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# Cost allocation model for distribution networks considering high penetration of distributed energy resources

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ABSTRACT

The high penetration of distributed energy resources (DER) in distribution networks and the competitive environment of electricity markets impose the use of new approaches in several domains. The network cost allocation, traditionally used in transmission networks, should be adapted and used in the distribution networks considering the specifications of the connected resources. The main goal is to develop a fairer methodology trying to distribute the distribution network use costs to all players which are using the network in each period. In this paper, a model considering different type of costs (fixed, losses, and congestion costs) is proposed comprising the use of a large set of DER, namely distributed generation (DG), demand response (DR) of direct load control type, energy storage systems (ESS), and electric vehicles with capability of discharging energy to the network, which is known as vehicle-to-grid (V2G). The proposed model includes three distinct phases of operation. The first phase of the model consists in an economic dispatch based on an AC optimal power flow (AC-OPF); in the second phase Kirschen's and Bialek's tracing algorithms are used and compared to evaluate the impact of each resource in the network. Finally, the MW-mile method is used in the third phase of the proposed model. A distribution network of 33 buses with large penetration of DER is used to illustrate the application of the proposed model.



## 1. Introduction

### 1.1. Background, methodology and aim

The design and development of cost allocation methods applied to users of transmission systems is a topic widely studied, resulting in several different methods for cost allocation. However, at the distribution system level, the cost allocation topic has been the target of deep study because its technical and operation characteristics are different from transmission systems requiring the development of new methodologies.

Traditionally, the operation costs in distribution systems are allocated to consumers connected in the network based on average operation costs [1]. With the increasing penetration of distributed energy resources (DER) in distribution systems, the traditional cost allocation methods are no longer valid, due to different directions of power flow in distribution systems caused by DER [2]. Thus it is necessary to develop new methodologies more adequated for the new operation paradigm.

In fact, the actual power systems are no more characterized by a central generation units connected to transmission systems and a passive consumers most of them connected to medium and low voltage distribution networks. This operation paradigm has gradually changed to a more decentralized one. Nowadays, most of the power systems are characterized by the high penetration of distributed generation connected in all voltage levels, the existence of storage systems (pumped hydro power plants and few batteries based systems), the growing introduction of electric vehicles and the active participation of consumers through the demand response programs and a more conscience concerning the efficiency use of the energy. Taking this reality into account, the methods traditionally used to determine the costs allocation of the distribution

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**Nomenclature**

*Parameters*

| | |
|---|---|
| $\eta_c$ | grid-to-storage/vehicle efficiency |
| $\eta_d$ | storage/vehicle-to-grid efficiency |
| $B$ | imaginary part in admittance matrix (S) |
| $c$ | resource cost in period $t$ [m.u./kWh] |
| $DF$ | pay factor used to determine the fixed costs allocation for each type of resource |
| $DN$ | pay factor used to determine the network use costs allocation for each type of resource |
| $DL$ | pay factor used to determine the system losses costs allocation for each type of resource |
| $E$ | stored energy in the battery of storage system or vehicle at the end of period $t$ (kWh) |
| $E_{Initial}$ | energy stored in the battery of storage system or vehicle at the beginning of period 1 (kWh) |
| $E_{Trip}$ | energy consumption in the battery during a trip that occurs in period $t$ (kWh) |
| $F$ | branch power flow (kW) |
| $G$ | real part in admittance matrix (S) |
| $L$ | branch Losses (kW) |
| $LMP$ | locational marginal price (m.u/kWh) |
| $N$ | number of resources |
| $S$ | apparent power flow in branch (kVA) |
| $T$ | total number of periods |
| $X$ | payment factor |
| $\bar{U}$ | voltage in polar form (V) |
| $\bar{y}$ | series admittance of line that connects two buses (S) |
| $\bar{y_{sh}}$ | shunt admittance of line that connects two buses (S) |

*Superscript*

| | |
|---|---|
| *Fixed* | fixed costs (m.u.) |
| *Loss* | losses costs (m.u.) |
| *NetUse* | network use costs (m.u.) |

*Indices*

| | |
|---|---|
| $i,j$ | node index |
| $dg$ | distribution generation index |
| $sp$ | external suppliers index |
| $st$ | energy storage system index |
| $t$ | time index in hours (h) |
| $v2g$ | vehicle-to-grid index |

*Variables*

| | |
|---|---|
| $\theta$ | voltage angle |
| $C$ | cost (m.u.) |
| $P$ | active power (kW) |
| $Q$ | reactive power (kVAr) |
| $TC$ | total allocation cost (m.u.) |
| $V$ | voltage magnitude (V) |
| $Y$ | binary variable |

*Subscript*

| | |
|---|---|
| $\psi$ | inefficiency costs |
| $A$ | fixed component of cost function (m.u./h) |
| $B$ | linear component of cost function (m.u./kWh) |
| *Branch* | branch |
| $C$ | quadratic component of cost function (m.u./kWh$^2$) |
| *Ch* | storage or V2G charge process |
| *Dch* | storage or V2G discharge process |
| *DG* | distribution generation |
| *DR_A* | active power reduction of load |
| *DR_B* | active power curtailment of load |
| *GCP* | generation curtailment power |
| *Load* | loads |
| *LTC* | loads total cost |
| *Max* | upper bound limit |
| *Min* | lower bound limit |
| *NSD* | non-supplied demand |
| *SP* | external supplier |
| *V2G* | vehicle-to-grid |

network, in which the consumers pay all the costs, are no more adequate. A new methodology is proposed in this paper for the costs allocation in distribution network, taking into account the new operation paradigm with large penetration of several types of DER. The main goal of the proposed method is to distribute the costs fairer to all players connected to the distribution networks taking into account the effective use of the network in each period (15, 30 or 60 min). As mentioned, the proposed methodology considers several types of DER, namely distributed generation (DG); direct load control demand response (DR); energy storage systems (ESS); and electric vehicles with the capability to charge and discharge energy, usually referred as vehicle-to-grid (V2G) resources.

The methodology considers the combination of three different cost allocation methods with the aim of take advantage of the main qualities of each one, to develop a more fairly cost allocation model. The methodology comprises three levels. The first level consists in the energy resources schedule optimization considering the merit order, in this case the operation cost. By considering an AC OPF it is also possible to obtain the locational marginal prices (LMP) in each bus, including the energy LMP, the losses LMP, and the congestion LMP (marginal method). The second level intends to determine the share/impact that each energy resource has on the network power flow (tracing method). Two different approaches based on the proportional sharing principle are tested and compared to determine the impact of each resource in the network. The third level consists in the application of allocation costs method to each type of resource (variant of MW-mile method).

### 1.2. Literature review and specific contributions

The cost allocation is a topic widely studied in transmission networks [3–24]. However, the increasing penetration of DER at distribution level forces the need to adapt traditional cost allocation methods used in transmission system to the distribution level. In general, the cost allocation methods for transmission systems may be classified into three distinct categories: nodal marginal methods [3–7]; rolled-in methods [8–11]; embedded-methods [12–24]. The cost allocation based on nodal marginal pricing for transmission systems is presented in [3–5], in which are considered the long-term and short-term marginal costs related to energy, reliability, investments and demand side. Similar approaches for distribution networks considering distributed generation are proposed in [6,7]. These approaches have some limitations. In [6] the tariff scheme only considers the consumers disregarding the generation units. In [7] the fixed costs scheme for demand and DG resources are considered but only for extreme scenarios.

The rolled-in methods are characterized by their easy implementation ensuring return on the total system operation costs. These methods allow getting a tariff based on the average cost of the system. The postage stamp [8,9], contract path [10], and