Cost Allocation of Losses in Autonomous Power Systems with High Penetration of RES

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Abstract: - Cost allocation of losses in power networks is an essential issue especially under modern electricity markets with high penetration of renewable energy sources (RES). This paper proposes the application of an efficient loss allocation method developed to evaluate the marginal loss coefficients of dispersed generation. The coefficients provide the contribution to the active and reactive losses of each producer/consumer in order to define the respective tariffs. One innovative feature of the proposed loss allocation method is that, unlike other proposed approaches, it is irrespective of the reference bus selection and takes in consideration the impact of reactive flows on active power losses. Crete's power system has been considered as a representative study case for the demonstration of the presented method.

Key-Words: - Distributed generation, marginal loss coefficients, high renewable energy penetration, transmission and distribution loss allocation.

1 Introduction
Under ongoing deregulated and competitive energy markets, power systems need higher operation standards. Consequently, modern electric energy systems should operate under strong environmental restrictions in parallel with adequate service reliability at lower possible costs. Additional to the current structural changes, dispersed generation augments its penetration into power distribution systems, [1]. In [2] some of the reasons for an increasing share of dispersed generation in different countries has been summarized. The presence of dispersed generation in distribution systems alters radically the way these networks should be considered from both technical and economical aspects.

Distributed generation and especially dispersed generation of renewable energy sources can provide significant benefits, such as improved system reliability and enhanced power quality. Additionally, dispersed generation could increase system efficiency through co-generation and local voltage support, while under specific conditions could even decrease network operational cost.

Generally, the dispersed generation changes distribution networks from passive networks, with power flows from higher to lower voltage levels, into active networks with multi-directional power flows. Furthermore, transmission and distribution infrastructures require specific economic regulations in order to hold access price near the marginal cost and to provide full-powered incentives minimising total costs, [3].
On of the most important conditions for an essential competition development is a non-discriminatory access to the available transmission and distribution networks by all the system's suppliers. This is a network pricing issue [4], where network cost comprises of investment cost, congestion cost and operating cost, part of which is the cost of losses. The allocation of this significant cost to each individual generation and/or load is in essence the allocation of responsibility for system losses.

A large number of methodologies dealing with cost allocation problem of transmission services have been described [5-9] and certain maturity has been obtained in this area. Furthermore, since the advent of competitive electricity markets, several methods have been proposed for loss allocation. More precisely, these are: the proportional sharing loss formula, the pro rata method, the incremental transmission loss, and the incremental bilateral contract path.

The proportional sharing technique [10-11] provides a computationally efficient procedure for loss allocation, it fails to satisfy the economic efficiency objective, as no messages are conveyed to users regarding costs they impose on the system. In [12] the proposed method tries to overcome the previous difficulties, by establishing direct relationship between losses in each branch of the network and injected active and reactive power in the nodes on which path to the power supply point the branched is placed. The pro rata loss allocation method has been applied in the electricity markets of mainland Spain [13] and England and Wales [14]. The method does not consider the relative location of the generators and the loads. This method has a beneficial impact to remotely located generators or loads in contrast to all others. In the incremental techniques [15] the loss allocation depends on the choice of the reference bus and the direct application of the coefficients leads to an over-recovery of losses. A loss allocation scheme for bilateral contracts is proposed in [16] where approximations are poor if the electrical distance between the contractors is small. In the context of multilateral trades [17] a loss allocation method based on a quadratic approximation of losses is proposed. In [18], the proposed loss allocation formula, leads to significant differences between losses calculated from AC power flow solution and those obtained from the proposed method, because of the several approximations assumed. All these methods do not address the issue of the choice of the reference bus and its impact on loss allocation and moreover, most of these schemes ignore the impact of reactive flows on active power losses. In [19] the loss allocation method based on marginal losses has been proposed, while in [20] a method that applies the same concept as in [19], determines the prices at different nodes in the distribution networks using nodal factors.

In this paper, loss allocation method based on the concept of marginal cost is investigated. The method provides loss allocation factors for both active and reactive power enabling the contribution of active and reactive power consumption and generation to system losses to be quantified. Furthermore, the factors can be positive or negative reflecting the user’s impact on losses, which is essential in addressing the impact of counter flows, preventing thus temporal and spatial cross-subsidies. A mechanism is also proposed for neutralizing the impact of choice of reference node on the magnitude and the polarity of loss allocation factors by apportioning total losses equally between generators (including the reference node) and loads.

2 Problem Formulation

According to the economic theory the marginal losses reflect the Short-Term Marginal Costs (STMC) and therefore achieve short-term economic efficiency [19-20]. The marginal loss coefficients (MLC’s) are sensitivity factors measuring the change of total active losses $P_L$ when a marginal change in consumption/generation of active $P_i$ and reactive power $Q_i$ occurs at each node $i$ in the network. Then:

$$\tilde{\alpha}_P = \frac{\partial P_L}{\partial P_i}, \quad \tilde{\alpha}_Q = \frac{\partial P_L}{\partial Q_i}, \quad (1)$$

where $\tilde{\alpha}_P$ and $\tilde{\alpha}_Q$ are the active and reactive MLCs, respectively. For the voltage control nodes (PV) there are no loss related charges for the reactive power they inject in the system. There are no loss related charges for the reference bus as well, such as the injected/absorbed power to keep the system in power balance after changes in injections in other nodes. This is expressed by:

$$\frac{\partial P_i}{\partial Q_i} = 0, \quad i \in \{PV\} \quad (2)$$

$$\frac{\partial P_L}{\partial P_r} = 0, \quad r \equiv \text{reference bus} \quad (3)$$
The calculation of MLCs is based on a solved power flow in a particular operating point of the system. The voltages and angles are used as intermediate state variables as there is no explicit relationship between losses and power injections. Applying the standard chain rule, the following system of linear equations gives the MLCs.

$$\begin{bmatrix} \frac{\partial P}{\partial V} & \frac{\partial Q}{\partial V} & \cdots & \frac{\partial P}{\partial V} \\ \frac{\partial P}{\partial \theta} & \frac{\partial Q}{\partial \theta} & \cdots & \frac{\partial P}{\partial \theta} \\ \frac{\partial P}{\partial (\alpha_i \cdot g)} & \frac{\partial Q}{\partial (\alpha_i \cdot g)} & \cdots & \frac{\partial P}{\partial (\alpha_i \cdot g)} \\ \frac{\partial P}{\partial (\alpha_i \cdot g')} & \frac{\partial Q}{\partial (\alpha_i \cdot g')} & \cdots & \frac{\partial P}{\partial (\alpha_i \cdot g')} \\ \frac{\partial P}{\partial (\alpha_i \cdot g'')} & \frac{\partial Q}{\partial (\alpha_i \cdot g'')} & \cdots & \frac{\partial P}{\partial (\alpha_i \cdot g'')} \\ \frac{\partial P}{\partial (\alpha_i \cdot g''')} & \frac{\partial Q}{\partial (\alpha_i \cdot g''')} & \cdots & \frac{\partial P}{\partial (\alpha_i \cdot g''')} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P}{\partial (\alpha_i \cdot g^{[N]})} & \frac{\partial Q}{\partial (\alpha_i \cdot g^{[N]})} & \cdots & \frac{\partial P}{\partial (\alpha_i \cdot g^{[N]})} \end{bmatrix} \cdot \begin{bmatrix} \alpha_i \\ \alpha_i \\ \alpha_i \\ \alpha_i \\ \alpha_i \\ \alpha_i \\ \vdots \\ \alpha_i \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \alpha_i} \\ \frac{\partial Q}{\partial \alpha_i} \\ \frac{\partial P}{\partial \alpha_i} \\ \frac{\partial Q}{\partial \alpha_i} \\ \frac{\partial P}{\partial \alpha_i} \\ \frac{\partial Q}{\partial \alpha_i} \\ \vdots \\ \frac{\partial P}{\partial \alpha_i} \end{bmatrix} \cdot \alpha_i$$ (4)

where the first term is the transposed Jacobian matrix $[\mathbf{J}]^T$.

The approximately quadratic relationship between losses and power flows is responsible for the twice amount of losses calculated applying the MLCs to the following equation:

$$\sum_{i=1}^{N} \bar{\alpha}_{PM} \cdot P_i + \sum_{i=1}^{N} \bar{\alpha}_{QM} \cdot Q_i \approx 2 \cdot P_L$$ (5)

where is the active power injection and the reactive power injection at node $i$, respectively.

A simple reconciliation method is to apply a constant multiplier in the order of 50% to both MLC’s. Thus, the vectors of MLCs, $\bar{\alpha}_{PM}$ and $\bar{\alpha}_{QM}$ reconciled by the constant scaling factor $\kappa_M \approx 0.5$:

$$\bar{\alpha}_{PM} = \kappa_M \cdot \bar{\alpha}_P \quad \text{and} \quad \bar{\alpha}_{QM} = \kappa_M \cdot \bar{\alpha}_Q$$ (6)

enable the allocation of the total system active power losses to individual users such that:

$$\sum_{i=1}^{N} \bar{\alpha}_{PM} \cdot P_i + \sum_{i=1}^{N} \bar{\alpha}_{QM} \cdot Q_i \approx P_L$$ (7)

Reconciliation by constant multiplier factor has the tendency to weaken economic signals by diminishing price differentials between nodes.

The assumption that the MLCs at reference node are zero, has as consequence the dependence of MLCs, in terms of magnitude and polarity, from the choice of reference node. It is important for the method to be consistent by yielding consistent values of MLCs irrespective of choice of reference node. By shifting both active and reactive power loss allocation related factors by constant factors and respectively a given generator loss contribution ratio can be achieved, as shown in [19].

For equal overall division of losses between generation and losses a value of equal to 0.5 should be used. The finally allocation of the total system active power losses to individual users, irrespective of choice of reference node is given from the following equation:

$$\sum_{i=1}^{N} (\bar{\alpha}_{PM} + \delta_P) \cdot P_i + \sum_{i=1}^{N} (\bar{\alpha}_{QM} + \delta_Q) \cdot Q_i \approx P_L$$ (8)

Thus, the reconciled MLC’s are finally given by:

$$MLC_P = \bar{\alpha}_{PM} + \delta_P$$ (9)

$$MLC_Q = \bar{\alpha}_{QM} + \delta_Q$$ (10)

Neglecting the reactive MLCs, the Active Marginal Values or Active Additional Values and the revenue for each generator calculated as follows:

$$AAV_i = (\bar{\alpha}_{PMi} + \delta) \cdot P_{gi} \cdot \Pi_i = MLC_P \cdot P_{gi} \cdot \Pi_i$$ (11)

$$REV_{Pi} = \Pi_i \cdot P_{gi} \cdot (1 - MLC_P) = \Pi_i \cdot P_{gi} - AAV_i$$ (12)

where $\Pi_i$ is the price in €/kWh and $P_{gi}$ in MW. The difference of the revenues assessed before and after the MLC’s appliance gives the revenue percentage change.

$$RPC_{Pi} = 100 \cdot \left( \frac{REV_{Pi} - \Pi_i \cdot P_{gi}}{\Pi_i \cdot P_{gi}} \right)$$ (13)

### 3 Case Study

In order to investigate and estimate the applicability, the accuracy and the overall effectiveness of the presented method a network with significant dispersed generation and substantial RES penetration is needed. Crete's power system is one of the most representative case studies for an essential demonstration of the Marginal Loss Allocation method.

#### 3.1 Power System of Crete

Grete is the largest Greek island with approximately 8.500 Km2 and one of the largest in Mediterranean
region. Its population is more than 600,000 inhabitants that triple in summer period. Fig.1 depicts the time evolution of load demand and energy consumption, using official long-term data (1975–2008). It is clear that there is a considerable annual increase of electricity demand approaching the 7% during the last decade, when the corresponding national figure is 3.5%. As a result, the annual energy consumption during 2008 surpassed the 3TWh in comparison with the modest 280 GWh of year 1975.

Additionally, there are 25 wind parks installed with nominal power of 124.85MW in specific and appropriate regions of the island (Fig. 3). These WPs are connected to the grid through HV/MV substations of 20kV/150kV.

In addition, comparing the mean hourly load demand variation all year round, there is a considerable electricity generation diversification between months and seasons, as it is clearly shown in figure 2.

Fig. 2 Monthly variation of min and max load demand

However, even during the low consumption periods, minimum load demand is greater than current system technical minimum (approximately 100 MW).

Island's electricity generation system is based mainly on three (3) oil-fired thermal power units, located as it is shown in Fig. 3. The official capacity of the local power plants is 742.9 MW, although the real power of the system is 693 MW for winter and 652 MW for summer operation.

The conventional generation system consists of three (3) thermal power plants having four groups of generating units. More precisely, power system conventional generation is based on six (6) relatively outmoded steam turbines of total capacity amounting at 111.25 MW, one combined cycle power unit of 135 MW and four (4) internal combustion engines (diesel units) of 49 MW. The technical minima of all these units are approximately 100 MW, excluding the annual service periods.

The annual peak load demand occurs on a winter day and overnight loads can be assumed to be approximately equal to 25% of the corresponding daily peak loads. The steam and diesel units mainly supply the base-load. The Gas turbines normally supply the daily peak load or the load that cannot be supplied by the other units in outage conditions. These units have a high running cost that increases significantly the average cost of the electricity being supplied.

One-line diagram shown in Fig.4 is a realistic model of the power system of Crete. The model consists of 64 bus-bars, 20 generator (PV) buses, 25 wind power generator buses and 33 load (PQ) buses.

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Fig. 5 Wind power penetration in power system of Crete

In Fig. 5 the wind power production in parallel with the overall production in a specific day within 2008 is presented. In this case the portion of the corresponding wind generation varies between 22% and 32% of the total power supply that is considered as a significant high penetration for an autonomous system such as Crete's network.

4 Results

MLCs calculations are based on actual loads and generations’ time series in the period April-June 2008. In this section the results obtained, for three days with similar load profile, of the month April and for 24 hours are presented. The W/P nodes considered is node 58 Xerolimni as the most remote bus of the network and node 47 Moulia, the only centrally located. Fig. 6, 10, and 14 illustrated the load and the generation profiles of each day. It has to be mentioned that in Fig. 14 the wind power generation should be divided by 100 (as shown in figure caption). Fig. 7, 11, and 15 illustrate the revenue change that can be achieved for each day, applying the loss allocation method. The related to active and reactive injections MLC’s time series are illustrated in Figs. 8, 9, 12, 13, 16, and 17.

Fig. 6 System load profile and active power generation from Wind Parks for the 1st day

Fig. 7 Revenue percentage change (RPC) for the 1st day

Fig. 8 MLC’s related to active injections and AAV’s at bus Moulia for the 1st day

Fig. 9 MLC’s related to active injections and AAV’s at bus Xerolimni for the 1st day

Fig. 10 System load profile and active power generation from Wind Parks for the 2nd day
It can be seen from the load profile and the revenue percentage change for each day that the active power injections at low load time periods decrease the revenue percentage change for the Wind Parks. In some cases as illustrated in Figs. 8 and 14 and for the low load early hours the remote node 58 Xerolimni will be penalized. On the contrary, active power injections at high load increase revenues.

It is very interesting to notice that for the 3rd day when penetration is very low both nodes as illustrated in Fig. 13 should be rewarded. These conclusions concern only the three studied days and they are not general conclusions for the MLCs.

In long term, the increase of revenues due to loss allocation can be quite considerable. The average revenue increase for a Wind Park typical day is approximately equal 1% to 2%. In higher load or extreme operating conditions a 5% or more...
5 Conclusion

Cost allocation of losses in power systems' network in case of dispersed generation and high penetration of renewable energy resources is a complex problem whose importance may increase as competition in power generation intensifies.

This paper through comprehensive and comparative studies for cost allocation of losses presents the applicability and the effectiveness of a loss allocation method, based on the concept of marginal cost. The method provides appropriate signals to the network users in order to take economically efficient operating decisions. The choice of reference node has no impact on the magnitude and the polarity of loss allocation factors.

The method is efficient and easy to implemented, while tests results on a representative power network such as power system of Crete island demonstrate the effectiveness of the method are looking forward to seeing you at the Conference.

References:


