Pulsed power network with potential gradient method for scalable power grid based on distributed generations

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Abstract: The potential gradient method is proposed for system scalability of pulsed power networks. The pulsed power network is already proposed for the seamless integration of distributed generations. In this network, each power transmission is decomposed into a series of electric pulses located at specific power slots in consecutive time frames synchronized over the network. Since every power transmission path is pre-reserved in this network, distributed generations can transmit their power to individual consumers without conflicts among other paths. In the network operation with a potential gradient method, each power source selects its target consumer that has the maximum potential gradient among others. This gradient equals the division of power demand of the consumer by the distance to its location. Since each of the target consumer selection is shared by power routers within the power transmission path, the processing load of each system component is kept reasonable regardless of the network volume. In addition, a large-scale power grid is autonomously divided into soft clusters, according to the current system status. Owing to these properties, the potential gradient method brings the system scalability on pulsed power networks. Simulation results are described that confirm the performance of soft clustering.

1 Introduction

As one of the neo-futuristic schemes for the smart grid, a pulsed power network is already proposed [1, 2]. In this scheme, each power transmission is decomposed into a series of electric pulses located at specified power slots in consecutive time frames that are synchronized over the network. The power slots are pre-reserved throughout the power transmission path from the power source to the consumer (from now on, the power transmission path is simply called power path). This reservation of power slots preceding determination of power paths is executed autonomously by individual nodes of the power source, consumer, and intermediate power routers. Their procedures follow inherent algorithms that refer to information exchanged among adjacent nodes.

In contrast, current smart grid models mainly focus on the structure of the information network covering the power system and strategy for the system control based on the information exchanges [3]. On the other hand, power transmission itself is based on a conventional scheme where continuous sinusoidal waveform conveys power. In this scheme, because power lines are always filled with sinusoidal waveform, distributed generation should adjust the phase and voltage of its reverse tide to the power line. This may become difficult because of conflict with other generations located near. Moreover, because the whole of the power system is electrically connected, partial system failure may propagate and cause a widespread power outage.

The pulsed power network is initially proposed to solve these problems in the conventional power systems. Especially, the scheme is applicable to the power systems where distributed generations are the fundamental source of power.

The advantages of pulsed power network over conventional power systems are itemized as follows:

(i) The affinity with distributed generations. This means the easiness for the generations to connect with the power network. When an owner of the generation intends to sell power to some consumer, he can reserve currently vacant power slots throughout the power path to the consumer and transmit electric pulses without any conflict against other power transmissions.

(ii) The high reliability of the power system. This means when a partial system failure occurs, the failure does not cause propagative troubles such as system blackout [4]. This is because first, the system is controlled with a decentralised algorithm installed to each node individually and no centre station exists. Second, the algorithm instantaneously complements the partial failure by bypassing power paths established by neighbouring power routers.

(iii) Energy colouring [5, 6] is possible by each consumer based on auxiliary information received from the power source. The information may include the power source classification, distance to its location, and the charge of each electric pulse. With this energy colouring, individual power trading becomes possible between any specified pair of power sources and consumers.

These advantages of pulsed power networks may be available also in the energy packet networks already proposed [7–10]. In these proposals, energy packets are composed of energy payload and additional signals for packet routing like conventional data packet structure. At each router, the routing information is extracted from the packet, and the energy itself is stored until the link to the next hop becomes vacant.

In contrast to these conventional schemes, the pulsed power network is firstly based on direct relaying in networking. Secondly, electric pulses and information signals are separately transmitted and operated individually. As no energy storing is necessary throughout the power transmission and associated simple construction of the power routers [An example of the power router construction is demonstrated in IEEE GCCE2017 [11]], low loss property in the power transmission and high reliability of the routers are obtained in the pulsed power network.

One of the problems of this scheme is that the system operation method is yet unclear. Considering the property of pulsed power network where every power path is established by a power source targeting on a consumer, the system operation method should satisfy the following requirements:

(i) Every power path establishes and releases are triggered by alterations of consumer demand.

(ii) Every consumer can receive power from multiple power sources simultaneously. Inversely, every power source can transmit power to multiple consumers, simultaneously. [In this context of ‘simultaneous’, the time resolution range equals synchronised frame length. Therefore, power transmissions by electric pulses at
different power slots in each frame are recognised as simultaneous. Details are explained in the next section.[(iii) The power network with the system operation method involves system scalability.

Among these requirements, the third one: system scalability is especially important for a neo-futuristic smart grid where a large amount of distributed generations possibly be dispersed over an extended area of power system [12]. In this power system, the generations and more number of consumers form a power market based on point-to-point trading utilising energy colouring that is the third advantage of a pulsed power network.

A system operation method for the pulsed power network is already proposed [13] that satisfies the first and second requirements above itemised. However, because the method focuses on localised power systems with limited system extension, the third requirement is not satisfied.

In this paper, the potential gradient (PG) method is proposed for the scalable system operation of pulsed power networks. In this method, each power source selects its target consumer that has the maximum value of ‘PG’ among all ones. This gradient equals the division of the current power demand of the consumer by the length of the power path to the consumer. This target selection scheme emulates the behaviour of water. The water tends to flow along the slope with the maximum gradient at each branch point, and finally, a preferable destination is selected naturally. Similarly, in the proposed method, the target selection is done step by step at power routers along the power paths from the candidates, and therefore the network volume scarcely affects the processing load of each system component.

This property of the scheme brings the component scalability that concerns the processing load of each component. Moreover, with this scheme, the power distribution over the system performs as an aggregation of individual clusters. Each cluster transforms adaptively according to the localised status of power sources and consumers regardless of the whole network extent. This adaptive clustering (called ‘soft clustering’), brings the network scalability on pulsed power networks. In this paper, the system scalability consists of component scalability and network scalability.

In Section 2, the overview of the pulsed power network is explained. In Section 3, the proposed PG method is described. In Section 4, the overall operation procedure of the pulsed power network is described including the PG method as the core element. In Section 5, soft clustering is explained first, and then the results of computer simulations are presented that confirm the performance of the pulsed power network with the PG method focusing on the soft clustering. The final section concludes this paper with residual discussions.

In the Appendix, some details are described of advancement achieved in this paper compared to previous papers [2, 13] that concern the operation of the pulsed power network.

2 Overview of the pulsed power network

The pulsed power network is configured with power sources, power consumers, power routers, and power communication links (from now on, power consumers and power routers are called simply consumers and routers, respectively). The system operation is based on a synchronised frame structure and direct relaying of routers. The overview of these subjects is explained in this section.

2.1 Network configuration

In the pulsed power network, the time axis is equally divided into consecutive frames. These frames are synchronised over the network. [Global positioning system (GPS) time signal is one of the available standards for this time synchronisation [14].] Each synchronised frame is equally subdivided into N power slots. An example of the frame structure is shown in the upper part of Fig. 2.

Fig. 2 also shows two cases of the electric pulse flow. In one case, two pulses occupy individual slots and are transmitted from power source A to consumer F (indicated by solid contours) [The locations of these nodes are indicated in Fig. 1. As Fig. 1 shows, node E locates next to router L. The electric pulse flows are observed at router M].

Assuming that one electric pulse conveys 100 J and frame length equals 1 s, 200 W is transmitted by two pulses in the former case, and 100 W by one pulse in the latter case [Detailed parameters of the pulses are not specified. In case that the system takes over already existing power lines for cost-saving, the parameters should follow the conventional ones including the voltage level].

For the purpose to smooth electric pulses received and to store electric power during a short time, every consumer is assumed to be equipped with a small storage battery [Almost no power dissipation occurs from this short time power storing provided a large capacitor is adopted [16].]. Owing to this power storing, the time resolution range of power reception at each consumer expands more than the duration of the synchronised frame.

2.2 Synchronised frame

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2.3 Power router

Each power path is configured through direct relaying by routers within the path. Two cases of the direct relaying in Fig. 1 by routers K, N, and M are shown by the lower part of Fig. 2. In one
In the upper part of Fig. 3, a pulsed power network is indicated with power source A, consumers B–D, and routers E and F. Power communication links are indicated by grey thick lines. The power demand of each consumer is indicated in watts. The distance between adjacent nodes is indicated in metres. In this case, the power source A selects consumer B as its target among others. This selection takes three steps as follows (PG of node Y at node X is denoted as $PG_{XY}$):

(i) Router E calculates $PG_{aE}$ and $PG_{bc}$. These values equal 8.00 ($=800 \ [W]/100 \ [m]$) and 5.00 ($=600 \ [W]/120 \ [m]$), respectively. These values are indicated in the lower part of Fig. 3 on the vertical dashed line at E (other PGs are also indicated similarly). Comparing them, E selects node C as its target [This target C of router E is defined for convenience. E itself does not supply the target with power.].

(ii) Since C is selected as the target of adjacent router E, router F calculates $PG_{bE}$ and $PG_{cE}$. These values equal 5.56 ($=500 \ [W]/90 \ [m]$) and 3.81 ($=800 \ [W]/(110+100) \ [m]$), respectively. Comparing them, F selects node B as its target.

(iii) Finally, power source A calculates $PG_{ab}$ that equals 2.63 ($=500 \ [W]/(90+100) \ [m]$). Since no other PGs are calculated for comparison, power source A selects consumer B as its target.

In this example, the target selection process at power source A among three consumers B–D is shared by two routers E and F. Each router individually selects its target among candidates that include a target of an adjacent router or a consumer itself. In this target selection, the power demand of the consumer and distance to its location are considered evenly. Therefore, A selects close consumer B even though other ones have larger power demands.

As explained later in Section 4, this target selection repeats for every synchronised frame. With this frame progression, the number of electric pulses in the frame to the target B increases. Accordingly, the power demand of B decreases. Therefore, $PG_{ab}$ will fall behind $PG_{ac}$ at some point of time. At this critical point, power source A changes its target to C and transmits power to C afterwards. This critical point may become earlier provided other power sources exist. For example, if another source is connected to router F and has the same target B, the critical point approaches twice as fast.

3.2 PG table

Besides the target selection explained in the previous subsection, the shortest power path to the target and available power slots throughout the path are necessary to be determined in the pulsed power network operations. To manage these essential information collectively, PG table is adopted in the PG method.

Every node in the pulsed power network has its own PG table and updates the table repeatedly according to the inherent algorithm with information exchanged among adjacent nodes.

Examples of PG table are shown in Fig. 4 referring nodes A and D in Fig. 3. The upper part of the figure shows the PG table of power source A, whereas, the lower part shows the table of consumer D.

As shown in the figure, each PG table consists of six parts (i)–(vi). In case of power source A (upper part of the figure), these parts are as follows:

(i) Indicates the target consumer to which the current value of PG is maximum among all ones.

(ii) Indicates the power demand [kW] of the target.

(iii) Indicates the length [m] of the power path to the target.

(iv) Indicates the PG [W/m] of the target. This value equals the division of value (ii) by (iii).

(v) Indicates the power path from the owner node to the target [The power path length (iii) is the accumulation of each link length along this power path.].

(vi) Indicates the status of power slots to the target denoted by a circle or a cross (here, the number of power slots $N$ is set to 6). Circle means that all of the power slots at every node within the...
power path are not reserved. On the other hand, the cross means that at least one power slot at some node is reserved.

In the case of router (E or F in Fig. 3), the definitions of these contents are the same. Whereas, they are somewhat different in the case of consumer D (lower part of the figure) as follows:

(i) Indicates the consumer itself. This means the target is identical to the owner node.
(ii) Indicates the power demand \([\text{kW}]\) of the consumer itself.
(iii) Equals zero because the target is itself.
(iv) Indicates nothing.
(v) Indicates only the consumer. No power path exists.
(vi) Indicates which power slots are in use at the consumer. At the power slots denoted by crosses, the consumer may currently receive electric pulses from some power sources in the network.

### 3.3 PG table update process

The PG table update is executed at every node in the network simultaneously. In this subsection, each update process at an individual node is described. The process is defined according to the node classification.

In the case of the consumer, it updates the contents in part (ii) and (vi) in the lower part of Fig. 4. No need to change other parts. On part (ii), its current power demand is written. On part (vi), the current status of each power slot is marked.

On the other hand, in the case of router or power source, the PG table update process is repeated until the target of every power source is determined according to the power demand of every consumer [The required repetition time for PG table update may have some relevance to the network volume. However, a detailed investigation of the network behaviour assures the network scalability with the PG method. This subject is discussed in the final section.]. One process in this repetition consists of synchronised two stages as follows.

At the first stage, every node makes a copy of its PG table (this copy is called PG buffer). Next, the node refers to all of the PG tables of adjacent nodes through the communication links. Then, based on the referred information, parts (i)–(vi) of the PG buffer are updated.

At the second stage, the node overwrites its own PG table with the updated PG buffer. At this point, the PG table update is accomplished.

Since these stages are synchronised over the network [As mentioned in Section 2, GPS time signal is available for this synchronisation [14].], and PG buffer is adopted for temporal table update, the referred information from adjacent nodes are kept stable during the first stage.

The PG buffer update in the first stage is broken down into the following three processes (the owner of the PG buffer is called the owner):

(i) The candidate should be a consumer or a router. In contrast, power sources are discarded.
(ii) The power path (v) indicated in the PG table of the candidate should not include the owner.
(iii) The logical product of power slot status (vi) indicated in the PG table of the candidate and the status of the owner [This status is not part (vi) in the PG table of the owner. However, the status of the owner itself is similar to part (vi) of consumer D in Fig. 4.] should have more than one true. Here, the logical product is derived by replacing circle and cross in each slot with true and false, respectively. Therefore, derived true means the slot is reservable to the target.

Among the above requirements, the second one avoids the meaningless power path loop occurring. The third one assures the power path to the target via the candidate with at least one reservable slot.

Second, the owner calculates all of the PGs of targets in the PG table of selected candidates. At this calculation, the power path length is the addition of that indicated in the PG table and link length from the owner to the candidate (examples will be shown in Fig. 5). Among these derived PGs, one maximum is selected and the associated adjacent node is determined (this finally selected node is called next node [Since the node is the next hop to the target] and its PG table is called the next PG table).

Finally, the owner updates its PG buffer with the next PG table as follows:

(i) Parts (i) and (ii) of the PG buffer are replaced with that of the next PG table.
(ii) Part (iii) is replaced with the addition of that of the next PG table and link length from the owner to the next node.
(iii) Part (iv) is replaced with the division of (ii) by (iii).
(iv) Part (v) is once replaced with that of the next PG table. Then, the owner node is added as the first node of power path.
(v) Part (vi) is replaced with the logical product of that of the next PG table and the status of power slots of the owner node.

### 3.4 Example of PG table update

Fig. 5 shows an example of a PG table update. The upper part of the figure shows a part of the network that consists of consumers F–H and routers A–E. In this network, focusing on router A, an example of its PG table update process is described [As described before, this process is executed similarly by every power source and router in the network simultaneously]. as follows:

(i) At the beginning of the update (the first synchronised stage described in the previous subsection), router A makes the PG buffer and refers to the PG tables of adjacent four nodes B, C, D, and G. These tables are shown in the lower part of Fig. 5. According to the requirements described in the previous subsection, router A discards the PG tables of C and D. In the case of C, the power path includes A itself (indicated by a dashed circle). Whereas in the case of D, the logical product of the slot status (dashed frame) and the status of A (grey) leaves no reservable slot.

(ii) Since the targets of selected nodes B and G are F and G, respectively, router A calculates PGaf and PGag. Considering the distances of B and G from A (indicated in the figure), \(\text{PG}_{af} = 6.4 \text{ [kW]}\) and \(\text{PG}_{ag} = 1.5 \text{ [kW]}\).

(iii) According to the final process of PG buffer update described in the previous subsection, router A updates its PG buffer with the
Fig. 6 Rough time chart of the preparation process
(a) Every consumer examines its power demand, (b) Every consumer with power excess releases excess power paths, (c) Every node resets its PG table, (d) Every power source and router updates its PG table, (e) Every power source decides its target consumer, (f) Every power source reserves an elemental path to its target

Fig. 7 Example of soft clustering with three clusters. Power source A₅ has just failed

next PG table and overwrites its own PG table with the buffer at the second synchronised stage. The updated PG table of A is shown at the bottom of Fig. 5.

4 Operation procedure of pulsed power network
Based on the PG method described in the previous section, the pulsed power network is operated according to power demand alterations of consumers. In this section, the total system operation procedure of the network is explained including power path establishes and releases.

The system operation procedure consists of the repetition of the preparation process and the repetition of the execution process. These processes run concurrently and their time interval is adjusted to the synchronised frame of the pulsed power network.

In the preparation process, every power path establishes and releases are planned for the execution process of the next time interval. Accordingly, every schedule of electric pulse transmission, reception, and relaying of the next interval is determined at individual nodes of power source, consumer, and router, respectively.

Whereas, in the execution process, every node executes the scheduled task determined in the previous preparation process. Therefore, actual power transmissions through the power paths, and their releases begin with this execution process.

The rough time chart of the preparation process is shown in Fig. 6 over one interval of a synchronised frame.

(i) At the beginning point (a) of the interval, every consumer examines its current power consumption and power reception. If the former exceeds the latter, the difference means the power demand [This power shortage is temporarily complemented by short-time power storage described in Section 2]. On the other hand, if the power reception of the consumer exceeds its consumption, the difference means the power excess [This power excess may be used as the power storage charging]. In the case of power excess, the consumer releases the excess power paths as the next paragraph.

(ii) During the interval (b), every consumer with power excess releases the excess power paths. Every consumer is assumed to store information of all the power paths that the consumer currently terminates. The information includes the power source and intermediate relay nodes to the source. During the interval (b), the consumer with power excess communicates with the power sources and releases the power slots throughout the excess power paths.

(iii) At point (c), every node resets its PG table. Each consumer records its current power demand [No power excess remains because the excess power paths are released during the interval (b)] and the current status of its power slots on the table. Power sources and routers clear all of the contents on their PG tables. In addition, every node reconstructs its list of adjacency that consists of indexes of adjacent nodes. This process is necessary for unstable network topology caused by unexpected node troubles including synchronisation failure or so [Power transmission breakages caused by these troubles are soon be retrieved through the reconstructed network].

(iv) During the interval (d), every router and power source updates its PG table. They repeat synchronised two stages described before in Section 3.3. The repetition time is predetermined in relation to the network volume.

(v) At point (e), every power source decides its target consumer according to its PG table. Coincidentally, the power path to the target and reservable power slots throughout the path is determined.

(vi) During interval (f), every power source reserves the power path with one power slot to the target consumer. This elemental power path is called elemental path. Through this elemental path, one electric pulse is transmitted every synchronised frame to the target. This power transmitted by a pulse every frame is called elemental power. The reservation process of the elemental path to the target begins with reservation signal transmission through the path. If the reservation fails and the error signal returns, the power source retries with another reservable slot. Details of this power path reservation are described in the previous paper [2].

5 Computer simulation
In this section, the results of computer simulations are presented that confirm the performance of the pulsed power network with the proposed PG method.

Among the requirements for the system operation method itemised in Section 1, the first one (consumer demand priority) is obviously satisfied in the PG method as described in Section 3. On the other hand, the second requirement (power transmission simultaneous) is already confirmed by simulations [13] as the inherent property of pulsed power networking.

In this section, the third requirement (system scalability) is focused on and associated system performances of the pulsed power network with the PG method are confirmed by simulations.

As described in Section 3.1, the target selection sharing among routers assures the scalability of pulsed power networks. On the other hand, the PG method additionally assures the network scalability by soft clustering. In the following, first, the soft clustering and system scalability is explained. Second, the simulation model is introduced with a moderately large volume and the results of the simulations are described concerning the soft clustering.

5.1 Soft clustering
When pulsed power distribution with the PG method is applied to a large-scale power grid, the grid is divided into soft clusters autonomously where each one consists of a central power source and surrounding consumers that receive power from the centre node. This means that power transfers are almost completed within each cluster. The word ‘soft’ means that the circumference of each cluster adaptively modified and overlaps with neighbouring ones because of the property of the PG method.

No matter how large the power grid is designed, the power distribution over the system performs as an aggregation of individual soft clusters. Owing to this soft clustering, first, the system scalability is obtained. Second, high-system reliability is assured against partial failures within the system.

Fig. 7 shows an example of a soft clustering. In this figure, three clusters A, B, and C exist as neighbours. These clusters include power source A₅, B₆, and C₇, respectively. Other nodes D–H
are consumers. An arrow indicates a power transmission through a power path.

Within the cluster C, nearby consumers G and H of C1 receive power from the centre node. Whereas, because consumer F locates immediately between B1 and C1, F becomes the target of both power sources. Therefore, clusters B and C share this node and their circumferences partially overlap each other.

The system reliability against a partial failure is explained by cluster A. The dashed circumference and arrow mean that cluster A just disappears due to the failure of A5. In this case, because power demand of consumer D increases with no power supply, D becomes the target of B5. Accordingly, the circumference of cluster B modifies and includes consumer D as shown in the figure.

5.2 Simulation model

Fig. 8 shows the simulation model that consists of 140 consumers, 4 power sources, and 36 routers. Power routers config. 6 × 6 square grid that is equally classified into four areas A–D indicated by dashed lines [This classification depends only on geometrical equivalence and differs from the soft clustering described in the previous subsection.]. In each area, the central router connects with one power source and three consumers as the left part of the figure shows. Each of the other routers connects four consumers. The power source in area A is denoted as A1. Other power sources are denoted as B1–D1 similarly. The interval of adjacent routers is set to 50 m. The synchronised frame duration and the number of power slots N are set to 5 s and 500, respectively.

The simulation scenario is as follows:

(i) Initially, every consumer i is set to its power demand \( P_i \) that indicates the number of electric pulses the consumer needs to be supplied at each frame. [If one pulse conveys 100 J, \( P_i = 10 \) means 200 W of power demand (10 × 100 [J]/5 [s]).]. The average \( P_{\text{avg}} \) and deviation \( P_{\text{dev}} \) of \( P_i \) is initially set, then the power demand \( P_i \) of consumer i is assigned randomly between \( P_{\text{avg}} \pm P_{\text{dev}} \).

(ii) After the simulation begins, every node in the network operates itself following the procedure described in the previous section. Accordingly, every power source decides its target consumer at point (e) in Fig. 6 and increases an elemental power to the target. As the result, the target decreases its power demand [In the simulations, only elemental path increases and associated behaviour of soft clusters are observed. Elemental path releases during (b) in Fig. 6 are not simulated.].

(iii) As the power demand of a consumer decreases, its PG at the power source also decreases. Therefore, the target of a power source may change to another consumer frequently. Owing to this reason, power demand of every consumer decreases almost uniformly and finally becomes zero.

5.3 Simulation results

Fig. 9 shows a simulation result that indicates the increase of power paths from four power sources A–D to area A. The horizontal axis represents the number of synchronised frames counted from the beginning of the simulation. Actual elapsed time is derived as the product of this number and frame duration time 5 s. The vertical axis represents the number of power paths established.

At the beginning, \( P_{\text{avg}} \) is set to 10. Whereas, \( P_{\text{dev}} \) is set to 0 or 10. The results of the former and latter cases are indicated by solid and dashed lines, respectively.

In this simulation, focusing on area A only, the following properties of the soft clustering are estimated:

(i) According to the PG method, where each power source concerns power demand of consumers and distant to their locations, consumers in area A receive power almost from A1, especially when the initial deviation \( P_{\text{dev}} \) of power demand equals 0.

(ii) Even when \( P_{\text{dev}} = 10 \), this initial deviation may be decreasing because of the property of the PG method where a consumer with large power demand tends to be supplied power first. Therefore, the influence of \( P_{\text{dev}} \) may become insignificant gradually.

These properties are confirmed by the simulation results indicated in Fig. 9. First, as the line ‘A1→ area A’ (closely gathered by solid and dashed lines) indicates, almost power demand in area A is satisfied by power transmissions from A1 only. Since the total power demand in this area equals 350 (average 10 power demand multiplied by 35 consumers), the number of power paths does not exceed this value. This maximum point appears when the synchronised frame count reaches 350 as shown by the dashed vertical line. This is because A1 is assumed to increase the elemental path to its target every frame and the total power demand in area A is 350. This frame count 350 indicates the fulfil time when every consumer power demand is satisfied.

However, a slight deviation appears in Fig. 9 from these descriptions caused by a little contribution from other power sources. In the case of initial power demand deviation \( P_{\text{dev}} = 0 \), power paths from B1 and D1 appear at about 150 on the horizontal axis and slightly increase [Owing to the geometrical symmetry in relation to area A, distinction between B1 and D1 is omitted.]. Whereas, in the case of \( P_{\text{dev}} = 10 \), the appearance point moves forward to about 100. However, the difference between these two cases decreases as the simulation proceeds. This confirms the second point above itemised: the influence of \( P_{\text{dev}} \) may become insignificant gradually.

Fig. 10 shows a simulation result that confirms the system reliability based on soft clustering. In this simulation, power source A1 in Fig. 8 is assumed to be failed and other sources B1–D1 substituting transmit power to consumers in area A. In other words, concerning the clustering image, the failure of \( A_1 \) directly incurs the gradual replacing of cluster A by expanding neighbours B–D and...
The PG method is proposed for the system scalability of pulsed power networks. In pulsed power networks, each power source transmits power to its target consumer by a series of electric pulses located on pre-reserved power slots in synchronised frames. With the proposed PG method, each power source selects the target consumer based on the PG that equals the division of power demand of the consumer by the distance to its location. The system scalability is brought to pulsed power networks by two properties of the PG method: process sharing of target consumer determination at each power source with other nodes, and soft clustering that autonomously divides extended power grid depending on the current system status.

Simulations are executed to confirm the performance of a pulsed power network with the PG method where a moderately large simulation model is adopted that is divided equally into four areas: A–D. Simulation results are as follows:

(i) Consumers in area A are almost satisfied with their power demand by the central power source of the area especially when the initial deviation of power demand is set low.

(ii) When the initial deviation is set high, the circumference of clusters modifies autonomously and power transmissions to area A from neighbouring areas increases.

(iii) When the power source in area A fails, the cluster surrounding the failed source disappears and is divided by neighbouring other areas. As the result, consumers in area A satisfies their power demand.

The first and second results confirm the autonomy and flexibility of soft clustering. The third one confirms the reliability of the pulsed power network with the PG method.

In Section 3.3, the relevance is referred to as the network volume and the required repetition time for the PG table update. This relevance possibly impairs the scalability of pulsed power networks. However, concerning the soft clustering in actual system operations, this problem may not seriously affect the scalability. In usual network configurations where power sources are dispersed almost evenly, PG data of nodes outside a cluster scarcely arrive at the central power source. Such distant data may be discarded on the circumference of the cluster. Therefore, in this case, the repetition time for PG table update is roughly determined depending on the average cluster size or several times larger. No need to account for the network volume itself.

However, in exceptional cases such as almost of power sources are failed caused by serious disasters, and therefore a limited number of survived power sources transmits power to distant consumers, the required repetition time for PG table update possibly exceeds the pre-determined value. This problem should be investigated more in further studies.

7 References

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8 Appendix

Some details are described of advancement achieved in this paper compared to previous papers [2, 13] that concern the operation of the pulsed power network. In these previous papers, the network operations are based on a power transmission capacity (PTC) table. The PTC table is owned by each node in the power network similar to the PG table proposed in this paper.
The essential difference between the PTC table from the PG table is the number of entries that constructs a table. In a PTC table, one entry points a node in the power network consisting of the node index, next hop to the node, reservable slots to the node, and associated other information. Each entry points to an individual node, and one of the pointed nodes equals the owner node itself. Therefore, the number of entries in a PTC table equals the number of nodes in the network. In contrast, the number of entries in a PG table is only one that points to the target node with a maximum PG value.

Obviously, the processing load of the table update is roughly proportional to the number of entries in the table. Therefore, if the network volume increases largely, the operation of the pulsed power network based on PTC tables becomes not executable. Whereas, the processing load of the PG table update may be kept reasonable regardless of the network volume.

The rough estimation of the computational complexity $C_c$ expended by a node for the PG table update is as follows.

As described in Section 3.3, the PG table update is repeated until the target is determined. This repetition time is denoted by $R$. At each update, these values are considered: number $M$ of adjacent nodes, calculation amount $C_m$ of a candidate check, number $K$ of the candidates, calculation amount $C_k$ of the PG value derivation, and calculation amount $C_t$ of PG buffer update.

Though these values fluctuate around some average in actual system operations, the rough estimation of $C_c$ is derived as

$$C_c = R(M \cdot C_m + K \cdot C_k + C_t).$$

As described in the final section, the repetition time $R$ is roughly determined by the average cluster size. $M$ and $K$ are determined by local network topology and node statuses. Each of $C_m$, $C_k$, and $C_t$ consists of elemental processes of symbols or digits. Though accurate estimation of $C_c$ is somewhat difficult, the estimation is obviously not affected by the network volume.