

# Compartmentalisation-based design automation method for power grid

ISSN 2398-3396

Received on 14th January 2017

Revised on 3rd February 2017

Accepted on 10th February 2017

doi: 10.1049/iet-cps.2017.0006

www.ietdl.org

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**Abstract:** Power grid design and maintenance are conducted to solve the problems caused by load growth over time and to stay within the constraints of voltage drop, power factor, etc. Typically, solutions to these problems are optimised individually. Considering multiple problems simultaneously and applying different solutions require vast design space exploration. This exclusively needs advanced algorithms and complex global optimisation methods which are not easily-applicable in different scenarios. In the state-of-the-art methods, for solving multiple problems simultaneously, these individually optimised solutions are applied sequentially to the power grid. In this so-called uncoordinated method, the final solution may not be optimal solution considering all the variables, since it is considering the overlapping effect of the solutions on the power grid. To validate the compartmentalisation method, a detailed distribution grid has been modeled. After analysing the possible solutions and optimisation, power loss was reduced 45% and total cost decreased by 71%, compared to the uncoordinated method.

## Nomenclature

We provide a variable list that is complementary to [1].

### Sets

$TO$	thermal overload
$VD$	voltage drop
$PF$	power factor
$WU$	wire upgrade
$VU$	voltage upgrade
$CA$	capacitor addition
$LT$	load transfer
$\Psi^{BE}$	edges of the existing grid
$\Psi^{NE}$	nodes of the existing grid
$\Psi^P$	all problems calculated after an analysis
$\Psi^D$	load edges
$\Psi^G$	distributed generation edges

### Real variables

$C_k^f$	fixed costs for installation for solving a given problem $k$ from the $\Psi^P$ set
$Z_{level,j}$	indicates the $z$ -level dependency of the $j$ th node

### Complex variables

$I_i$	current of edge $i$
$I_i^{Max}$	maximum current capacity of edge $i$ (i.e. thermal limit of edge)
$I_i^{Slack}$	the slack of edge $i$ , defined as $I_i^{Max} - I_i$
$V_j$	voltage measured at node $j$
$V_i^{DB}$	localised VD measured for edge $i$ with respect to nodes $j_{from}$ and $j_{to}$ of the edge.
$V_i^{DN}$	voltage DROP measured for edge $i$ with respect to the nominal voltage and node $j_{to}$ of the edge
$PF_i$	power factor measured at edge $i$ with respect to node $j_{to}$

$\phi_i$  phase angle between voltage and current measured at edge  $i$  with respect to node  $j_{to}$

### Parameters

$V_{nom}$	nominal voltage of the existing system
$d_j$	nodal load at node $j$
$\omega_{cost}$	designer-defined weight preference for objective function to minimise cost
$\omega_{solved}$	designer-defined weight preference for objective function to maximise number of problems solved
$\Delta V\%$	maximum tolerable voltage deviation from $V_{nom}$ , expressed as a percentage
$I^{Max\%}$	maximum tolerable current with respect to thermal capacity, expressed as a percentage. May be different based on the types of components
$PF_{lagging}^{Max}$	maximum tolerable lagging power factor.
$PF_{leading}^{Max}$	maximum tolerable leading power factor
$N_{solve}$	number of solutions to implement per run
$List_{TypeSolve}$	an ordered list that indicates the type of power grid problems to solve first

## 1 Introduction and related work

Since the beginning of the industrial revolution, the design and maintenance of power grids for the purpose of providing the residential and industrial demands have been very important responsibilities of governments, corporations, utilities, and individuals alike. The problems arising from design and maintenance of these grids, are whether from load growth or from a disturbance caused by adding new loads/components to a stable existing system. Examples of these problems include conductor thermal overload, excessive voltage drops (VD), power factor (PF) regulation, etc. [2–6].

Many regulating bodies and owners of the power grids set specific constraints for reliability and efficiency purposes. Reliability is met by following the operational requirements set by the manufacturers

of the various components that comprise the power grid (such as the transformers and voltage regulators). Maintaining reliability would help extend the longevity of these devices. Efficiency is met through both meeting reliability standards as well as examining where power losses occur significantly, either due to the system operating at a low-voltage level or due to an inability to maintain a high PF as desirable, etc. Typically, not meeting these constraints are considered as power grid problems [7].

Typically, solutions to these problems are applied by optimising just a single variable of the power grid. Hence, they are considered easily-applicable for power grid designers. On the other hand, when considering multiple problems and variables simultaneously, there may be overlapping effect of the solutions on the power grid which will deviate our solution from the optimum point. These multi-variable problems are typically solved using global optimisation methods [8, 9]. However, considering this wide range of solutions and components simultaneously in order to optimise multiple variables for lower implementation cost is too complex to handle (see Section 3). As a result, multi-variable global optimisation methods are not applied to power grid design and maintenance in practice. Therefore, in the state-of-the-art methods, designers utilise the single-variable optimised solutions sequentially to address the problems [2]. They might implement multiple solutions before checking if the problems are resolved. In this so-called uncoordinated method, since the designers are not considering the overlapping effect of the solutions on the power grid, the final solution may not be optimal in terms of cost. Moreover, the interconnected nature of the power grid adds further complexity to this process [10, 11].

In this paper, we present a novel compartmentalisation-based method to solve multiple problems in the power grid, using the existing optimised single-variable individual solutions for lowering the implementation cost. Compartmentalisation is the method of condensing the possible solutions to the aforementioned power grid problems into solution blocks, such that the optimiser may use them interchangeably when attempting to meet all the system constraints. A critical importance to this method is the possibility of solving a type of problem in multiple ways, e.g. a thermal overload that is measured across an overhead conductor segment can be solved by multiple approaches. Examples of which include: upgrading the conductor type, shifting part of the load serviced by the conductor to another subsection of the power grid or re-purposing the feeder the conductor is located at, such that it operates at a higher system voltage [12, 13].

Although the concept of compartmentalisation is simulator-agnostic, the power grid simulator chosen for this work is GridMat [14] which includes GridLAB-D [15]. GridMat helps us to model, simulate, and analyse the power grid. Besides its open-source nature and increasing popularity of GridLAB-D in the power grid community, the package also provides an excellent set of power flow solvers, such as the forward-back sweep method for strictly radial feeders, and the Gauss-Seidel [10] and Newton-Raphson methods [11] for three-phase, unbalanced, and non-radial systems.

Ziari *et al.* [12] investigate the most optimal method to distribution grid upgrades when considering temporal-induced load growth, line losses, and reliability problems. This method includes steps for examining solutions on a year-by-year basis and an emphasis on dispatchable distribution generation as a possible solution type. Franco *et al.* [16] consider the implications of imposing radiality constraints on power grid optimisation problems. In another paper, Franco *et al.* [13] present a mixed-integer linear programming model for the purpose of solving specific conductor replacement problems, and proposes the costing matrix when replacing conductors. Ziari *et al.* [17] examine integrated distribution system planning, more from a reliability perspective, and use a modified discrete particle swarm optimisation method for the purpose of performing the needed optimisation. Lotero and Contreras [18] present a basis for defining the objective functions based on economic matrices and consider both immediate construction costs as well as long-term maintenance costs. Nassif *et al.* [19] and Jiang *et al.* [20] discuss the rationale for design automation in

energy networks, as well as geographic information system representations of distribution networks.

In these papers, authors have used single-variable global optimisation to solve each individual power grid problem and uncoordinated method to solve multiple problems. However, these methods suffer from huge complexity and non-optimality, when considering multiple power grid variables and problems simultaneously (for details see Section 3).

## 1.1 Problem and research challenges

In summary, the problem of solving multiple power grid design problems simultaneously poses the following challenges:

- (i) Complexity of a multi-variable global optimisation as a non-practical method for solving multiple power grid problems while designing or upgrading.
- (ii) Considering the overlapping effect of the solutions when solving multiple problems sequentially, e.g. when using uncoordinated method.
- (iii) Accounting the order of applying the individual solutions for solving multiple power grid problems simultaneously.

## 1.2 Our novel contributions

To address the aforementioned challenges, our design automation method of compartmentalisation is proposed to do:

- (i) Compartmentalising sets of optimised and standard solutions implemented for power grid design and maintenance in order to tackle each type of design problem based on the desired constraints.
- (ii) Analysing the order of applying these sets of solutions and their effects (possible overlapping effect) on power grid considering implementation cost.
- (iii) Optimising the order of sequential implementation for these solutions at system level which allows the designers to find the most cost-effective final solution while checking to see if more solution is required.

The components required for our compartmentalisation-based design automation method with further details of its implementation are abstracted in Fig. 1.

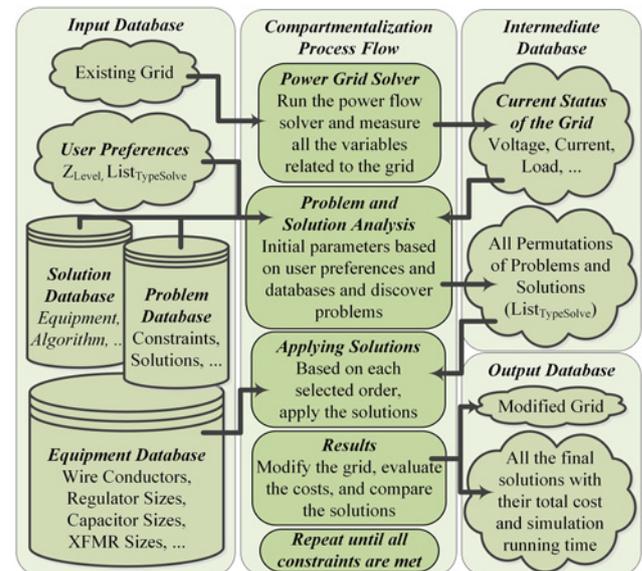


Fig. 1 Our compartmentalisation-based design automation method

## 2 Definitions, design problems and solutions

**Definition 1:** The compartmentalisation (see Fig. 1) is a method of representing, solving, and optimising power grid design problems. It uses the existing optimised solutions, to solve the power grid problems and meet all the design-time constraints. It also provides a process for testing different solution types for any given power grid problem. This method requires component databases which contain the possible different types of power grid components to choose from, as well as costing information for the different types of solutions.

### 2.1 Power grid definition

Defining an existing power grid is the very first step, and requires specifying a netlist that electrically and spatially defines the connectivity. Electrical definition is achieved by specifying the *nodes* and *edges* in the system, while spatial definition provides geographical coordinates of these nodes and edges. Typical X-Y-Z coordinate system may be used for determining distances between nodes. Nodes serve as electrical connective points, where voltage is usually defined and edges are the various electrical components between the nodes. Typically, each component which forms an edge, is connected to a number of nodes, depending on the type of component.

**Definition 2:** A component database is a set ( $ED^{Type}$ ) of different varieties of one type of electrical component, where  $s^i \in ED^{Type}$  is a unique electrical component.  $s^i$  holds parameter information such as: name of the component, type of the component, electrical parameters relevant to the component, and costing information. The component database also serves to limit the components to consider when solving and optimising the system, as a solution  $h$  will only be considered if  $\forall s^i \in ED^{Type}$  is true.

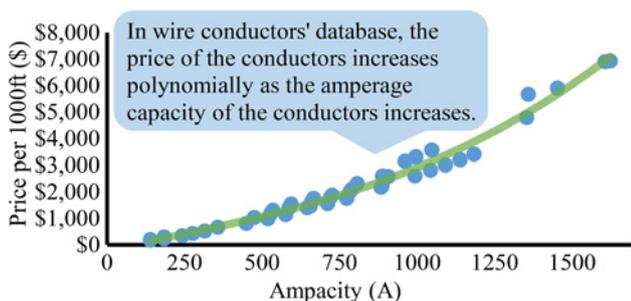
The component databases that will be used in this paper are:  $ED^{OH}$  for overhead conductors,  $ED^{UG}$  for underground conductors,  $ED^{REG}$  for regulators,  $ED^{XMPR}$  for transformers, and  $ED^{CAP}$  for capacitors.

For instance, we have generated a database for wire conductors it consists of their electrical characteristics and the associated cost for their implementation, as shown in Fig. 2.

The two aforementioned steps are critical for defining the power grid, but for both the regular power flow simulation and the compartmentalisation method, designer-defined parameters and design-time constraints will need to be defined.

**Definition 3:** Design-time constraints are the limitations a designer imposes on the power grid to dictate specific power quality or reliability metrics. They may also be related to electrical parameters such as currents and voltages.

They are the maximum tolerances on the operating parameters of any electrical component such as distributed/central consumers and generators whether at transitive or stable state of grid operation. These parameters may include:  $\Delta V^{Max\%}$  for defining the maximum tolerable voltage deviation from the system nominal



**Fig. 2** Cost of upgrading wire conductors with different ampacities [21]

voltage ( $V_{nom}$ ),  $I^{Max\%}$  for defining the maximum tolerable current with respect to an edge's thermal capacity, and both  $PF_{lag}^{Max}$  and  $PF_{lead}^{Max}$  to define the maximum tolerable lagging and leading PFs, respectively. Common values for these parameters are [22, 23]:

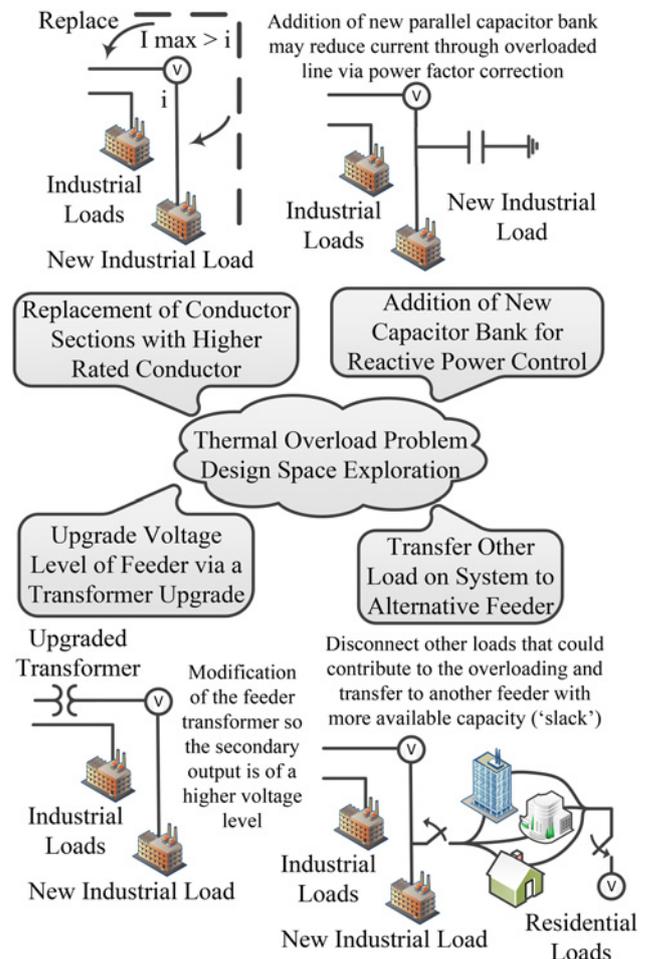
- $\Delta V^{Max\%} = 10\%$
- $I^{Max\%} = 100\%$
- $PF_{lag}^{Max} = PF_{lead}^{Max} = 0.95$

### 2.2 Power grid design problems and solutions

The following are multiple common power grid design problems that many utilities and regulating bodies consider critical. Each type of problem comes with a possible set of easily-applicable solutions. The decision to implement a certain type of solution depends on the electrical parameters, designer's preference, and the circumstances of each problem.

**2.2.1 Thermal overloading:** Many components have a maximum acceptable current (i.e. thermal limit) that must be respected for longevity purposes. Utilities have standards to allow for above-normal current during contingency conditions, however, the frequency of these contingencies is supposed to be low. Consequently, building a steady-state power grid that obeys these thermal limits is very important. Typically 100% of the component's ampacity capacity (ampacity) is an established constraint, however some utilities may opt to follow a more stringent constraint (90% of this ampacity) to allow for extra margin.

Thermal overloads are critical problems that may be solved using the following easily-applicable solutions, as seen in Fig. 3:



**Fig. 3** Possible solutions to an example thermal overload problem

**Algorithm 1:**


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**Input:** Grid with wires  $w_i \in \Psi^{BE}$  / nodes  $n_i \in \Psi^{NE}$   
**Output:** New Grid with wires  $w_i \in \Psi^{BE}$  / nodes  $n_i \in \Psi^{NE}$

```

1 while True do
2   foreach  $w_i \in \Psi^{BE}$  do
3     if  $(I^{Slack}(w_i) \leq 0)$  then  $WU_i = 1$ 
4     else  $WU_i = 0$ 
5   foreach  $n_i \in \Psi^{NE}$  do
6     if  $(PF_{n_i} \leq PF_{lag}^{Max})$  then  $CA_i = 1$ 
7     else  $CA_i = 0$ 
8     if  $(|\Psi_T^P| \in \Psi_{Feeder(n_i)}^{BE} \geq Num_{TO,Feeder}^{Max})$  then
9        $VU_i = 1$ 
10    else  $VU_i = 0$ 
11  if  $(load\ imbalance \geq Max\ imbalance)$  then  $LT = 1$ 
12  else  $LT = 0$ 
13  if There is no problem then break
14  foreach  $w_i \in \Psi^{BE}$  based on  $Z_{level}$  and  $List_{Type,Solve}$  do
15    if  $(WU_i == 1)$  then
16      Find  $WS$  with  $I^{Max}(WS) \geq I(w_i)$ 
17      Upgrade  $w_i$  to a new wire type  $WS$ 
18  foreach  $n_i \in \Psi^{NE}$  do
19    if  $(CA_i == 1)$  then
20      Determine capacitor size  $Q$  (VARs) based on  $PF_i$ 
21      Add capacitor  $Q$  in parallel with edge  $w_i$ 
22    if  $(VU_i = 1)$  then
23      foreach  $V_{level} \geq V_{nom}$  do
24        if  $V_{level}/Z_{w_i} \leq I^{Max}(w_i)$  then
25          Perform voltage upgrade by adding
          transformer
26  if  $(LT = 1)$  then
27    Let  $X_s$  be  $X_i$  with  $max\ DOWNLOAD(X_i)$ 
28    Let  $X_t$  be  $X_i$  with  $min\ DOWNLOAD(X_i)$ 
29     $\delta = DOWNLOAD(X_s) - DOWNLOAD(X_t)$ 
30     $S = \emptyset; T = \emptyset$ 
31    foreach vertex  $v \in X_s$  sub-tree do
32      if  $DOWNLOAD(v) \geq \delta$  then
33        Add  $v$  to  $S$ 
34    foreach vertex  $v \in X_t$  sub-tree do
35      if  $I^{SLACK}(v) \geq \delta$  then
36        Add  $v$  to  $T$ 
37    Find a pair  $(s \in S, t \in T)$  with the shortest distance
38    Add a tieline between  $(s, t)$ 
39  return  $\Psi^{BE}, \Psi^{NE}$ 

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**Fig. 4** Thermal overload solution selection algorithm

- (i) Replace the existing conductor with a conductor of a sufficient thermal rating.
- (ii) Adding an appropriately-sized capacitor to achieve a more efficient PF and reduce thermal overloading.
- (iii) Increasing the voltage level of the section with the thermal overloading problem via a transformer addition or upgrade.
- (iv) Transferring load on the overloaded section to another less-loaded section of the whole grid.

As there are multiple types of solutions, an ordering (permutation) of the easily-applicable solutions must be done. It is important to note that while not all solution types fit a specific problem, it is

not always true that only one solution perfectly solves a problem. An assessment of a variety of different solutions must be allowed. Consequently, binary terms for each problem  $i$  must be assessed to determine whether they can be implemented or not. Algorithm 1 (see Fig. 4) shows exemplary solutions to thermal overloads, and uses the binary terms  $WU_i$ ,  $CA_i$ ,  $VU_i$ , and  $LT_i$  to evaluate the possibility of using wire upgrades, capacitor additions, voltage upgrades, and load transfers, respectively. The designer-defined list  $List_{Type,Solve}$  specifies the designer's preference for the order of trying out different solutions; an example of such a list for thermal overloading problem may be  $List_{TO,Solve} = [WU, LT, VU, CA]$ . It needs to be noted that, this ordering shown in Algorithm 1 (Fig. 4) is an example of illustrating the solution applying process. However, the algorithm can be generalised and the solutions can be applied in any ordering defined by the compartmentalisation method and its optimiser.

**2.2.2 Voltage drop:** VD is the degradation of voltage potential across a series of lines and device components that make up the power grid, due to the inherent impedance of these components (as per Ohm's law). Many of the devices have a limited VD tolerance from the nominal voltage for proper operation. Therefore, the Utility is responsible for VD correction, in order to ensure a high-standard reliability and power quality. Although ANSI standards specify a  $\Delta V^{Max\%} = 10\%$  from nominal, in general, many utilities usually opt to follow a more strict voltage tolerance (e.g.  $\Delta V^{Max\%} = 5\%$ ) instead. Although VD is usually an important constraint to the objective function, its exact implementation is not the same across different utilities. As such, giving the designer flexibility in specifying the constraints is key. VD violations are critical problems that may be solved using the following easily-applicable solutions:

- (i) Replace existing conductors upline to the problem area with a conductor of lower impedance so as to reduce the VD of the conductor.
- (ii) Adding a voltage regulator upline to the problem area.
- (iii) Increasing the voltage level of the section with the VD problem via a transformer addition or upgrade.
- (iv) Transferring load from the problem section to another less-loaded section of the whole grid

For conductor replacement, the objective is to replace a sufficient amount of conductor such that the VD at the problematic area is reduced to the designer-defined system tolerance ( $\Delta V^{Max\%}$ ). Placing regulators is another alternative to solve VD problems. Regulators at the distribution level feature negative-feedback control loops that attempt to maintain a constant voltage level. The addition of regulators is a much simpler, and usually a less expensive option, than performing wire upgrades. However, regulators also add more power loss to the system and may not be desirable to add if there are already many regulators for maintaining the voltage levels.

**2.2.3 Power factor:** PF is another type of constraint typically applied by utilities. It is primarily a reflection of power efficiency (as a very low PF indicates a much higher reactive power component, which entails a higher current running through the system than needed). Some power grid components may have constraints for the PF, they are capable of operating at. Consequently, this constraint is a more useful guide towards improving power efficiency, rather than as a critical power operation constraint.

Achieving higher PF ( $\approx 1.00$ ), only comes through a reduction in reactive power consumption. Consequently, PF correction, usually in the form of adding capacitor, is typically the best way to solve PF problems. Balancing the reactive power with a suitable sized capacitor to bring lagging PFs back to leading is the best approach, and is similar to the capacitor addition algorithm. The converse situation of needing to correct a leading PF is not as common, but may occur during non-peak load periods, when there are more capacitors added to the grid than are needed. As the focus of the

compartmentalisation method is on peak power conditions, the leading PF problem will not be examined in great detail.

### 3 Optimisation formulation and comparisons

To properly validate compartmentalisation, it is necessary to compare its performance to other types of design methods. In one method which utilises multi-variable global optimisation, all power grid problems  $\Psi^P$  are solved during post-analysis time simultaneously while considering all the power grid variables [8, 9]. The multi-variable global optimisation method may not be applied in power grid design and maintenance in practice, see the following for the justification; each problem in a power grid can be defined by multiple constraints, where each one of them addresses a specific aspect of the problem. There might be some constraints that overlap (i.e. meeting a constraint or solving the problem in that aspect, may benefit other constraints in other aspects of the problem). Moreover, for each subproblem or constraint, there may be multiple variables to consider, in order to discover the problem and apply an individual solution. These variables that need to be measured, evaluated or modified, comprise the solution space  $S_{s_i}$  (the space for solution  $s_i$ ). The space size depends on the specific solution for the problem. For instance, in the wire conductor upgrading algorithm which may be used to solve the thermal overloading problem [see Algorithm 1 (Fig. 4)], the solution space includes all the nodes (with or without load), edges connecting the nodes, and the database of wire conductors given to the solution. The algorithm needs to search through the database of wire conductors ( $ED^{OH}$ ) to find the best one by checking the values for voltages of the nodes ( $\Psi^{NE}$ ) and currents through the edges ( $\Psi^{BE}$ ) to meet the constraints defining the problem. Therefore, the space size for this particular solution is  $O(|ED^{OH}| \times |\Psi^{NE}| \times |\Psi^{BE}|)$ . Moreover, the size of the solution space may indicate the order of the complexity of the algorithm. The time it takes for the algorithm to solve the problem may be  $O(f(\text{size of the solution space}))$ , where  $f(n)$  is a polynomial function of  $n$ . Moreover, by considering more subproblems and constraints at the same time, the multi-variable global optimisation method needs to search through the space of all the solutions to the problems. Therefore, the total solution space ( $S_T$ ) would be multiply of the solution spaces and the size of it will be asymptotically multiple of the size of the solution spaces and it will increase exponentially:

$$S_T = \prod_{i=1}^n S_{s_i} \quad (1)$$

$$|S_T| = \prod_{i=1}^n |S_{s_i}| \quad (2)$$

On the other hand, both in our compartmentalisation method and in the state-of-the-art uncoordinated method, since the solutions are applied sequentially (implementing solutions one after another with/without considering the overlapping effect), the total solution space will be the sum of the solution spaces. As such, the size of the sum of the solution spaces will be asymptotically the size of the largest solution space and it will increase in polynomially. This is due to the fact that the bottleneck of the total solution will be asymptotically defined by the complexity of the largest solution [24]:

$$S_T = \sum_{i=1}^n S_{s_i} \quad (3)$$

$$|S_T| = \max_i |S_{s_i}| \quad (4)$$

Although relaxing the solution space in the multi-variable global optimisation method may help the practicality of the method in terms of complexity, it may deviate from the global optimum solution. Therefore, global optimisation may not be applied in power grid design and maintenance in practice. On the other hand, the complexity of the uncoordinated method increases polynomially,

since the single-variable optimisations are done sequentially. However, in our compartmentalisation method the permutation or ordering of the solutions (single-variable optimisation) is also optimised which enables us to consider the overlapping effect of the solutions (see Section 4). This becomes more efficient, since the compartmentalisation is checking the power grid to see if more solution is required before applying. This will result in a solution close to the global optimum point for multi-variable optimisation which was not possible in uncoordinated methods.

### 4 Present compartmentalisation method

Compartmentalisation method is trying out and substituting different solutions to certain power grid problems. The cost of the final solution is evaluated just by the summation of all the individual solutions recommended. However, the attempt of finding the most cost-effective solution, requires exploration across different scenarios (i.e. implementing a voltage upgrade solution as opposed to a wire upgrade for a thermal overloading problem). Moreover, there is an important value in performing mid-optimisation evaluation; examining how effective one single implemented solution is to the whole. One possible metric is to evaluate how many subproblems a single solution implementation solves, another metric is to evaluate the cost per subproblem solved. These costs include both the cost of purchasing materials as well as the cost of installing the materials onto the system. When considering wire upgrades on an existing line section, the solution cost also includes the cost of removing the existing conductor. Finally, the selection and ordering of the solutions for a single type of problem need to be optimised.

*Definition 4:* The cost of a solution  $C_{k,h}$  is defined as the total value (monetary and manpower effort) needed to implement a solution  $h$  to a power grid problem  $k$ . It needs to be noted that the maintenance cost for each solution or component can also be included in the capital cost as extra information in order to be considered during the optimisation of the compartmentalisation method.

*Definition 5:* The designer-defined weights for the objective function parameter  $\omega_{\text{cost}}$  and  $\omega_{\text{solved}}$  represent how much impact the cost of a solution and the number of solved problems per solution has on guiding the optimisation, respectively.

The objective function focuses on minimising the cost of the solution  $h$  proposed for each problem  $k$  in  $\Psi^{BE}$ , as well as maximising the number of solved problems per solution. This function is represented through (5), with the constraints listed in (6)–(9). The weights  $\omega_{\text{cost}}$  and  $\omega_{\text{solved}}$  allow the designer to guide exactly how much weight the optimiser should assign to either minimising the cost of the solutions proposed over maximising the problems solved per solution, respectively. The actual meaning of these weights is a joint interest in both the designer's preferences for monetarily cheaper solutions in the final (by reducing the cost of a solution over all solutions recommended) implementation, as well as to guide the sequential optimisation (by solving the maximum number of problems per solution). It should be acknowledged that the former weight is universally useful to the designer, while the latter weight is useful only to the guidance of the optimisation.

$$\min. C_{\text{tot}} = \sum_{h \in \Psi^{BES}} (\omega_{\text{cost}} C_{k,h} - \omega_{\text{solved}} \text{Num}_{i,h}^{\text{Solved}}) \quad (5)$$

$$\text{subject to: } \forall i \in \Psi^{BE} \quad (6)$$

$$I_i \leq (I_i^{\text{Max}})(I^{\text{Max}\%}) \quad (7)$$

$$V_i^{\text{DN}} \leq (V_{\text{nom}})(\Delta V^{\text{Max}\%}) \quad (8)$$

$$\left| \text{PF}_{\text{lag}}^{\text{Max}} \right| \leq \text{PF}_i \geq \left| \text{PF}_{\text{lead}}^{\text{Max}} \right| \quad (9)$$

A critical component of the compartmentalisation is the selection and ordering of the solutions in solution library. It takes in information about the problem being solved and determines the best possible types of solution to implement. In addition, it also has access to the component database in order to know what possible components to upgrade to. Cost information about the component upgrades is also included in the component databases from [21, 25, 26], so that it may be calculated towards the cost-based objective function. The designer can specify the order of trying out individual upgrades by modifying  $List_{Type,Solve}$ , which not only contains the overarching types (thermal overload, VD, PF, etc.), but also the individual solutions for each type (wire upgrade, voltage level change, capacitor additions, etc.). The optimisation must be able to analyse and compare multiple solution orderings to find the most cost-effective one. For the purpose of comparison, the power grid simulator will need to re-run to perform the analysis. This is achieved by calling a function such as Algorithm 1 (Fig. 4), applying the solutions in the defined order, and checking the new power grid. As an example, a common  $List_{Type,Solve}$  and  $List_{TO,Solve}$  may be:

$$List_{Type,Solve} = [TO, VD, PF] \quad (10)$$

$$List_{TO,Solve} = [WU, LT, VU, CA] \quad (11)$$

Compartmentalisation needs to be able to explore the solution space and attempt different solutions. As demonstrated in the solving methods, multiple solutions may be provided to a given type of problem. Consequently, the need to examine each solution and explore the benefits of each, needs to be represented. The optimisation process should consider not only the total benefits of all solutions proposed, but also the delta benefit provided by a single solution. For instance, one solution implementation that solves five problems could be considered more preferable over one solution implementation that only solves 2 problems. Unfortunately, it is possible that this per-solution optimisation may result in finding only a local optimum as opposed to a global optimum. For a solution  $h$  to a problem  $i$ , the variable representing this number of problems solved by the  $h$  solution would be  $Num_{i,h}^{Solved}$ . This value would ideally be at least 1 (solving the problem  $i$  itself), but a higher value would be indicative of being more desirable.

To solve the problems, the optimiser performs multiple iterations of modifying the grid via the information provided in  $List_{Type,Solve}$ . When attempting multiple solutions at once before applying them (as controlled by  $N_{solve}$  parameter), different permutations across these solutions are also considered.

## 5 Experimental results

### 5.1 Experimental setup

To properly validate the compartmentalisation method, we have used 'IEEE 123 Node Test Feeder' [27] model as the base grid, and expanded it by connecting four more of these 123-node systems. Each system has different load growth rate which is generated randomly. The availability of the four systems linked only at the substations, allows us to transfer the load from an overloaded system to another under-loaded one. The power grid behaviour has been defined and simulated by the state-of-the-art power grid simulator software GridLAB-D [15] and GridMat [14, 28] using complex equations inside their libraries. Though many methods of power flow analysis exist, we have used Newton-Raphson method because of its very fast convergence rate [29]. Moreover, the algorithms for the optimiser in compartmentalisation (see Section 4) are implemented using the Python programming language [30]. The main optimisation has been done using an exhaustive search. Multiple Python scripts are implemented to parse the grid model (GLM file), export it as a set of databases, and model the new grid after applying the solutions. These databases holding information

about the grid are used as inputs to our compartmentalisation method. The modular programming is used to provide the designer, the capability to add or remove specific problems, constraints or solutions in the algorithm.

### 5.2 Case studies and method analysis

For each solution applied to a problem, we have used a variable called ( $N_{solve}$ ) that defines the number of individual solutions applied for each subproblem before doing the simulation again to check whether the power grid needs more solutions. We analyse the effect of  $N_{solve}$  on the result of the compartmentalisation method. By increasing ( $N_{solve}$ ), more solutions will be applied per iteration, as a result, there might be more solutions overlapping and resulting in higher total cost. On the other hand, by decreasing ( $N_{solve}$ ), less solutions will be applied in each iteration, as a result, some subproblems may be solved by other existing solutions which would mean that the said subproblems would be ignored in following iterations resulting in an overall less total cost (Fig. 5). On the other hand, the number of solutions applied totally may increase with a larger  $N_{solve}$ . However, there is a point ( $\beta$ ) in which the increase in the number of solutions gets less than the increase in the total cost. This means that for simulations, where  $N_{solve}$  is larger than  $\beta$ , it is observed that more expensive solutions are used.

Analysing  $N_{solve}$  while considering all possible permutations of problems and solutions shows that increasing  $N_{solve}$  more than a specific point ( $\alpha$ ), increases the total cost significantly (see Fig. 5). The value of  $N_{solve}$  at point  $\alpha$ , depends on the overlapping factor between individual solutions to the problems. Moreover, if two individual solutions to a problem have overlapping effect on the grid (e.g. applying two individual solutions may improve VD on the same node, though the solutions are supposed to improve the VD of two other nodes), applying both in one iteration without checking whether the problem still exists, may increase the total cost, though it could have been solved with less total cost. On the other hand, increasing  $N_{solve}$  and total cost may result in further reduction of power loss in the wires. Although excessive power loss reduction benefits the Utility, the total solution may get expensive for the same constraints.

The uncoordinated method is like applying all the individual solutions ( $N_{solve} \rightarrow \infty$ ) sequentially (with an arbitrary ordering), with the assumption that they do not overlap. In this case, the total cost reaches the maximum value possible (Fig. 5). The power grid is not checked to see if more type of solution is required or not. Despite the large total cost of implementing the state-of-the-art uncoordinated method, the results show the most reduction in power loss as a result of over-engineering.

As we saw in Figs. 5 and 6, increasing  $N_{solve}$  too much will result in significant increase in total cost and getting solutions further from optimum point. Therefore,  $N_{solve} = 16$  at point ( $\alpha$ ), may be the best simulation setting to find the best solution for this particular grid system. By applying the solutions around the optimum point, we have decreased the total cost of the final solution (\$ 251 K) by 70.7% compared with the uncoordinated method (\$ 846 K) and minimised the power loss about 45%. This value is called the

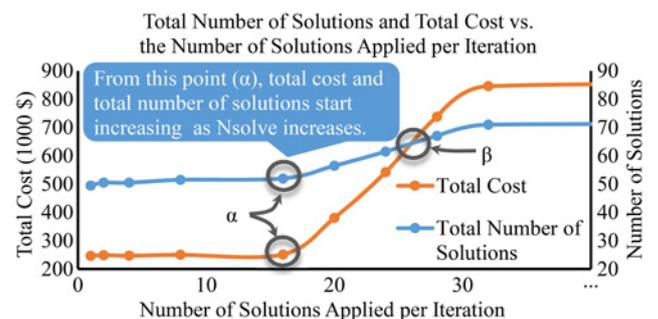


Fig. 5 Analysis of total number of solutions and total cost

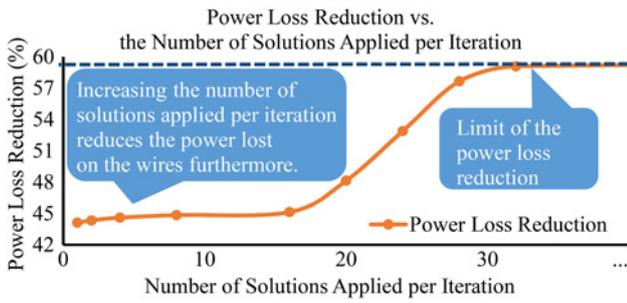


Fig. 6 Analysis of power loss reduction

efficiency of the method:

$$\text{Efficiency (\%)} = \frac{\text{Total Cost}_{\text{uncoordinated}} - \text{Total Cost}_{\text{optimum}}}{\text{Total Cost}_{\text{uncoordinated}}} \times 100 \quad (12)$$

Final solutions may vary by changing the order of applying them to address the problems. As shown in Fig. 7, multiple types of solutions may be applied to solve different problems. As it has been stated before, the order of applying solutions is crucial. For instance, the load of the grid connected to *node\_72\_2* is transferred to *node\_54\_4*; another portion of the grid. This transfer resulted in one wire conductor upgrade for the edge connecting *load\_52\_4* and *load\_53\_4*. On the other hand, if the wire upgrade solution is applied before the load transfer solution, there would be more wire upgrades in the overloaded grid, resulting in a possible greater total cost.

On the basis of the number of solutions and problems, we have analysed 24 different orders with *Nsolve* assumed to be 16 (the optimum point). Some of them are shown in Table 1.

There are two different types of permutations; permutation of solutions or subproblems within a problem, is called intra-permutation and permutation of problems at the higher level is called inter-permutation.

### 5.3 Intra-permutation

Changing the order of subproblems or solutions within a problem might have less effect, since the constraints may not overlap significantly. As shown in the 1st and 2nd rows of Table 1, applying the LT (load transfer) solution before applying the WU (wire upgrade) solution for the thermal overload (TO) problem may have less total cost (1.3% decrease). In addition, applying the capacitor addition (CA) solution before the WU (wire upgrade) solution for the VD problem may decrease the total cost (0.5% decrease) [The rates used for evaluating the costs may have a

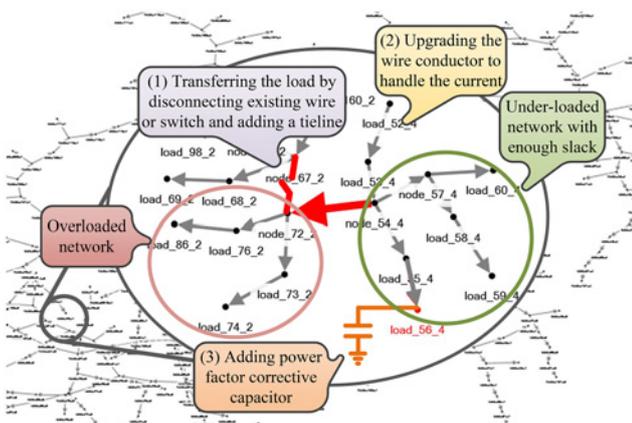


Fig. 7 Process of applying different solutions for solving the problems

Table 1 Different orders of all problems and solutions (List<sub>Type,Solve</sub>) are analysed with their total cost

	Total ordering			Total
Problems	VD	PF	TO	
Solutions	WU CA	CA	LT WU	
# of Problems	123	0	27	150
Cost, \$	235,762.23	0	21,532.82	257,295.04
Problems	VD	PF	TO	
Solutions	WU CA	CA	WU LT	
# of Problems	123	0	27	150
Cost, \$	235,762.23	0	24,827.10	260,589.32
Problems	TO	PF	VD	
Solutions	WU LT	CA	WU CA	
# of Problems	40	42	21	103
Cost, \$	55,228.26	177,253	13,061.93	245,543.19
Problems	TO	PF	VD	
Solutions	WU LT	CA	CA WU	
# of Problems	40	42	21	103
Cost, \$	55,228.26	177,253	11,822.63	244,303.89
Problems	PF	VD	TO	
Solutions	CA	WU	WU LT	
# of Problems	42	81	27	150
Cost, \$	174,562.00	61,432.35	23,944.27	259,938.62
Problems	VD	PF	TO	
Solutions	WU CA	CA	WU LT	
# of Problems	123	0	27	150
Cost, \$	235,762.23	0	24,827.10	260,589.32
Problems	PF	TO	VD	
Solutions	CA	LT	WU CA	
# of Problems	42	40	24	106
Cost, \$	174,562.00	52,838.97	14,665.09	242,066.06
Problems	TO	PF	VD	
Solutions	LT WU	CA	WU CA	
# of Problems	40	42	21	103
Cost, \$	53,021.28	177,253	13,913.88	244,188.16
Problems	PF	TO	VD	
Solutions	CA	LT	CA WU	
# of Problems	42	40	24	106
Cost, \$	174,562.00	52,838.97	14,226.51	241,627.49
Problems	PF	VD	TO	
Solutions	CA	CA	LT WU	
# of Problems	42	81	27	150
Cost, \$	174,562.00	60,603.01	21,532.82	256,697.82

significant effect on the total cost. If a solution is more preferable, it may be assigned less cost or weight in order to get the optimiser to consider that as the best order.].

### 5.4 Inter-permutation

On the other hand, looking from higher level, by changing the order of problems to be solved, we might get better results. Moreover, the overlap between different problem may be large enough that solving one may benefit another one, resulting in less total cost. Moreover, some problems may have the same solution to meet their constraints, e.g. VD problems and PF problems may have the same solution as CA. For instance, the fifth and sixth rows in Table 1, show that solving PF problems before VD problems would result in a non-significant decrease in cost (0.2% decrease); which can be explained as such since both problems use the same solution to meet a constraint. Moreover, solving the PF problem before the TO problem would decrease the total cost (0.9% decrease) (shown in 7th and 8th rows), though the problems do not overlap enough to change the result significantly. On the other hand, by looking at 9th and 10th rows, solving the VD problems before TO problems may result in a significant decrease in the total cost (6% decrease). The reason for this is suggested to be that these are using different solutions to meet different constraints, which results in overlap in some parts of the grid. Moreover, when TO problems are solved before VD problems, more constraints are met (i.e. the number of total problems decreased). Therefore, it seems the overlapping effect not only improved the total cost but also solved some other problems, which also may be the reason for the observed decrease in total cost.

The final solution total cost depends greatly on the cost of the components. Moreover, the labour cost may change the total cost. The difference between the total cost at the point with optimum

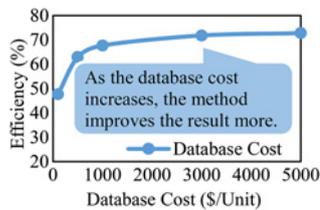


Fig. 8 Effect of the database cost on the method efficiency



Fig. 9 Effect of the labour cost on the method efficiency

simulation settings against that of the uncoordinated method, indicates the efficiency of the method in that specific case. As shown in Fig. 8, by increasing the price of the components, the efficiency of the method increases, resulting in much less total cost compared with the uncoordinated method [2] (better optimisation). On the other hand, in Fig. 9, by decreasing the labour cost we will get better efficiency. This may be due to the fact that increasing the labour cost might dominate the total cost, resulting in no space for optimisation.

## 6 Conclusion

The problems existing in the power distribution grid are handled individually by single-variable optimised standard solutions which require a significant amount of both information processing and iterations. However, when considering multiple problems and variables simultaneously, the complexity of the global optimisation method increases exponentially. Moreover, using uncoordinated method to solve the problems sequentially may not give the optimal solution, due to the overlapping effect of the solutions. We have presented a novel compartmentalisation-based design method to solve multiple problems and meet the regulatory constraints. The algorithmic formalisation of the design solutions, as well as the ability to experiment with the ordering of these solutions, allow the designers to determine the optimal ordering of these sequential solutions to the holistic system. In our experiments, multiple orders of solutions have been analysed and the best one is chosen, in which the total cost of the solution may decrease about by 71% compared with the uncoordinated method and minimise the power loss about by 45% after optimisation.

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