

An Approach for Establishing a Common Grid Model for Flow-based Market Mechanism Simulations

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Abstract—The discussions on the development of an electricity market model for accommodating cross-border cooperation remains active in Europe. The main interest is the establishment of market couplings without curtailing the fair use of the scarce transmission capacity. However, it is difficult to gain mutual consensus on this subject because of the absence of convincing simulation results for the entire region. To achieve that, researchers need a common grid model (CGM) which is a simplified representation of the detailed transmission model which comprises aggregated buses and transmission lines. A CGM should sufficiently represent the inter-area power flow characteristics. Generally, it is difficult to establish a standard CGM that represents the actual transmission network with a sufficient degree of exactness because it requires knowledge on the details of the transmission network, which are undisclosed. This paper addresses the issue and reviews the existing approaches in transmission network approximation, and their shortcomings. Then, it proposes a new approach called the adaptive CGM approximation (ACA) for serving the purpose. The ACA is a data-driven approach, developed based on the direct current power flow theory. It is able to construct a CGM based on the published power flow data between the inter-connected market areas. This is done by solving the issue as a non-linear model fitting problem. The method is validated using three case studies.

Index Terms—Common grid model, flow-based market mechanism, genetic algorithms, linear optimal power flow problems, transmission network approximation.

I. INTRODUCTION

THE liberalization of electricity markets and the increasing use of renewable energy sources (RESs) in the European power systems have created many trade and collaboration opportunities. Naturally, large RES generators (such as offshore wind farms) are built further away from the load centers [1], [2]. This motivates more cooperation in transmission network expansion, cross-border power exchanges, and power systems integration; as well as the creation of several cross-border trading mechanisms [3].

Currently, researchers are uncertain on the eventual market model which best facilitates the power exchange in the entire region. A guideline developed under the European internal electricity market (IEM) program [4] favors the adoption of a flow-based market mechanism (FBMM) [5], [6], which basically conducts generation dispatch planning based on a common transmission network model mutually agreed to by all of the participating transmission system operators (TSOs). The network model is called the common grid model (CGM) [7].

The CGM is a simplified representation of the regional power system. It either consists of: 1) buses representing market areas and inter-connectors representing the interfaces between the market areas [7]–[9] (the term “inter-connector” is used henceforth for a transmission line in the CGM); or 2) buses representing reasonable aggregation of a number of buses possessing similar electrical properties and inter-connectors representing reasonable aggregation of transmission lines connecting the aggregated buses [10], [11]. The CGM is presently adopted in the central-west Europe (CWE) flow based market coupling (FBMC) mechanism for calculating the available (cross-border) transfer capacity. For practical reasons, one CGM is built (in the FBMC) for each of the 24 hours of the day of dispatch [9], [12]; and the building process begins at 48 hours before the hour of dispatch.

The core of the FBMM is the implementation of least-cost direct current optimal power flow (DCOPF) [13]–[15] on the CGM for obtaining the most efficient generation dispatch plan for the entire region. The method is capable of suggesting a solution that does not violate the known transfer limit of the transmission lines connecting two neighboring areas. It also maintains the representation of the physical characteristics (i.e., the loop flow) of power flow within the network.

For the time being, researchers are not able to fully quantify the potential benefits of implementing FBMM. This is because, they do not have a standard and publicly accessible CGM. The problem remains critical to academic studies, because the CGM is a common reference for establishing conclusive debates [11]. Thus, a method capable of appropriately approximating the CGM is needed within the research community.

Several researchers have proposed methods for representing the Pan-European transmission network (e.g., [10], [11], [16], [17], to name a few). Nevertheless, these methods are not strictly developed for serving flow-based simulation purposes. Among others, the method presented in [10], [11] is popular. It approximates the impedance of all transmission lines, by

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measuring their length from the published European network for TSO for electricity (ENTSO-E) map and computing the values based on the impedance per unit length estimation [11]. Transmission lines possessing a voltage level less than 220 kV are ignored in this procedure.

In order to reduce the model's complexity, it aggregates transmission lines and buses based on similarity in electrical properties. The method is used in [16] for creating a pan-European transmission network with aggregated buses and transmission lines. In this model, the buses are aggregated such that the transfer capacity within the aggregated buses is higher than the transfer capacity between them. It is also used in the RE-Europe dataset [17], which builds a reference transmission network model of mainland Europe for studies of electricity markets with a high share of renewable generation.

These approaches could affect the quality of the resulting model because the power flow results derived from simplifying a detailed transmission network model are sensitive to the correctness of the assumed parametric values of its components and their changes. For example, a mismatch in the estimated impedance of one transmission line would cause different power flow for every other transmission line, let alone the effect of excluding some of the transmission lines from the model (as in [10], [11]).

To cope with this, the authors propose a data-driven approach called the adaptive CGM approximation (ACA) for constructing a valid CGM based on the published physical power flow data. This method approximates the impedance values of the inter-connectors in the CGM using genetic algorithm (GA). This method is formulated based on the direct current (DC) power flow theory. Thus, a CGM is sufficiently established once the impedance values are correctly approximated. This method is adaptive and highly feasible as it does not require any prior knowledge on the actual transmission network configurations.

II. THE ADAPTIVE CGM APPROXIMATION

The ACA automatically constructs a CGM consisting of: 1) a number of buses which represent a group of buses (they could also represent the market areas); and 2) inter-connectors which represent the interfaces between the represented buses. It is generally designed for constructing 2 types of CGM: 1) the reduction of a detailed transmission network model to a simplified version consisting of aggregated buses; and 2) the reverse engineering of published inter-area power flow data into a CGM. The procedure begins with the acquisition of published (ex-post) power flow data of a transmission network, followed by the establishment of a CGM through inverse computation of the impedance of the inter-connectors.

For example, the transmission network model shown in Fig. 1 could be represented by a simplified form possessing 3 buses as shown in Fig. 2. The ACA could then approximate the impedance of the inter-connectors based on the ex-post power flow data. Also, the zonal market model of the meshed Nordic transmission network (see Fig. 3) could be represented by a CGM consisting of 12 buses (each of the buses represents a market area) and 20 inter-connectors. The representation of

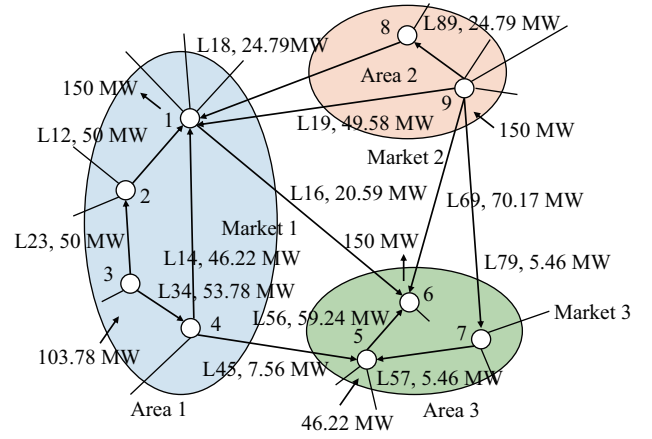


Fig. 1. A stylized 9-bus (3-area) transmission network model.

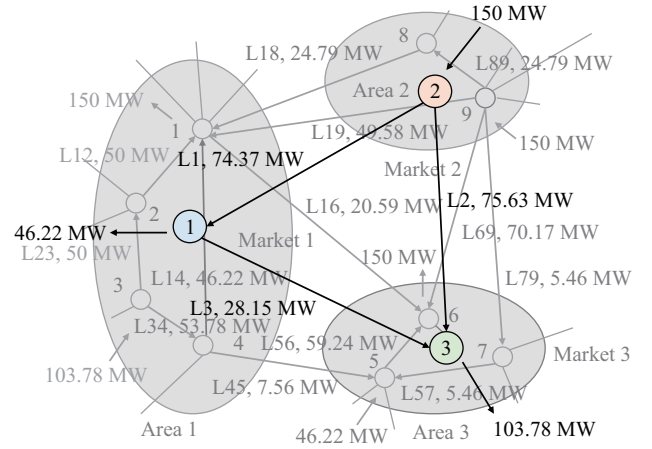


Fig. 2. The aggregation of the 9-bus transmission network model.

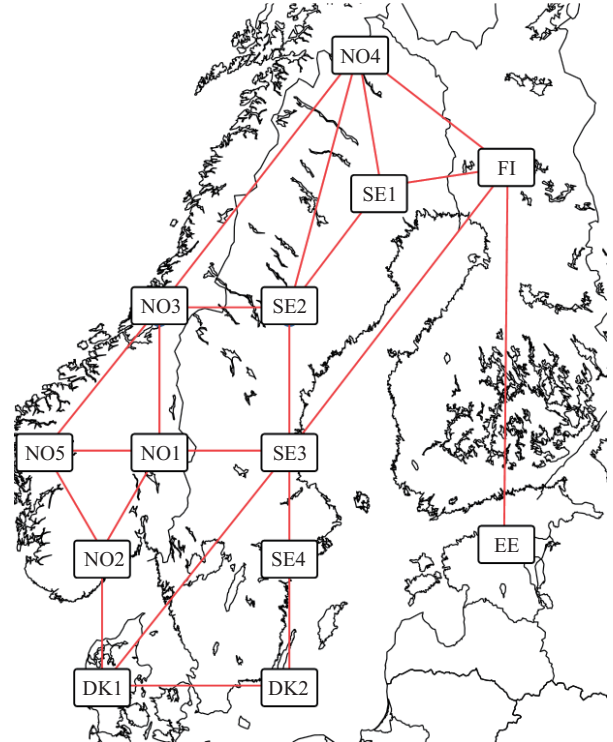


Fig. 3. The CGM of the Nordic electricity market [20].

the inter-connected market areas in the form of the CGM is especially meaningful because a market area is designated by a TSO with consideration that it has sufficient internal transfer capacity and the power flow within it has high liquidity. There is no bottleneck of power transfer within each of the designated market areas.

The power transfer distribution factors (PTDFs) of the CGM could be computed once the impedance values of the transmission lines are known. The PTDFs are useful in the regional least-cost dispatch simulation of the FBMM (e.g., the Nordic Flow-Based Market Coupling (FBMC) [9], [18]) because they are the indicators of the sensitivity of a power dispatch on the power flow on each of the inter-connectors. The ACA does not require any prior knowledge on the configurations of the components in the transmission network. Its objective is to create a simplified but physically intuitive higher-order representation of the transmission network.

III. THE ACA FORMULATIONS

The ACA is a method derived based on the DC power flow theory [19]. The theory relates the voltage angle to the net active power at the buses of a transmission network comprising N buses as follows.

$$\mathbf{P} = \mathbf{B} \boldsymbol{\theta} \quad (1)$$

The $\mathbf{P} = [P_{\text{net},1}, P_{\text{net},2}, \dots, P_{\text{net},N}]^T$ contains the net active power at each bus. The $\mathbf{B}$ is a two-dimension matrix known as the nodal admittance matrix of the inter-connectors. The $\boldsymbol{\theta} = [\theta_{\text{net},1}, \theta_{\text{net},2}, \dots, \theta_{\text{net},N}]^T$ contains the voltage angle of every bus. The elements in $\mathbf{B}$ are defined using the susceptance of the inter-connectors, $b_{ij} = 1/x_{ij}$ (where the indices i and j denote the buses that are connected by an inter-connector); such that $B_{ii} = -b_{ij}; \forall i \neq j$ and $B_{ii} = b_{ii} + \sum_{j \neq i}^N b_{ij}$.

The value of θ is needed for calculating the power flow on each inter-connector, which is computed from (1) as follows.

$$\boldsymbol{\theta} = \mathbf{B}^{-1} \mathbf{P} \quad (2)$$

Then, the power flow on the inter-connectors connecting buses i and j , F_{ij}^* can be calculated as follows.

$$F_{ij}^* = B_{ij} \Delta \theta_{ij} = B_{ij} (\theta_i - \theta_j); \forall i, j \in N \quad (3)$$

Clearly, knowing the exact value of x_{ij} of the CGM is essential for computing (1)–(3). Fortunately, an approximated value of x_{ij} could be found by exploiting (3) by means of reverse engineering, as long as the ex-post power flow of the inter-connectors, F_{ij} is known. This serves as the basis of the ACA.

The key to the implementation of the ACA is the approximation of the x_{ij} value of each inter-connector, which yields the F_{ij}^* that is as close as possible to the corresponding F_{ij} . In other words, it finds an approximated variable, $\mathbf{X}^* = [x_{01}, \dots, x_{ij}], \forall i, j \in N, i \neq j$ which could be used for deriving the $\boldsymbol{\theta}$ (in (2)) and the F_{ij}^* (in (3)) that meet the following objective function, ϕ .

$$\phi = \sum_{i,j=0}^N |F_{ij} - F_{ij}^*| \approx 0 \quad (4)$$

This is a non-linear problem because we have 2 unknown variables in (2) that have to be simultaneously solved: 1) the B_{ij} (or, the x_{ij}) and, 2) the $\boldsymbol{\theta}$. Additionally, it is a model fitting problem because the equations are solved by finding a valid $\mathbf{X}^*$ which fulfills the requirement of (4). The component of the derived $\mathbf{X}^*$, x_{ij} , can be used for calculating the PTDF matrix as follows.

$$\mathbf{PTDF} = \mathbf{B}_r^{-1} \mathbf{B}_f \quad (5)$$

where $\mathbf{B}_r$ is the reduced $\mathbf{B}$ (when the B_{ij} associated with an arbitrarily selected reference bus with $i = 0$ removed); and $\mathbf{B}_f$ is the reduced line flow admittance matrix. A line flow admittance matrix is a two dimensional matrix where each of its rows is associated with an inter-connector connecting buses i and j ; the column value of the row is $-x_{ij}$ when the column index is equal to i ; and x_{ij} when the column index is equal to j . The reduced line flow admittance matrix is formed by removing the column of $\mathbf{B}_f$ associated with the reference bus.

The row within the derived PTDF matrix (in (5)) is associated with an inter-connector, k which connects buses i and j . Each element in the row is the F_{ij} (in MW) associated with the generation of 1 MW of active power at a bus indexed similarly as the column's index, m and a simultaneous consumption of it at the reference bus (bus 0). The elements are denoted by $\mathbf{PTDF}_{m \rightarrow 0, k}$.

The same matrix can be used for computing the PTDFs associated with the simultaneous generation and withdrawal of power at any bus within the CGM. For instance, the PTDF of inter-connector k corresponding to the generation of 1 MW of active power at bus m and the withdrawal of 1 MW of active power at bus n is calculated as below.

$$\mathbf{PTDF}_{m \rightarrow n, k} = \mathbf{PTDF}_{m \rightarrow 0, k} - \mathbf{PTDF}_{n \rightarrow 0, k} \quad (6)$$

The validity of (5) and (6) is independent of the choice of the reference bus.

IV. THE SOLVER

Non-linear model fitting problems are best solved using iterative improvement algorithms [21]–[24]. Generally, a classical iterative improvement algorithm (e.g., hill-climbing algorithm) would create an arbitrary initial $\mathbf{X}^*$ at the start of its implementation, and then tries to improve it by iteratively applying an incremental change to its component, x_{ij} when it calculates the ϕ . Since the algorithm does not have a guiding mechanism for exploring the solution space, it tends to find the poor-quality local optimal $\mathbf{X}^*$. For that reason, the authors adopted the GA as the solver in ACA, due to its known capability in finding a global optimal solution compared to the hill-climbing algorithm [25]. Specially, the micro GA (μ GA) [26], [27] was applied in this study.

The GA is an iterative improvement metaheuristic algorithm which models the finding of the global optimal $\mathbf{X}^*$ in the solution space of the problem as a Darwinian evolution. Its implementation starts with the creation of a pool of M arbitrarily generated $\mathbf{X}^*$. The pool is known as a population of size equal to M . Each $\mathbf{X}^*$ is discretized as a binary solution string (called a chromosome), and is subjected to a series

of evolutionary operations (i.e., fitness evaluation, selection, crossover, and mutation) with the aim to produce a better offspring of $\mathbf{X}^*$. The operations are repeated M times, which constitute one generation. At the end of a generation, the best $\mathbf{X}^*$ found in the population is retained, while the rest of them are replaced by $(M-1)$ arbitrarily generated $\mathbf{X}^*$. A new round of evolutionary operations is then re-initialized and repeated. The algorithm continues to run until either 1) the ϕ of the best $\mathbf{X}^*$ found can no longer be improved and its value is less than $0.1 \times \sum_{i,j=0}^N F_{ij}$ (the stopping criterion of ACA), or 2) the number of generations becomes greater than a pre-defined limit.

The use of GA is not restricted by mathematical limitations of any kind because it simulates the problem solving process as a metaphor. Apart from its robustness, it is able to find the global optimal $\mathbf{X}^*$ as it could escape poor local optimal points within its solution space. This is because, it possesses a balanced mix of the search exploitation and search exploration features. On one hand, it is able to exploit a good $\mathbf{X}^*$ and tends to structurally retain the good quality elements within its discretized solution string (in the subsequent generations) [28], instead of discarding them (as in the hill-climbing algorithm). This leads to a guided convergence. On the other hand, it mixes the best $\mathbf{X}^*$ found in a generation with $(M-1)$ number of arbitrarily generated $\mathbf{X}^*$ to form a new population. This allows GA to explore a wider range of the solution space, leading to a better search diversity.

A properly diversified search within a solution space helps the GA to quickly identify the good $\mathbf{X}^*$ candidates and exploit them. Therefore, it is important to ensure that the GA would occasionally explore the solution space in a random manner. As a result, its search would quickly converge to the global optimal $\mathbf{X}^*$. An effective strategy to achieve this is by reducing the size of the population, M [29], [30]. By doing so, the search becomes more scattered. It also takes less time to complete each of the evolutionary operations. More importantly, the evolutionary operations are re-initialized more frequently with new arbitrarily generated $\mathbf{X}^*$ being introduced into the population. Fig. 4 summarizes the working principle of the μ GA.

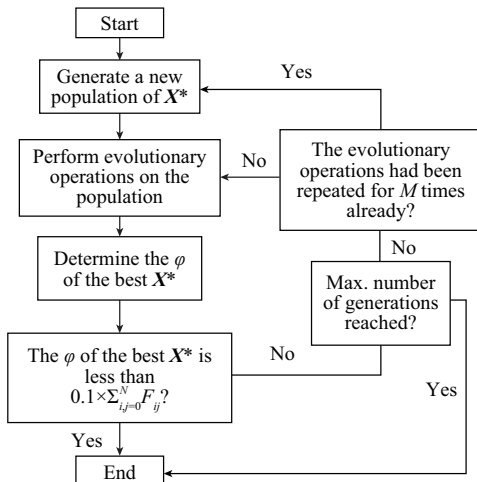


Fig. 4. The work-flow of the μ GA used in ACA.

V. CASE STUDY

Three case studies were conducted for validating the performance of the ACA. The first case (Case 1) uses the stylized 9-bus 3-area transmission network model shown in Fig. 1 for examining the ACA's capability in deriving the x_{ij} (in $\mathbf{X}^*$) of inter-connectors representing interfaces between aggregated buses (the aggregated form of the transmission network model is conceptually similar to the market areas shown in Fig. 2). The second case (Case 2) uses the published Nordic physical power flow data for examining its capability in constructing a CGM based on the inter-area power transfer. The third case (Case 3) is an extension of Case 2, where the ACA is tested with 6 sets of published (hourly) power flow data of the Nordic power systems. The objective of Case 3 is to investigate the applicability of ACA on other instances of the Nordic power flow data.

The μ GA was codified using an open source GA solver called Pyevolve [31]. The values of the parameters used in the solver are shown in Table I, which are adopted from [26], [27]. The algorithm adopts a population size of 5 and a maximum number of 100,000 generations (of the population).

TABLE I
THE VALUES OF PARAMETERS USED IN THE μ GA SOLVER

Parameter	Value
Population size	5
Maximum number of generations	100, 000
Crossover method	Uniform crossover
Mutation method	Gaussian mutation
Crossover probability	0.5
Mutation probability	0.2

A. Case 1

The ACA was applied to 2 sets of power flow data as inputs. The first set of power flow data is shown in Fig. 2 and the second set is shown in Fig. 5. These data are respectively called Case 1(a) and Case 1(b). The optimal value of the x_{ij} of the CGM in Case 1(a) and Case 1(b) (based on the global optimal $\mathbf{X}^*$ derived by the μ GA) is respectively shown in Tables II and III, along with the results of the DC power flow implemented using it. Clearly, ACA is able to approximate

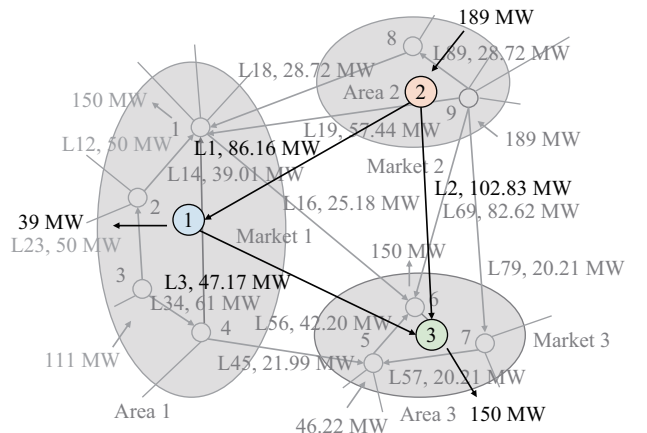


Fig. 5. The transmission network model of Case 1(b).

TABLE II
THE SOLUTION OF CASE 1(A)

Line	Bus <i>i</i>	Bus <i>j</i>	x_{ij}	F_{ij}^* (MW)	F_{ij} (MW)	$ F_{ij} - F_{ij}^* $
L1	B2	B1	4.71	74.3700	74.3722	0.0022
L2	B2	B3	7.58	75.6300	75.6278	0.0022
L3	B1	B3	7.92	28.1500	28.1522	0.0022
				$\sum F_{ij} = 178.1522$ $\phi = 0.0066$		

TABLE III
THE SOLUTION OF CASE 1 (B)

Line	Bus <i>i</i>	Bus <i>j</i>	x_{ij}	F_{ij}^* (MW)	F_{ij} (MW)	$ F_{ij} - F_{ij}^* $
L1	B2	B1	4.71	86.17	86.1702	0.0002
L2	B2	B3	7.58	102.83	102.8298	0.0002
L3	B1	B3	7.92	47.17	47.1702	0.0002
				$\sum F_{ij} = 236.1702$ $\phi = 0.0006$		

x_{ij} . As shown in the tables, the ϕ value is 0.066 MW for Case 1(a) and 0.006 MW for Case 1(b). Their respective deviation from the $\sum F_{ij}$ are 0.0037% and 0.0003%. Both values are negligible.

B. Case 2

The ACA was applied for constructing a CGM using the published power flow data of the Nordic power systems on Jan. 1, 2015 at 12:00 PM (local time) (data available at [19]). The net power, P_{net} at the buses of the CGM (each of the buses represents a market area) and the cross-border power flow data are shown in Tables IV and V.

TABLE IV
THE NET POWER, P_{net} INFORMATION OF THE BUSES IN THE CGM

Index	Bus	Area	P_{net} (MW)
0	B1	NO1	-2092
1	B2	NO2	-1327
2	B3	NO3	-1212
3	B4	NO4	-584
4	B5	NO5	616
5	B6	DK1	2340
6	B7	DK2	665
7	B8	SE1	1166
8	B9	SE2	1032
9	B10	SE3	1782
10	B11	SE4	-851
11	B12	FI	1535

TABLE V
POWER FLOW ON THE TRANSMISSION LINES IN THE CGM

Line	Bus <i>i</i>	Bus <i>j</i>	F_{ij} (MW)
L1	B1	B3	216
L2	B5	B1	805
L3	B10	B1	1503
L4	B2	B5	189
L5	B6	B2	1516
L6	B4	B3	155
L7	B9	B3	841
L8	B8	B4	506
L9	B9	B4	200
L10	B12	B4	33
L11	B6	B10	337
L12	B6	B7	487
L13	B7	B11	1152
L14	B8	B9	5
L15	B8	B12	655
L16	B10	B9	4
L17	B10	B12	913
L18	B11	B10	301

The optimal x_{ij} (based on the global optimal $\mathbf{X}^*$ derived by the μ GA) is shown in Table IV, along with the results of the DC power flow implemented using it. As shown, the computed power flow does not noticeably deviate from the published value. The maximum deviation occurs at L16 (which is 16%), which poses a negligible effect on the validity of the CGM because its value (0.64 MW) is significantly smaller than the total power flow within the network (9818 MW). As the deviation of ϕ from the $\sum F_{ij}$ is 0.096%, we can ascertain that the derived $\mathbf{X}^*$ has reliably reflected the physical attribute of power flow for the test case. The derived CGM is illustrated in Fig. 6 (the inter-connectors connecting 1) bus 3 and bus 5; and 2) bus 1 and bus 2 are not represented in the CGM studied because a physical power flow does not occur between these areas in the input model. Case 3 shows that the removal of these inter-connectors does not affect the quality of the CGM produced).

TABLE VI
THE SOLUTION DERIVED USING THE ACA

Line	x_{ij}	F_{ij}^* (MW)	F_{ij} (MW)	$ F_{ij} - F_{ij}^* $
L1	7.087	215.71	216	0.29
L2	4.758	804.90	805	0.10
L3	1.393	1502.81	1503	0.19
L4	8.490	188.90	189	0.10
L5	0.009	1515.90	1516	0.10
L6	9.954	156.70	155	1.70
L7	4.260	839.59	841	1.41
L8	4.101	505.33	506	0.67
L9	9.954	202.64	200	2.64
L10	6.141	32.72	33	0.28
L11	9.954	337.00	337	0.00
L12	1.951	487.10	487	0.10
L13	0.278	1152.10	1152	0.10
L14	9.894	5.59	5	0.59
L15	2.856	655.08	655	0.08
L16	9.954	4.64	4	0.64
L17	2.040	912.65	913	0.35
L18	6.918	301.10	301	0.10
				$\sum F_{ij} = 9818$ $\phi = 9.44$

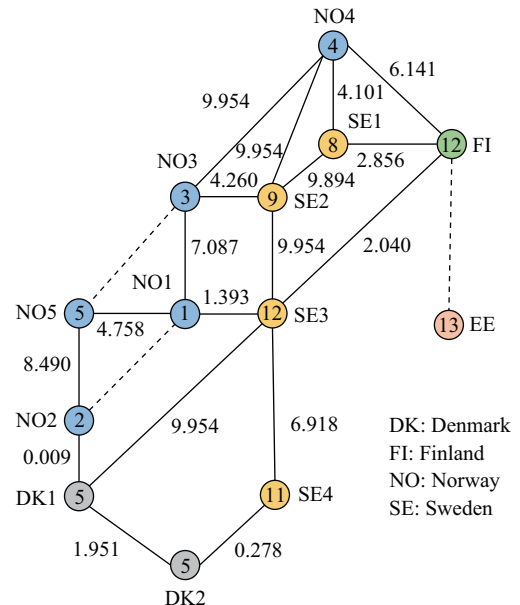


Fig. 6. A stylized representation of the Nordic CGM.

Since all of the x_{ij} are known, we can compute the PTDFs of the network (using (5) and (6)). For example, the PTDFs for the transfer of 1 MW power from B4 to B1 are shown in Fig. 7. As can be seen, the loop-flow effect in the meshed grid causes part of the power to flow to buses located in other market areas before reaching B1. This must be taken into account when a power exchange is being established. Otherwise, a direct transfer of power between two market areas may congest interfaces connecting other but irrelevant market areas.

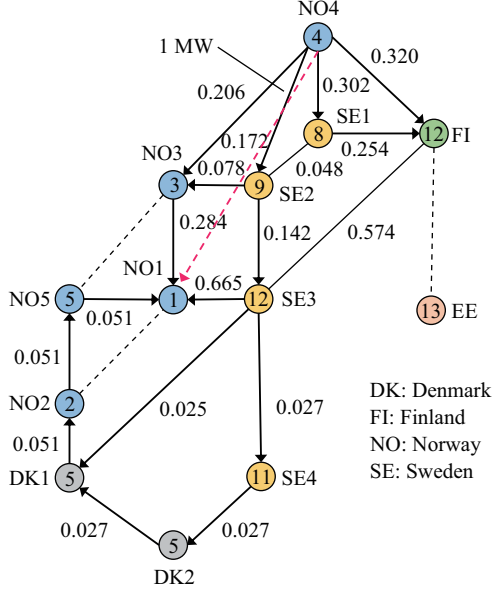


Fig. 7. The power changes on lines (PTDFs) for the transfer of 1 MW power from B4 to B1.

The performance of ACA can be quantified based on the time it needs for solving a problem. As shown in Table VII, the authors implemented 10 repetitions of the ACA on the test case using 2.40 GHz CPU speed (on a personal computer equipped with a 2.40 GHz $\times$ 8 Intel Core i7 vPro CPU and 8 GB RAM running the 64-bit Ubuntu 12.04 Linux operating system). Clearly, the total time, T taken for establishing the CGM varies for each case, with 3.85 minutes as the average. Overall, the ACA run-time is acceptable.

TABLE VII
THE TIME NEEDED BY THE ACA FOR FINDING THE OPTIMAL SOLUTION
(IN 10 REPEATED IMPLEMENTATIONS)

Run	T (min.)	ϕ (MW)	Δ (%)
1	6.88	9.46	0.096
2	5.44	9.44	0.096
3	2.03	9.82	0.100
4	1.11	9.79	0.099
5	3.84	9.55	0.097
6	7.19	9.60	0.098
7	1.13	9.90	0.100
8	1.37	9.48	0.097
9	7.68	9.82	0.100
10	1.85	9.77	0.099

In addition, the performance of the μ GA can be observed in Fig. 8 which presents 2 charts created based on data collected in the first repetition (in Table VII): 1) the time, t versus t and; 2) the fitness quality, α versus α chart, where,

$$\alpha = 100 \times \left(1 - \frac{\phi}{\sum F_{ij}}\right) \quad (7)$$

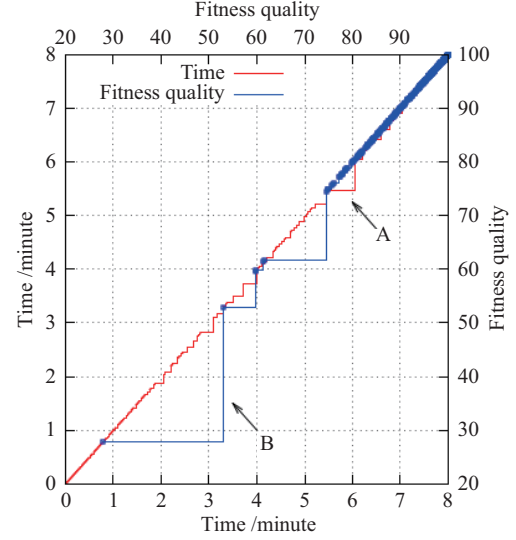


Fig. 8. Schematic showing the search performance of μ GA.

The first chart shows that the μ GA requires a short time interval, Δt to find an improved solution within the solution search space. Longer Δt is observed only at the time between $t = 5$ and $t = 6$ minutes (see label “A” in the figure), where the μ GA dwells slightly longer than 30 seconds before finding a better solution.

The second chart shows the extent of improvement in the α made by the μ GA in every subsequent solution. Clearly, the μ GA exhibits the expected performance as it quickly shifts its position within the solution space from a local optimal X^* to a substantially better one within a very short Δt at the earlier stage of its implementation. As shown, the α greatly improves as the first 4 solutions are found (the first α improvement is marked with label “B” in the figure). This reflects its exceptional search diversification capability.

Moreover, a good metaheuristic algorithm must be able to determine a promising local minimum after some attempts of search diversification, and subsequently exploit it for finding the global minimum solution [32]. This feature too has been demonstrated by the μ GA [33]. As shown, the μ GA identifies a promising local minimal X^* as the fourth solution is found, and then starts its search exploitation. The Δt needed for finding better solutions beyond that solution remains small, which indicates continuous (in time) improvements in the quality of the found solution.

In other words, the μ GA quickly finds a promising local minimum at the earlier stage of optimization. Afterwards, it intensifies its search around the local minimum. Also, it is able to make a continuous update of α until a global minimum solution is found.

C. Case 3

Case 3 is an extension of Case 2 for investigating the ACA’s capability in deriving a CGM that is usable in another time. The case was implemented based on the assumption

that a better CGM could be established if multiple input data (published power flow values) were used as inputs. The ACA was implemented on 6 input models respectively representing published hourly power flow data from 12 AM to 5 AM on Jan. 1, 2015. During implementation, the average value of Δ (of the 6 models) was used as the objective function value. Thus, the objective was to minimize the average percentage of deviation between the F_{ij}^* and the F_{ij} . The computation was terminated when the average Δ fell below 5%. The quality of the solution derived is presented in Table VIII.

TABLE VIII
THE QUALITY OF SOLUTION OBTAINED BY ACA IN CASE 3

Hour	$\sum F_{ij}$ (MW)	ϕ (MW)	Δ (%)
0	8763	449.6	5.13
1	10062	451.3	4.48
2	10714	454.0	4.23
3	10391	452.7	4.36
4	10219	264.0	2.58
5	10146	319.2	3.15

In order to verify the validity of the solution, the authors applied the derived X^* to another input model representing the published power flow at 6 AM of the same day. The derived ϕ is 4.82% of the $\sum F_{ij}$. Thus, the ACA is capable of deriving a CGM that could be used at different times.

VI. DISCUSSIONS

The ACA exhibits several advantages over the existing methods. First, it simplifies the CGM establishment process. It is a top-down approach that does not require detailed knowledge of the transmission network. Thus, it addresses the privacy concerns of the TSOs. Also, it does not require prior experiences in operating the transmission network (as in the CWE FBMC). Therefore, the establishment could be performed by a researcher.

Second, the number of buses of the established CGM is smaller compared to the actual transmission network. Therefore, the resulting CGM would increase the speed of the DCOPF calculations because of its small model size. This is useful for large scale dispatch and unit commitment planning. Third, the top-down nature of the establishment helps in avoiding the complicated task of deciding which transmission lines to be merged as an inter-connector in the CGM (a practice required in the existing methods that could create errors in the CGM). This increases the precision of the representation of the physical flow attribute.

Although the cases studied in this research have validated the performance of the ACA, two inter-connectors could not be represented in the CGM constructed in Case 2. This is caused by the absence of power flow data between the market areas connected by the inter-connectors at that period. Historical data presented on the website [19] show that a power flow between B3 and B5 does not exist in most of the time instances, while a power flow between B1 and B2 does not exist at the time specific to the input model.

This problem could be resolved by taking the mean value of the power flow on each of the inter-connectors over a longer time, and performing ACA on the averaged data. Apart

from being a viable solution to the “missing inter-connectors” issue, the adoption of mean values in the input model produces PTDFs that represent the actual power flow attributes more precisely, because the derived X^* is a global optimal solution for input cases of different times. In addition, we need the transfer limits for each of the borders (especially the bottlenecks) for completing the approximation of the CGM. The authors suggest to derive these values from the published power flow data, such as the historically maximum values transferred between the market areas. The validity of these approaches could be verified as part of future work.

The authors adopted the sum of the absolute values of $F_{ij} - F_{ij}^*$ in (4) for the purpose of proving the concept of ACA. This formulation is simplistic as the $F_{ij} - F_{ij}^*$ values associated with inter-connectors which have greater values of F_{ij} would have greater influence on the value of ϕ . This could cause greater and asymmetric perturbations in ϕ , leading to inefficient (though effective) convergence of the μ GA implementation. The weighted sum of squared values of the $F_{ij} - F_{ij}^*$ could be used to prevent this issue.

Last but not least, the authors have found an optimal X^* in Case 3, that remains valid when tested using the published physical power flow of a different time. This has validated the CGM established by the ACA.

VII. CONCLUSION

This paper has presented a method called the ACA for creating CGMs. It hybridizes the μ GA and the well-established DC power flow method and is capable of constructing a CGM using published power flow data. A CGM could be constructed either by means of aggregating buses and transmission lines into a simplified transmission network model, or by means of inverse computation of the impedance of the inter-connectors that represent interfaces between market areas (as in the Nordic case). The key is the construction of representative impedance for a CGM’s inter-connectors. The authors have outlined the reasoning and theoretical background of the method. Subsequently, it was demonstrated with 3 case studies. Cases 2 and 3 used the actual published inter-area power flow data for verifying the ACA’s applicability in a real-world scenario. The results obtained have validated the performance of the method in: 1) deriving a CGM of a detailed transmission network (after bus aggregation); 2) deriving a CGM for published inter-area power flow data (a single case) using inverse computation of X ; and 3) verifying the applicability of the derived CGM at different times. The authors suggested the investigation of other avenues to construct a CGM that could better represent the power flow pattern and transfer limit for the DCOPF simulation. These issues will be addressed as future work.

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