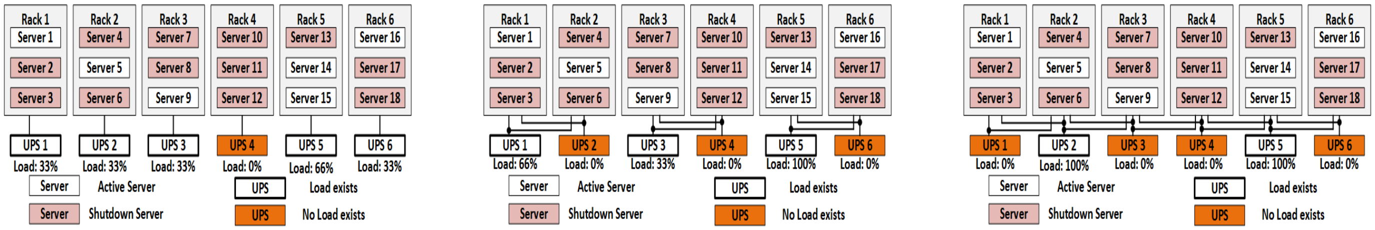
I. INTRODUCTION

Data centers (DCs) have been reported as major power consumers in Information and Communications Technology (ICT) sector, and a continuation of power usage improvement in the DC is mandatory at all facade of the DC. For example, as we reported in previous work [1], consolidation of electricity power delivery paths of rack servers in the DC through dynamic adaptation of Uninterruptible Power Supplies (UPSs) activity according to server consolidation outcomes, can bring significant power efficacy improvements. This is vital not only for reducing the power consumption of the DC but it could reduce the danger of having DC power surges or power outages due to UPSs power overloading and solutions for minimization of UPS overloading have been proposed in [2]. Considering the recent reports on the impacts of ICT power consumption, 14% of the consumed power of the ICT is being consumed by DCs [3]. Although leading IT companies such as Google, Microsoft, Amazon, and others have built very efficient DCs, 95% of DCs worldwide are count to small, medium and corporate DCs that are realised in legacy standard design [4] with low energy-efficiency. The recent report from Uptime Institute shows that a major part of the data processing and computing on those DCs are conducted on-premises [5]. This motivates DC owners to search for power usage efficiency (PUE) improvements in all parts of DC and especially in power supply segment where UPSs are one of the most important components.

Although server consolidation approach has been discussed in the literature as approach which can reduce the power consumption of the DCs [6], [7], power supply appliances in the DC such as UPS have been affected by this approach [1]. According to [1], [8], UPSs have efficiency characteristics correlated with the electricity load. If the applied UPS load is higher (close to the maximum capacity defined as the rated UPS power of the manufacturer), the UPS efficiency will be higher, and vice versa [8]. However, even at the lowest UPS load, UPS consumes non-negligible power consumption which can range up to 50% of the overall UPS power consumption [8]. Due to such power consumption inefficiency, the contribution of the UPSs to the overall DC power consumption with legacy power supply architectures (Fig. 1a) can be significant.

For that reason, we have proposed in a previous work [1] the server consolidation technique which includes UPS consolidation, where we suggested a modification on the electricity delivery paths. The technique was based on connecting neighbor server racks to each UPS appliance located near those racks, where each neighboring rack will have the electric power fed from the local UPS and a standby fed from the UPS which is the first neighbor to that rack. This solution has demonstrated improvements in both, overall power reduction and PUE of the DC [1]. However, we argue in this paper that even further improvements in DC energy-efficiency can be accomplished if more sophisticated UPS connectivity architectures on DC backup power supply paths will be devised.

Hence, instead of the previously proposed neighbouring connectivity, we propose in this paper serial connectivity of



(a) Legacy server consolidation architecture

(b) Neighboring (NB) consolidation architecture

(c) Proposed serial consolidation architecture

Fig. 1: Different architecture of UPS appliances at the power delivery path in DC

TABLE I: Parameters notation and correspoding values

Parameter	Description	Value
$P_{IT,u}$ (W)	Instantaneous power consumption of server rack supplied over *u-th* UPS	79.921 - 892.41
$UPS_{Rate,u}$	The maximum power output of UPS u	1 kW
L_s,u,v (%)	Instantaneous utilization of *s-th* server	0-100
P_s, u (W)	Instantaneous power consumption of the *s-th* server supplied over $u-th$ UPS	79.921 - 89.241
N_s	Number of Servers	20,000
N_v /N_s, v	Overall no. of: VMs/VMs per server	80,000/4
N_r /N_u	Overall no. of: racks/UPSs in DC	2,000

DC server racks with UPSs. The serial connectivity ensures that each rack in the DC has primary feeding of electricity from the local UPS appliance and two standby feds from surrounding UPSs (e.g. preceding and subsequent UPSs in case of server rack surrounded from both sides with other racks). This enables single UPS to have the possibility of feeding the electricity to the three racks instead of at most the two racks, as proposed in the previous work based on neighbouring UPS connectivity [1]. However, these new modifications of the UPS and server racks connectivity paths require enhancement of the control flow in order to accommodate the new possibility of having three racks connected to a single UPS appliance. In this paper, the enhanced control flow of UPS scheduling is realized according to the proposed algorithm and tested through extensive simulations. Results of simulations were analyzed in order to compare proposed serial UPS connectivity solution with existing solutions in terms of DC energy-efficiency improvements.

The rest of the paper is organized as follows: in Section 2, the discussion related to the UPSs connectivity in DC is performed. Section 3 presents the proposed control algorithm used for establishing serial connectivity among UPSs and DC server racks. The description of the evaluation test-bed and analysis related to the obtained simulation results is given in Section 4. Some concluding remarks are given in Section 5.

II. UPS CONSOLIDATION ARCHITECTURES

Since UPS appliance has an efficiency curve that is inversely proportional to the supplying load [8], the control of the UPSs load and consequently its power consumption becomes important in DC operation and management. With the recent novel approach called server consolidation, the power consumption of DC is reduced by offloading the computing service among servers according to variations in computing load. The server consolidation in DCs is based on dynamic shutting down of some underutilized servers and transferring load of this shut down servers to servers which remain active (Fig. 1a). Reducing the power consumption and saving energy of the DC through dynamic consolidation of the number of active servers in the DC, mostly end up with UPS appliances which are under loaded or even not loaded at all (Fig. 1a), and those UPS appliances are operating inefficiently in the DC power delivery paths [1], [8]. Hence, the side effect of server consolidation is that constantly active UPSs in DCs with legacy power supply architectures increase the overall DC power consumption and reduce DC energy-efficiency.

In order to reduce presented problem of UPS energy inefficiency, we suggested in [1] a UPS neighbouring connectivity between two adjacent racks, where a single UPS feeds with electricity it own server rack and one neighbouring server rack (Fig. 1b). Hence, each rack is connected to a pair of UPS appliances for possible UPS consolidations. Whenever the load of the two racks does not exceed the UPS power rated capacity, only one UPS can be used for ensuring redundant power supply of active servers in the racks, while other neighboring UPS can be switched off (Fig. 1b). This approach called neighbouring (NB) consolidation architecture is illustrated in Fig. 1b, where the power delivery paths in DC are modified to connect neighbouring UPS appliances to each adjacent racks in a redundant connection. With the proposed NB consolidation approach, the aim is to consolidate the number of UPS appliances in DC by switching off (whenever possible) one of the adjacent UPS appliances. This approach has demonstrated PUE improvements at the DC level [1], however, we argued in this paper that even higher PUE can be achieved if other UPS connectivity schemes will be considered.

For that reason, the so-called serial consolidation architecture of UPS appliances is proposed (Fig. 1c). In this approach, each server rack in the DC will be connected with three UPSs for possible UPS consolidation, as illustrated in Fig. 1c. More specifically, each server rack will be connected with the local UPS, the preceding and subsequent UPSs of those server racks, which act as local UPSs to direct neighboring (left and right) server racks Fig. 1c. It is reasonable to expect that this approach based on dynamic on/off switching of UPSs in such serial power supply architecture (Fig. 1c) can additionally improve PUE of DC.

Algorithm 1 UPS Serial Consolidation

```
1:  $u = 1$
2:  while $u \le N_u$ do
3:    if $u + 2 \le N_u$ then
4:      if $P_{IT,u} + P_{IT,u+1} + P_{IT,u+2} \le UPS_{Rate,u+1}$ then
5:        Action: Off Load to UPS $u + 1$ and shutdown UPSs $u\&u + 2$
6:        $u = u + 3$
7:      else
8:        if $u + 3 \le N_u$ then
9:          if $UPS_{Rate,u+1} \le P_{IT,u} + P_{IT,u+1} + P_{IT,u+2}$ and $P_{IT,u+1} + P_{IT,u+2} + P_{IT,u+3} \le UPS_{Rate,u+2}$ then
10:           Action: Keep UPS $u$ on, $offloadtoUPSu + 2$ and shutdown UPSs $u + 1\&u + 3$
11:           $u = u + 4$
12:         else
13:           if $P_{IT,u} + P_{IT,u+1} \le UPS_{Rate,u+1} and UPS_{Rate,u+1} \le P_{IT,u} + P_{IT,u+1} + P_{IT,u+2}$ then
14:             Action: Off Load to UPS $u + 1$ and shutdown UPS $u$
15:             $u = u + 2$
16:           end if
17:         end if
18:       else
19:         if $u + 1 \le N_u$ then
20:           if $P_{IT,u} + P_{IT,u+1} \le UPS_{Rate,u+1}$ then
21:             Action: Off Load to UPS $u + 1$ and shutdown UPS $u$
22:             $u = u + 2$
23:           else
24:             $u = u + 1$
25:           end if
26:         else
27:           EXIT WHILE LOOP
28:         end if
29:       end if
30:     end if
31:     while $u \le N_u$ do
32:       if $P_{IT,u} \le UPS_{Rate,u}$ and $UPS_{Rate,u+1} \le P_{IT,u} + P_{IT,u+1}$ and $UPS_{Rate,u+1} \le P_{IT,u} + P_{IT,u+1} + P_{IT,u+2}$ then
33:         Action: No Offload
34:         $u = u + 1$
35:       end if
36:     else
37:       EXIT WHILE LOOP
38:     end if
39:   end if
40: end while
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III. CONTROL ALGORITHM

In this section, the control algorithm for implementation of novel concept based on serial connectivity between server racks and UPSs is presented. In Table I, the parameters and corresponding descriptions used in the paper are listed.

The pseudo-code of the proposed control algorithm is presented in Algorithm 1. The algorithm starts with u, pointing on the UPS appliance under check (Fig. 2a), and its value at the beginning of the control algorithm is equal to u=1 (line 1). Since the control algorithm considers architecture with three UPSs per one rack (Fig. 1c, Figs. 2), the first phase of the control algorithm checks the power supply availability of the first three UPSs (i.e. u, u+1, and u+2) for the first three racks (lines 2-6). The Algorithm 1 checks if there are in total minimally three UPSs or not (line 2), or does $u + 2$ is equal or exceeds the total number N_u of available UPSs in the DC (line 3). In the case of positive outcome, the summation of the three server racks instantaneous power consumption ($P_{IT,u}$, $P_{IT,u+1}$, $P_{IT,u+2}$) is compared with the rated power capacity of the one UPS appliance ($UPS_{Rate,u+1}$) (line 4). For simplicity, it is assumed that the rated power capacities of all UPSs are the same (Table I). If the results of the comparison show lower server racks power demand than rated UPS power capacity ($UPS_{Rate,u+1}$), two UPSs (u and $u + 2$) initially supplying preceding and subsequent server racks of the $u + 1$ server rack will be shut down (line 5) and three server racks will be fed by only one $(u + 1)$ UPS (Fig. 2a). The algorithm then moves serially the pointer (Fig. 2a) for UPS check three positions onward on position $(u + 3)$.

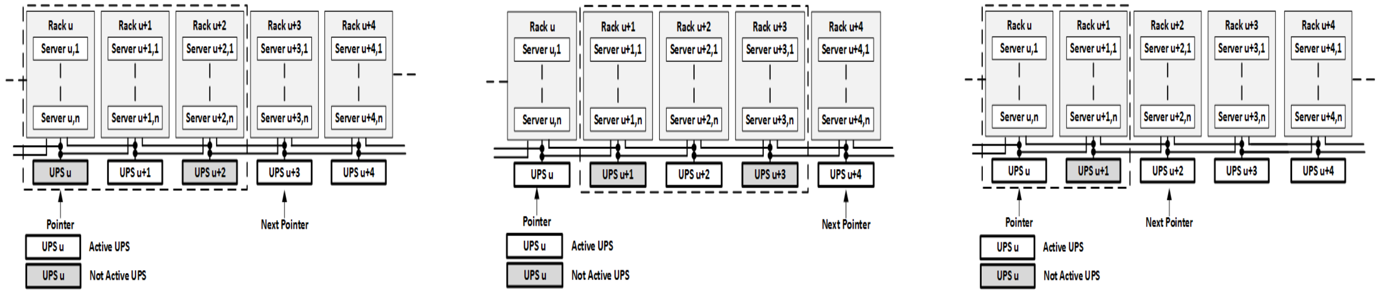
When there is no possibility to shut down some of the first three consecutive UPSs (for example UPS u or $u + 2$) due to higher server racks power loads compared to the UPS power rating of each UPS (firs inequality in lie 9), the second phase of the control algorithm is invoked (lines 7-11). Algorithm checks the possibility of feeding the consecutive group of next three racks ($u + 1$, $u + 2$, $u + 3$) over one UPS as shown in Fig. 2b. Initially, in the second phase of the algorithm, an appropriate number of UPSs for ensuring power supply of consecutive three racks by corresponding UPSs (i.e. $u + 1$, $u + 2$, and $u + 3$) will be checked (lines 8). Then, the summation of the three server racks instantaneous power consumption's ($P_{IT,u+1}$, $P_{IT,u+2}$, $P_{IT,u+3}$) is compared with the rated capacity of single server rack UPS ($UPS_{Rate,u+2}$), as shown in line 9 of the algorithm. If the comparison check is positive, then both UPSs ($u + 1$ and $u + 3$) will be shut down (Fig. 2b) and power supply to the corresponding racks will be fed over single UPS ($u + 2$), while UPS u will remain active (Fig. 2b). Control algorithm then moves the pointer serially to the next consecutive UPS ($u + 4$) which is not yet grouped within serial consolidation approach (Fig. 2b).

If due to the increased load of server racks only one UPSs of three initially active UPSs can be switched off after merging three racks with one UPS, the algorithm executes third phase procedures (lines 12-17) trying to merge one UPS with two server racks. Algorithm checks power load of three server racks (line 13) and if power load of two server racks can be satisfied with power capacity of one UPS, the only one among first three UPSs will be shut down (Fig. 2c) and load will be transferred to one of two remaining active UPSs (line 14).

If there is no possibility at the start of the algorithm to offload two (preceding and subsequent) UPSs per three server racks and maximally one UPS can be shut down per two server racks due to increased instantaneous server racks power consumption, the fourth phase (lines 18-30) of the control algorithm is incurred. In this phase, offloading of one UPS per two neighbouring server racks takes place as shown in Fig. 2c. The offloading process is done through the availability check of the appropriate number of UPSs (line 19) and the instantaneous power consumption check (lines 20). As a result of the fourth phase, the remaining active UPSs must satisfy the power load of two server racks (Fig. 2c) and only one of two UPSs can be shut down (line 21).

The pointer of UPS availability check during the execution of the proposed control algorithm moves to the every consequent UPS u in DC (lines 6, 11, 15, 22 and 24) after finalization of each phase.

Any of the previously described phases will end with the final phase characterized with one to one mapping between server racks and UPSs (lines 30-39), if the power consumption of server racks further increases (line 32) what results with no



(a) Two UPS offloading per three racks through arbitrary selection of active UPS

(b) Two UPS offloading per three racks through optimal selection of active UPS

(c) One UPS offloading per two racks through arbitrary selection of active UPSs

Fig. 2: Illustration of the proposed control algorithm.

possibility for UPS offloading. In this case, there will be no shutting down of UPS(s) and each UPS offers power supply to the corresponding server rack (line 33), what results with architecture equal to the legacy DC power supply architecture (Fig. 1a). In lines 27 and 37, *EXIT WHILE LOOP* procedures are executed to confirm finalization of all control flow phases and the closing of the while loops of the algorithm. According to Algorithm 1 pseudo-code, the phases of the control algorithm are dynamically changed based on the instantaneous power load of consolidated server racks. This load corresponds to the current computing activity of servers located in those racks.

IV. EVALUATION AND DISCUSSION

A. *Evaluation Testbed*

In this section, the proposed UPSs serial consolidation approach is compared with existing legacy DC power supply approach and with the NB consolidation approach proposed in [1]. The simulation testbed simulates DC with enabled server consolidation, where underutilized servers go to shut down state and dynamic activation or deactivation of servers during the consolidation process will take place in accordance to the oscillations in servers (computing) load. Values of the simulation parameters are presented in Table I. The simulation testbed of the DC is based on 2,000 server racks, each containing 10 servers having 4 central processing unit (CPU) cores. Every server hosts 4 virtual machines (VMs) what results with 80,000 VMs used in simulations (Table I). We have run the simulations 30 times with random VM workloads and we reported the average results of simulations. To show the significance of the proposed approach, the developed algorithm is examined with different workloads.

Every of four server central processing unit (CPU) cores can host one of 4 VMs without overlapping. In order to simulate a real DC operation, this VMs workload is simulated as a random generator function based on uniform distribution $U(0, 100)$, where 0 and 100 represent the minimal and maximal percentage of processor load (Table 1), respectively. During every time stamp of the simulation, each VM is executing its random generator function which is reported as a VM workload utilization. Hence, the summation of the co-hosted VM workloads contribute to overall server utilization. Assuming a set of servers $S = \{1, \cdots, s, \cdots, Ns\}$ (Table I), a set of VMs per server s V$_s = \{1, ..., v_s, ..., Ns, v\}$ and set of UPSs $U = \{1, \cdots, u, \cdots, Nu\}$, the workload of the *v-th* VM (L_v, s, u) executed on $s-th$ server supplied over $u-th$ UPS is modeled as a percentage of VMs utilization equal to L_v, s, u = 0 - 100% (Table I). The instantaneous power consumption of the $s-th$ server supplied over $u-th$ UPS will be:

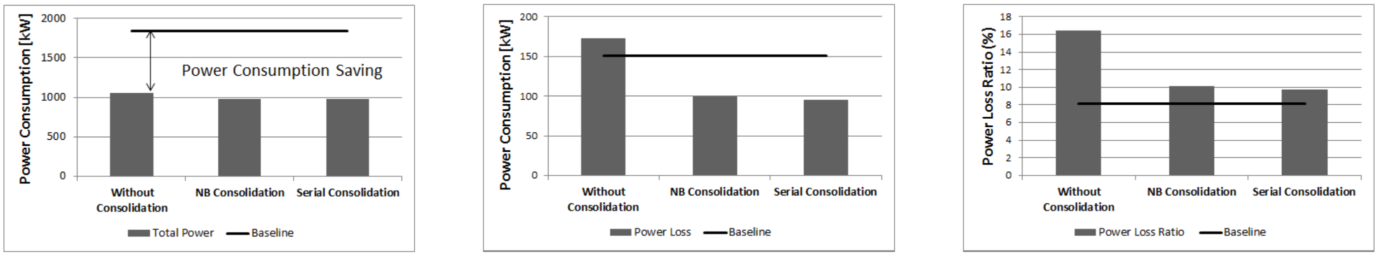
$$P_s, u = 79.921 + 2.33 \times \sum_{v=1}^{N_s,v} L_v, s, u \quad (W), \tag{1}$$

where max($\sum_{v_s=1}^{N_s,v} L_v, s, u$)= 4 represents dynamic and 79.921 W fixed part of the power consumption model (Table I) if the server is in the active state. The chosen power model was based on the IBM System x3650 benchmark [1]. Assuming that binary variable $X_{s,u} = 1$ indicate that $s-th$ server is supplied over $u-th$ UPS, and 0 otherwise, the instantaneous power demand of the $u-th$ UPS $P_{IT,u}$ will be

$$\begin{aligned} P_{IT,u} = \sum_{s=1}^{N_S} P_{s,u} \times X_{s,u} = 79.921 \times \sum_{s=1}^{N_S} X_{s,u} \\ + 2.33 \times \sum_{s=1}^{N_S} X_{s,u} \times \sum_{s=1}^{N_S} \sum_{v_s=1}^{N_s,v} L_{v,s,u} \quad (W) \end{aligned} \tag{2}$$

For simplicity, all servers used in the simulation are homogeneous with the same hardware configuration, what enables calculations of overall power consumption of individual server racks ($P_{IT,u}$) in DC according to relation (2). The overall number of UPSs in DC is equivalent to the number of racks in DC, what means that legacy DC power supply model is based on one UPS dedicated per each server rack. For legacy DC power supply model, maximal power consumption per server rack is equal to $P_{IT,u} = 10 \times P_{s,u} = 892.41$ W , if each VM of each server in the rack have maximal load (Table I). The proposed Algorithm 1 ensuring UPS consolidation is developed in Java and executed on a separate server. The execution time of the proposed algorithm is short (order of milliseconds) and can be implemented as a real-time application.

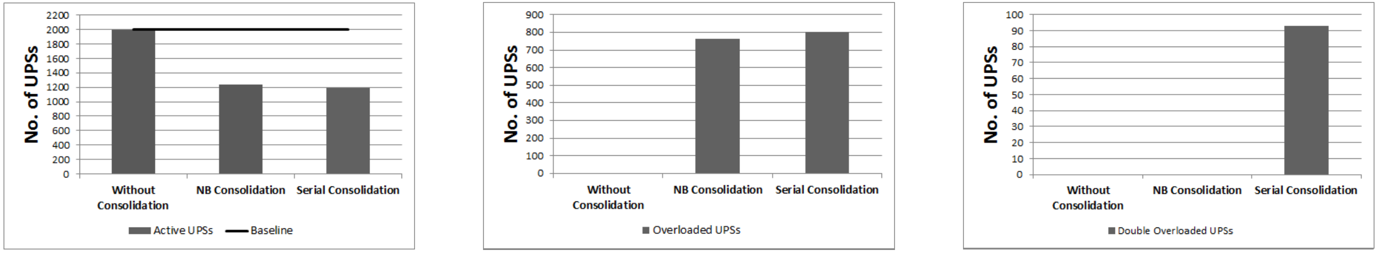
In the analyses, the three UPS consolidation approaches were simulated. The first approach is based on the DC with server consolidation and without UPS consolidation (denoted as without consolidation). This approach takes into account the state-of-the-art server consolidation for improving DC



(a) Overall DC power consumption

(b) Total power losses of UPSs

(c) Power losses ratio



(d) No. of active UPSs

(e) No. of overloaded UPSs

(f) No. of double overloaded UPSs

Fig. 3: Results of simulated DC testbed

energy-efficiency [6], [7] in legacy DCs (Fig. 1a). The second UPS consolidation concept is tested for DC and includes both servers and UPS consolidation approach. This approach is based on the concept of NB consolidation, as shown in Fig. 1b. The third consolidation approach (denoted as serial consolidation) is also based on simulation of the DC with both servers and UPS consolidation approach, but with the concept of connecting UPSs in proposed serial consolidation design (Fig. 2). Results of the analyses are presented and discussed in the next section.

B. *Results and Discussion*

The estimated maximal instantaneous power consumption of simulated DC testbed without the implementation of any (servers or UPSs) consolidation approach (baseline) is equal to 1.88 MW (Fig. 3a). According to the results presented in Fig. 3a, all three approaches (serial consolidation, without consolidation or NB consolidation) have demonstrated significant maximal power consumption reduction (and consequently energy savings) of DC. Obviously, somewhat higher reduction of overall maximal DC power consumption is seen for the NB and serial consolidation, since both of these approaches include UPS and server consolidation, while third (without consolidation) approach only perform server consolidation without UPS consolidation.

However, the main focus of this work is the reduction of the power losses caused by the constant activity of UPSs in DC after applying server consolidation. The power loss of UPSs is defined as the maximal instantaneous power consumption of all UPSs for each of the tested consolidation approaches. Fig. 3b shows the original UPS power loss of the simulated DC without the implementation of any UPS consolidation approach (denoted as a baseline), as well as the power losses for all three analyzed consolidation approaches. Fig. 3b clearly lights the potential problem of applying the server consolidation in the DC (without consolidation bar in Fig. 3b). According to the presented results, the UPS power loss is higher in the case of implementing server consolidation when compared to the original UPS power loss (baseline bar). This increase of UPS power loss in the server consolidation approach is mainly contributed from under-loaded UPS appliances in DC (Fig. 1a). According to [1], [8], the power efficiency of UPS increases with the increase of power load, and in the case of server consolidation (without consolidation approach in Fig. 3b), the load of the many UPSs will be decreased due to the server consolidation. This contributes to the increase of UPS power lose which becomes higher when server consolidation is applied in comparison when there is no UPS and server consolidation (baseline case).

On the other hand, the other two consolidation approaches, i.e. NB consolidation and serial consolidation have demonstrated significant UPS power loss reductions (Fig. 3b). This is a consequence of adaptation of the number of active UPSs to the number of active servers in racks during the server consolidation process. Such concept includes the UPS consolidation as part of the server consolidation, where offloading some UPSs and putting them in the shutdown state contributes to the increase of power load on those UPSs which remain active, what further contributes to the reduction of UPS power loss. According to the results presented in Fig. 3b., proposed serial consolidation outperforms NB consolidation in terms of power losses, since proposed serial consolidation enables consolidation (offloading) of the larger number of UPSs than NB consolidation.

According to the results presented in Fig. 3b, the server consolidation has a high impact on the DC PUE, since the power losses caused by UPSs have been considered as none IT power consumption contributors to the overall DC power consumption. Hence, besides monitoring the raw power loss values (Fig. 3b), the UPS power loss has been observed in terms of relative values and expressed as the percentage (%)

of the total DC power consumption (Fig. 3c). According to Fig. 3c, different consolidation approaches will have versatile UPS power loss ratios in the DC. Based on obtained results, serial consolidation approach shows the lowest UPS power loss ratio equal to 9.7% while without consolidation (server) approach and NB consolidation equal to 16.4% and 10.2%, respectively. This is a direct consequence of improvements in UPS power efficiency obtained through serial UPS consolidation.

However, according to Fig. 3c., the lowest percentage of power loss ratio (8%) will have the baseline approach lacking any consolidation technique. This is because the baseline approach is characterized by a one-to-one mapping between the constantly active UPSs and corresponding server racks. This approach is characterized with the absence of any type of consolidation which means that UPS load will be near the highest levels and consequently the UPS power loss will be low. However, this baseline approach, as the traditional approach to building DCs with redundant UPS power supply of rack servers is significantly energy inefficient and it is not in line with green DC initiatives which mandates the improvement of DC PUE.

The main reason which contributes to the variation of the UPS power loss among different consolidation approaches is related to the number of active UPSs in DC. Therefore, Fig. 3d, reports the total number of active UPS(s) for each of analyzed consolidation approaches. As expected, the server consolidation approach (without consolidation) has not reduced any active UPS appliance in the DC, since this consolidation approach only performs server consolidation without UPS consolidation (Fig. 3d). This is not the case for NB consolidation and serial consolidation for which simulation results show the reduction in the number of active UPSs in DC from 2000 to about 1237 and 1196, respectively. This is expected result since NB consolidation and serial consolidation approaches optimize the number of active UPSs which will be used for feeding the redundant electrical power in accordance with server(s) consolidation in racks.

Such a significant reduction in the overall number of active UPSs is the consequence of a higher load of UPSs that remain active in the process of consolidation. For that reason, analyses regarding two additional parameters, more specifically a number of overloaded UPS and a number of double overloaded UPS appliances is performed and presented in Fig. 3e and Fig. 3f, respectively. The number of overloaded UPSs shown in Fig. 3e corresponds to the number of active UPSs that feeds the electric power to exactly two server racks. As shown in Fig. 3e, the proposed serial consolidation has more overloaded UPS appliances (804 UPSs equivalent to 40.2% of all UPSs in DC) than the NB Consolidation approach (763 UPSs equivalent to 38.15% of all UPSs in DC). Hence, the proposed serial consolidation results with 2.05% higher number of overloaded UPS appliances in the DCs when compared to the NB consolidation. This is the consequence of the consolidation differences among the two approaches, where serial consolidation approach enables feeding of up to three server racks per UPS, what results with an increased number of overloaded UPSs in the case of serial consolidation (Fig. 3e).

The number of double overloaded UPSs are shown in Fig. 3f. Double overloaded UPSs represent the number of UPS appliances that feed with electric power exactly the three server racks (corresponding server rack and two neighbouring server racks). Obviously, the only approach which can have double overloaded UPSs is the proposed serial consolidation approach (Fig. 3f). About 93 UPS appliances were feeding the electric power to three racks in DC, which corresponds to the 7.77% of all active UPS appliances and 4.65 % of all UPSs in DC. According to the obtained results, the serial consolidation approach based on redundant powering of the three server racks over one UPS can contribute to the improvement of DC PUE.

V. CONCLUSION

Although the server consolidation approach improves the DC PUE, this approach contributes to power efficiency degradation of UPSs in DC. Hence, in this paper, the novel UPS consolidation approach for improving the power usage efficiency of the DCs is proposed. Proposed UPS consolidation approach is tested through simulations of real DC by means of executing a developed algorithm which enables control of UPSs scheduling activity in DC. It is shown that the proposed UPS serial consolidation approach along with server consolidation, can ensure a redundant power supply of up to three server racks with one UPS. In comparison with the previous NB consolidation approach and legacy DC design lacking any UPS consolidation, the proposed UPS serial consolidation approach contributes to the significant reduction in the total number of active UPSs. Also, it is shown that the implementation of the proposed serial UPS consolidation approach can bring a higher power usage efficiency of DCs. Our future research activities will be focused on development of more advanced UPS consolidation approaches which will enable feeding of more than three server racks with one UPS during the consolidation process.

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