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Decomposition Of Power Flow Used For Optimizing Zonal Configuration Of Energy Market

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Abstract:
Zonal configuration of energy market is often a consequence of political borders. However there are a few methods developed to help with zonal delimitation in respect to some measures. Paper quantifies the impact of the number of bidding zones on the network model, transmission flows and fuel shares. Towards this aim, a clustering algorithm is deployed to group nodes into zones, and an economic dispatch model is developed to determine the optimal electricity market outcome. A case study based on the central European electricity sector is considered. It is shown that, for the case study discussed in this paper, increasing the number of zones results in considerable improvements in market outcome (i.e., the zonal market outcome moves towards the optimal nodal market outcome). However, the marginal improvement decreases with increasing number of bidding zones.
This work presents the approach aiming at reduction of the loop flow effect – an element of unscheduled flows which introduces a loss of market efficiency. In order to undertake zonal partitioning, a detailed decomposition of power flow is performed. Next, we identify the zone which is a source of the problem and enhance delimitation by dividing it into two zones. The procedure is illustrated by a study of simple case. The real power and reactive power balances must be maintained in steady state operation of electrical power systems. The presence of reactive power in the power system was considered as a relatively trouble free phenomenon three decades ago. The regulator kept the reassigned set points of voltage levels at certain load buses using the local reactive power sources such as synchronous condensers and shunt capacitors in a decentralized manner. Things started to change around twenty-five years ago when the real importance of the problem was felt due to some reactive power problem becoming visible in heavily loaded long transmission systems. Reactive power problems lead to the phenomenon of voltage instability. Therefore, power

system engineers and researcher were motivated to understand and analyze the usage of components and devices in an optimal manner to regulate the reactive power from voltage stability point of view.
The responsibility of generation, transmission and distribution of electric energy was entrusted to one organization (generally, owned and managed by local government) in vertically integrated power utility structure up to late 90's. Such a vertically integrated power utility structure exhibits monopoly to serve the needs of the customers in their service territories. Energy service was considered as the main service whereas the reactive power support services were an integral part of the electricity supply and was not separated. Reactive power support service was only considered as a technical/engineering but not managerial/economic issue hence it was obligatory on part of all generators in the power system to accomplish the local reactive power demand and further no extra incentive was given for this service.

Index Terms—Power system analysis computing, Powertransmission, Load flow, Clustering methods

1. INTRODUCTION

The shape of the future bidding zone configuration is a subject of the debate among several institutions determining energy market policy in Europe. One of the main reasons is the urgent need for a close integration of the energy markets of EU members into one structure governed by a common power exchange algorithm – the Market Coupling (MC) [1]. The zonal structure has already been introduced in some European countries; zonal market works for instance in Central-Western Europe (CWE) and among three of CEE countries. These regions are expected to be merged with several independent state markets to form one pan-European market. The shape of current bidding zones (BZ) follows the actual international borderlines. For the reasons discussed further it does not constitute the optimal solution [2]. Therefore, European Network of Transmission System Operators for Electricity (ENTSO-E), which is responsible for introducing zonal model, has recently initiated the process of bidding zones' revision [3,4].

One of the most important problem concerning Transmission System Operators relates to network congestions. In 2011 Agency for the Cooperation of Energy Regulators (ACER) has published Framework Guidelines on Capacity Allocation and Congestion Management for Electricity (CACM). This framework gives strict recommendations that bidding zones should be defined in a way that provides efficient management of congestions. All known model-based approaches to zonal delimitation aim at setting the borders in the manner that congested lines become inter-zonal connections. There are two main groups of methods capable of achieving that goal. The first is based on Locational Marginal Prices [5-9] and aims at aggregation of nodes characterized by similar cost of energy delivered to the node in the nodal model. Second class of algorithms aggregates nodes characterized by similar Power Transfer Distribution Factors in respect to overloaded lines [10-12]. However, the existence of structural congestions is not the only aspect of efficient bidding zone delimitation. CACM states that efficient bidding zone configuration should minimize adverse effects of internal transactions on other BZs. Hence, another important issue that has to be addressed during the process of optimal delimitation is related to unscheduled flows. These flows introduce distortions to neighboring systems decreasing their efficiency and creating potential safety vulnerabilities. The thermal limits of a grid demand reserving sufficient transmission capacity in the form of reliability margin, whereas the magnitude of unscheduled flows can reach even 1000 MW injected into adjacent system without market-based agreements [2, 3, 13]. In some cases this leaves no exchange capability for actual power trade between systems.

The unscheduled flows are defined as the difference between market-driven (scheduled) and actual, physical power flow [13]. There are two components of such flow (i) loop flow, consisting of power transmitted through neighboring zone due to some internal (intra-zonal) transactions and (ii) transit flows which occur when inter-zonal exchange affects third party grids. It is worth mentioning that introducing Flow Based MC changes qualification of (ii) as the adverse effects affecting the zones not involved in bilateral transactions are taken into account while solving MC problem. The actual flows do not disappear, however their transparency increases, and thus they become a part of the decision-making process of MC, which allocates the transfer capability to a set of competing market transactions. Considering the aforementioned remark we point out that the shape of zonal borders affects the market efficiency in the light of the existence of unscheduled flows.
Configuration of BZs based on loop flow analysis does not exist. This paperis aimed at fulfilling this gap and introduces a new method that addresses the problem. First, we identify a zone, the internal transactions of which cause the most of adverse effects in the system in terms of unscheduled flows. Second, we attribute each node of this zone with an amount of injected/withdrawn power which is responsible for isolated effect of unscheduled flow. This allows for spatial separation of the regions being average positive and negative contributors of the effect. Division line splits the zone into two BZs.

As the result, transactions previously categorized as internal, become visible as inter-zonal ones and start to be controlled by the Market Coupling. In order to achieve a new shape of the market, the method needs a certain bidding zone structure as a reference point. That is why the presented reasoning can be used on zonal structures resulting from the LMP or PTDF-based delimitations, as well as on structures that follow borders of countries or are defined by expert knowledge. The following sections present a mathematical background of the loop flow identification, clustering methods and an exemplary case study that illustrates the presented approach.

2. LITERATURE REVIEW:

The reactive power management has been a major concern for secured and reliable power system operation in recent deregulated electricity industry. In fact, inadequate reactive power led to voltage collapses and had been a main cause of major power outages across the world in the past. The findings of US–Canada Power System Outage Task Force [4] for blackout occurred in US and Canada in April 2004 indicate that ‘‘insufficient reactive power was an issue in the blackout’’. The difficulties associate d with a market-based reactive power management are due to following significant differences between the reactive power market and the real power market:

· The local geographic character of the reactive power market versus the system wide character of the active power market.

· The relatively smaller investments in new equipment needed to supply reactive power as compared to real power generation.

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Hence, an appropriate reactive power market settlement mechanism is needed to give proper incentives and motivate the market participants for providing the required reactive power services in a deregulated electricity industry. The ISO must ensure an adequate payment mechanism for reactive power ancillary services that guarantees the economic feasibility of this business.

In a competitive electricity market, the reactive power management mainly constitutes the appropriate selection of market structure, payment mechanism and pricing scheme. The structure of reactive power ancillary service market is suitably decided on the basis of regional and political environment. The reactive power ancillary services are unbundled from the real power or energy service (main commodity) and a separate market is required for reactive power ancillary service. The reactive power ancillary service market may be settled after the energy market settlement on day-ahead basis. The outcomes of the reactive power market settlement are the reactive power schedules for all the reactive ancillary power service providers (generators/synchronous condensers) along with their associated payments. A suitable payment mechanism must be designed for all the reactive power ancillary service providers by considering different technical issues.
The 2013 European electricity system is used as a basis for the case study. The case study covers a full year on an hourly basis and includes 10 countries: Austria, Belgium, Czech Republic, Germany, France, Italy, Luxembourg, the Netherlands, Poland and Switzerland.

Hourly national load data for the year 2013 is taken from ENTSO-E [13]. Exchanges with countries outside the geographical scope of the model are imposed to the model as a fixed parameter, based on hourly exchange data obtained from ENTSO-E [13]. Electricity generation from renewables (wind, solar, hydro and biomass) and small-scale fossil-fuel cogeneration is implemented as load reduction, based on historical 2013 generation data [13] and 2010 wind and solar profiles [16].[2]

The generation portfolio is taken from the PLATTS World Electric Power Plants Database [17] and consists of 941 generation units with an aggregated installed capacity of 323 GW. Standard rated efficiencies are assumed for the power plants, depending on their year of commissioning [18]. 2013 historical fuel prices and CO_2 emission price are used to calculate the marginal generation costs of each power plant.[3]

The DC grid model of the European interconnected electricity system developed by Zhou and Bialek is used in this case study [19]. The model consists of 1486 transmission lines and 968 nodes. This model is based on publicly available data and includes all nodes with a voltage level equal to or above 220 kV. Line reactances are estimated based on a fixed reactance value per kilometer of transmission line length. Electric load is distributed over the nodes proportional to the population density. Renewables generation is distributed over nodes according to installed capacity data or regional generation data. The grid model does not include maximum line capacities of transmission lines within countries, and therefore a fixed power rating is used.[4] Line capacities are reduced by 10% to account for an operational security margin and reactive flows.

The model is calibrated, by means of a derated capacity approach, in order to match the simulation results (of the nodal market) with historical generation data.

2.1 Impact On Zonal Network Parameters

Nodes are clustered into zones as such that intra-zonal congestion is as low as possible and that nodes within a zone have a similar impact on inter-zonal links. The latter can be achieved by clustering nodes with similar nodal PTDFs. The smaller the differences in nodal PTDFs within a zone, the more accurate the inter-zonal line flows are represented in the model. This is important since both an overestimation and an underestimation of inter-zonal flows by the market model have negative effects. An overestimation of inter-zonal flows unnecessarily constrains the market outcome and results in welfare losses. An underestimation of inter-zonal flows may jeopardize secure operation of the electricity grid.

2.2 Impact On Line Flows

Since the market clearing is based on a simplified network representation in a zonal electricity market, the resulting generation schedule can result in network infeasibilities. Figure 2 shows the average hourly line overload, aggregated over all lines, that occurs in the network when the generation schedule from the zonal market clearing is imposed to the nodal network model. Line overloading clearly decreases with an increasing number of zones. A higher number of zones results mainly in a decrease of intra-zonal congestion, since zones are clustered with the objective to avoid intra-zonal congestion. However, inter-zonal congestion reduces at a slower pace when increasing the number of zone. Besides, the marginal improvements in line overloading are limited beyond twenty zones.

2.3 Impact On Fuel Shares

The network model imposed to the market clearing algorithm also impacts the fuel shares. Figure 4 shows for the different fuels the difference between the annual generated electricity in a zonal simulation model and in a nodal simulation model. Generation from nuclear units, coal-fired units and lignite-fired power plants is always larger in a zonal model than in a nodal model, while the reverse holds for gas-fired power plants. The difference between fuel shares in zonal and nodal networks decreases with increasing numbers of zones.

A zonal market model favors the scheduling of low-cost generation units. However, this has to be corrected for by the system operator by rescheduling generation after the day-ahead market clearing (i.e., re-dispatching), since not all scheduled low-cost generation can be facilitated by the network. Re-dispatching results in a net cost for the system operator since cheap generation (i.e., nuclear, coal or lignite-fired generation) has to be replaced by more expensive generation (i.e., gas-fired generation).

The zonal market simulations result in lower system-wide generation costs than the nodal simulation (the nodal economic dispatch is more constrained than any zonal economic dispatch). However, the zonal market outcome has to be corrected to avoid line overloading and this comes at a cost (i.e., the re-dispatch cost). The sum of this redispatch cost and the zonal generation costs is at least as high as the nodal generation costs.
As mentioned in the previous two subsections, the optimal reactive power market settlement and congestion management require the optimization of one or several important objective functions. Moreover, these optimization problems may be formulated as either single-objective or multi-objective optimization frameworks. In a single-objective optimization framework, the optimization problem is formulated as minimization or maximization of

single and well defined objective function subject to various equality as well as inequality constraints [10]. Such type of optimization problem seeks the best (lowest or highest) value of the given objective. In contrast to this, a pure multi-objective optimization framework pertains to the minimization or maximization of multiple (more than one) objective functions simultaneously while satisfying various equality as well as inequality constraints. In general, a common multi-objective optimization problem may be formulated as follows:

$$Minimize \quad f_i(x) \; \forall \; i = 1, \ldots\ldots\ldots, N_{obj} \qquad (1.1)$$

$$subject\ to: \begin{cases} g_j(x) = 0 & j = 1, \ldots\ldots\ldots, M \\ h_k(x) \leq 0 & k = 1, \ldots\ldots\ldots, N \end{cases} \qquad (1.2)$$

where $f_i(x)$ is the i^{th} objective function; x is a decision vector that represents a solution; N_{obj} is the number of objective functions; M and N are number of system equality and inequality constraints respectively.

Almost all the real world optimization problems involve optimization of (i.e. whether minimization or maximization or combinations of both) the multiple objectives simultaneously. In fact, these objectives are non-commensurable and often conflicting in nature. Multi-objective optimization with such conflicting objective functions gives rise to a set of trade-off optimal solutions, instead of one optimal solution [11]. Therefore, in a multi-objective optimization framework, ideally the effort must be made in finding the set of trade-off optimal solutions by considering all objective to be important. After finding a set of such trade-off solutions, a decision maker (ISO in the present research work) may then use higher level qualitative consideration (or expert knowledge and experience).

3. PROPOSED METHOD:

A methodological framework is developed in this paper to quantify the impact of bidding zones on the electricity market outcome. This framework consists of four steps. First, the nodal market outcome is simulated with an economic dispatch model based on a nodal network model. Second, the optimal zonal clustering is determined by a clustering algorithm, given a number of zones and based on the critical lines identified in the nodal simulation. Third, the zonal network parameters are calculated based on the results from the previous two steps. Finally, the zonal market outcome is simulated with the economic dispatch model based on a zonal network model. The second, third and fourth step are repeated for different number of zones (the nodal market outcome is determined once).

A DC power flow representation of the electricity network is used in this paper. A DC power flow is a linearization of the AC power flow equations, based on the assumption of lossless transmission lines, small voltage angle differences between neighboring nodes and a flat voltage profile [9]. In a DC power flow, the network characteristics are described by Power Transfer Distribution Factors (PTDFs). PTDFs give the linear relationship between power injections in the network and flows through lines. The Flow-Based Market Coupling is based on a DC power flow description of the electricity network (whereas the Available Transfer Capacity method is based on a simpler trade-based description of the network).

The remainder of this section presents the clustering algorithm, the calculation of the zonal Power Transfer Distribution Factors and the economic dispatch model (the same model is used for the nodal and zonal simulations).

3.1 Clustering Algorithm

The clustering algorithm groups nodes into a predefined number of zones, in a way that intra-zonal congestion is infrequent and that nodes within a zone have a similar impact on inter-zonal lines.

Different clustering algorithms are presented in the literature. The two most prominent methods are clustering based on Locational Marginal Prices (LMPs) [5]-[7] and clustering based on nodal Power Transfer Distribution Factors (nodal PTDFs) [9]-[11]. The rationale behind LMP-based clustering is that differences in nodal prices indicate grid congestion. By clustering nodes with similar LMPs, clusters (i.e., bidding zones) with low intra-zonal congestion are obtained. The rationale behind PTDF-based clustering is that nodes with similar nodal PTDF-values for congested lines have a similar impact on these congested lines. By taking the congested lines as intra-zonal links and clustering nodes with similar PTDF-values for these congested lines (congested lines are known from the nodal simulation), a zonal configuration is obtained with low inter-zonal congestion in which all nodes in a zone have a uniform impact on the intra-zonal links. PTDF-based clustering is used in this paper.

In the context of clustering nodes into zones, contiguity constraints according to the network graph need to be imposed to ensure connected clusters. Hierarchical Agglomerative Clustering (HAC) algorithms are particularly suited for this

[12]. HAC algorithms start from singleton clusters and proceed by successively merging the clusters with the smallest merging cost. The contiguity requirement can easily be included as an additional constraint on the merging of clusters. In this paper, HAC based on Ward's minimum variance criterion is used to cluster nodes with similar nodal PTDFs

[13]. The nodal PTDFs are weighted to ensure that the most constraining transmission lines are located between zones. Klos et al. postulates weighting nodal PTDF-values proportional to the average shadow cost of the transmission capacity constraints for the congested lines, resulting from the nodal market simulations [8]. However, proportional weighting attributes a disproportionately high importance to the most congested lines. Therefore, a logarithmic weighting is applied in this paper.

4. RESEARCH METHODOLOGY:

The whole process consists of several stages; market simulations allow to identify power flow on transmission lines in multiple scenarios of load patterns, this allows for estimating the magnitude of average loop flow effect. The zone responsible for the most of the inefficiency is chosen and clustered into two sub-regions in order to reduce the unscheduled power transmission. The following paragraphs introduce the details of the procedure.

A. Load flow simulation

In order to achieve a set of nodal injections and withdrawals, market coupling algorithm [1] is utilized to determine accepted bids and offers, and, in consequence, nodal injections. To determine the power flows, we solve a DC power flow problem for these injections.

B. Identification of loop flows

There are four possible categories of power transmission which seem to be important from the perspective of holding responsibility for utilizing the transmission infrastructure; (i) internal exchange, (ii) import/export, (iii) transit flow and (iv) loop flow. The basic understanding of the aforementioned terms in respect to attribution of nodes to different zones is the following:

i. internal exchange (IN) takes place if all, generator, load and transmission line are placed in the same zone,

ii. import/export (IE) refers to situation when generator and load are in different zones, but both ends of the line are attributed to at least one of these zones,

Obviously, in a real power system, a power flow in a given transmission line rarely can be categorized strictly into one of the four above classes, since the power flowing through the line usually cannot be attributed to one source (generation) node and one destination (load) node. Thus, we need to perform a decomposition of the power flowing in the line in order to divide it into components resulting from transfers between sets of loads and generators placed in the same zone, or from any pairs of different zonal attribution. Such an analysis demands determination of mutual interactions between sources and sinks participating in the power exchange.

Many authors devoted their studies to the subject of tracing the flow of electricity. This work is based on Bialek's Proportional Sharing Principle (PSP) [14], which along with lossless DC power flow analysis constitutes the main assumption of the study. The PSP can be summarized by the following statement: each node works as a "perfect mixer," which means that mutual proportion of in-flows is reflected by the components of out-flows (Fig. 1).

The method derived from the aforementioned rule has been improved by adding functionalities that allow for detailed power flow decomposition, i.e. exploring the magnitude of power flowing through each line as the result of exchange between each generator/load pair and categorizing flows' elements into the four classes defined above. Furthermore, the construction of all variables has been rephrased in the language of linear algebra, which allows for neat and more effective implementation For a given line *k*, one can find the matrix of mutual power exchange ($\mathbf{X}^k$) which means that node *i* gets from generator *j* power equal to $X^k ij$ (cf. Appendix). Having this information, it is essential to ask which part of power transmission is actually a loop flow, and which constitutes more desirable forms of transaction-based power exchange. In order to categorize flows listed in matrices **X**, one must discover interdependencies between zonal ascription of both ends of particular line and of the pair generator-load imposing transmission over the line.
The complete profile of the options (Fig. 2) allows to perform a decomposition in respect to each line of the system (below, line *k* connects nodes *k1*, *k2* and for each node *u*, Operator z(*u*) returns the zonal attribution of *u*).

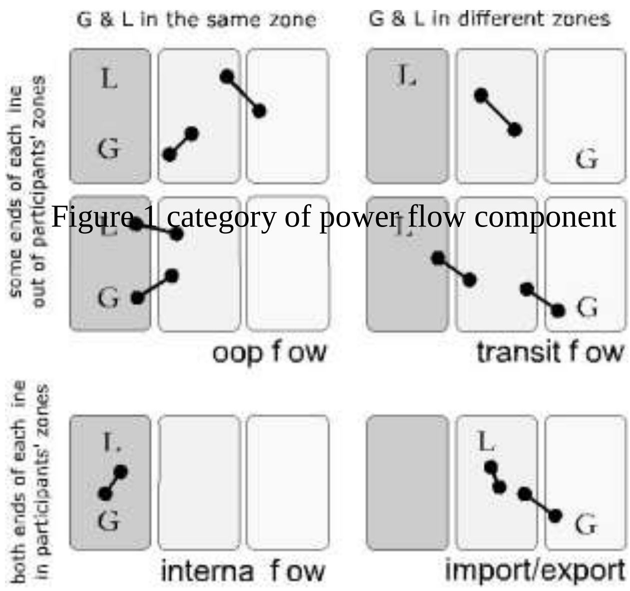

Figure 1 category of power flow component

Figure 1.depicts the category of power flow component is based on two indicators: zonal attribution of transaction parties (columns) and localization of transmission line (rows). The picture presents possible relations between the aforementioned. Different shades of figures indicate separate zones. Generation and load (G & L) refer to nodes of aforementioned source and sink denoted as *i*, *j*.

Target zone – definition and clustering

As the method aims at enhancing a zonal configuration by increasing number of zones, it starts with identification of one zone which can be treated as the greatest contributor to the loop flow phenomenon. The choice is made according to the ranking of the adverse effects of each zone's internal transactions. In this work, we decided to pay attention for the absolute values of flows, however relative approach (Juxtaposing amount of flow in respect to the transmission capability of the line) is also an acceptable solution.Once the influence of each node of the zone on the loop flow is determined by PF decomposition, hierarchic clustering can be used to group nodes of the target zone. Our approach is to utilize values of power injections responsible for loop flows (and only them – cf. last equation of Appendix) as an input into the clustering routine. The area characterized by net positive "loop flow inducing" injections would be separated from region which behaves as net importer. As the result the zone responsible for the greatest amount of the unscheduled flow would be divided into two parts.

5. CONCLUSION:

The presented analysis is a consequence of the assumptions highlighted in sec. II. Although neglecting transmission losses may be treated as a reasonable simplification, the basic rule expressed by PSP ought to be discussed in the light of some concurrent premises. The main alternative which can be used for determining power flow decomposition is founded on the concept of superposition of power flows. The existence of counter-flows (two flows of opposite direction, which add up to one, visible "net" power flow) makes the model more complicated, however it allows for performing much deeper analysis of all possible interactions between selected generator and complete set of loads (or load against all generators). Particularly, a loop flow caused by two nodes: generator 2 and load 1 was not transparent according to the PSP, generator 2 introduces no contribution into line 2. The alternative assumption would result in increasing LF originating in zone 1 as well, however the fact that these two loops are of opposite direction, the superposition of effects could in fact be close to the one achieved by presented “net” effect. This does not change the fact that widely accepted Proportional Sharing Principle leads to satisfactory conclusions.

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