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 [5-10] 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, [11-17]. A loss allocation scheme using the bus impedance Z-bus was presented in [18]. Other allocation schemes are presented in references [19-21].

The proportional sharing technique [22-23] 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 [24] 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 [25] and England and Wales [26]. 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 [27] 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 [28] where approximations are poor if the electrical distance between the contractors is small. In the context of multilateral trades [29] a loss allocation method based on a quadratic approximation of losses is proposed. In [30], 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 [31] the loss allocation method based on marginal losses has been proposed, while in [32] a method that applies the same concept as in [31], 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

Cost allocation of losses methods should meet the following requirements in general:

• *Economical Efficiency*: Losses should be allocated so that depict the contribution to the active and reactive losses cost of each producer/consumer, i.e. none crossway subsidies should be exist both between producer/consumer and time interval of network usage.
• *Evenness, Accuracy and Coherence*: It is clear that cost allocation of losses in networks with dispersed generation should be even and fair, in parallel with accuracy and coherence.
• *Network Data Acquisition*: Real time monitoring and collection feasibility of all the necessary network data is considered as an essential issue.
• *Simplicity and Applicability*: Algorithm simplicity and easy application is significant for a clear and fast cost allocation of losses to the network users.

The current methods that have been proposed for deregulated energy market applications could classified in the following categories:

1. Pro rata or postage stamp
2. Proportional sharing loss formula
3. Incremental transmission loss
4. Incremental bilateral contract path

The majority of the proposed methods could not successfully deal or/and solve the problem of both reference bus selection impact and reactive power impact in active power losses of the transmission grid. The method that is presented in this paper [31], [33], supplies losses allocation coefficients for both active and reactive power, defining the participation of each parameter in the final losses cost. Furthermore, an algorithm for neutralizing the reference bus selection impact is proposed.

2.1 Marginal Loss Coefficients Method

According to the economic theory the marginal losses reflect the Short-Term Marginal Costs (STMC) and therefore achieve short-term economic efficiency [31-32]. 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:

$$\tilde{\alpha}_{P_i} = \frac{\partial P_L}{\partial P_i}, \quad \tilde{\alpha}_{Q_i} = \frac{\partial P_L}{\partial Q_i} \tag{1}$$

where $\tilde{\alpha}_{P_i}$ and $\tilde{\alpha}_{Q_i}$ 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:

$$\frac{\partial P_L}{\partial Q_i} = 0 \quad , i \in \{PV\} \tag{2}$$

$$\frac{\partial P_L}{\partial P_r} = \frac{\partial P_L}{\partial Q_r} = 0 \ , r \equiv reference\ bus \tag{3}$$

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.

$$\begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial Q}{\partial \theta} \\ \frac{\partial P}{\partial V} & \frac{\partial Q}{\partial V} \end{bmatrix} \cdot \begin{bmatrix} \tilde{\alpha}_P \\ \tilde{\alpha}_Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P_L}{\partial \theta} \\ \frac{\partial P_L}{\partial V} \end{bmatrix} \Rightarrow \begin{bmatrix} \tilde{\alpha}_P \\ \tilde{\alpha}_Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial Q}{\partial \theta} \\ \frac{\partial P}{\partial V} & \frac{\partial Q}{\partial V} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \frac{\partial P_L}{\partial \theta} \\ \frac{\partial P_L}{\partial V} \end{bmatrix} \tag{4}$$

where the first term is the transposed Jacobian matrix $\left[J^T\right]$.

$$\begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial Q}{\partial \theta} \\ \frac{\partial P}{\partial V} & \frac{\partial Q}{\partial V} \end{bmatrix} = J^T \tag{4a}$$

$$P_L = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\left[\left(V_i^2 + V_j^2\right) - 2V_iV_j\cos\theta_{ij}\right]g_{ij} \tag{4b}$$

$$\frac{\partial P_L}{\partial \theta_i} = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\left[2V_iV_j\sin\theta_{ij}\right]g_{ij} \tag{4c}$$

$$\frac{\partial P_L}{\partial \theta_j} = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\left[2V_iV_j\sin\theta_{ij}\right]g_{ij} \tag{4d}$$

$$\frac{\partial P_L}{\partial V_i} = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\left[2V_i - 2V_j\cos\theta_{ij}\right]g_{ij} \tag{4e}$$

$$\frac{\partial P_L}{\partial V_j} = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\left[2V_j - 2V_i\cos\theta_{ij}\right]g_{ij} \tag{4f}$$

2.2 Additive Reconciliation Factor

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:

$$\sum_{i=1}^{N}\tilde{\alpha}_{P_i}P_i \cdot + \sum_{\substack{i=1 \\ i\notin PV,ref}}^{N}\tilde{\alpha}_{Q_i}Q_i \approx 2\cdot P_L \tag{5}$$

where P_i is the active power injection and Q_i 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, $\tilde{\alpha}_{PM}$ and $\tilde{\alpha}_{QM}$ reconciled by the constant scaling factor $\kappa_M \approx 0.5$:

$$\tilde{\boldsymbol{\alpha}}_{\boldsymbol{PM}} = \boldsymbol{\kappa_M} \cdot \tilde{\boldsymbol{\alpha}}_{\boldsymbol{P}} \text{ and } \tilde{\boldsymbol{\alpha}}_{\boldsymbol{QM}} = \boldsymbol{\kappa_M} \cdot \tilde{\boldsymbol{\alpha}}_{\boldsymbol{Q}} \tag{6}$$

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

$$\sum_{i=1}^{N} \tilde{\alpha}_{PM_i} \cdot P_i + \sum_{\substack{i=1 \\ i \notin PV, ref}}^{N} \tilde{\alpha}_{QM_i} \cdot Q_i \approx P_L \quad (7)$$

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

2.3 Additive Reconciliation Factor

Taking into the account the desirable simplicity without significant augment of the total error, the estimation of κ_A factors is based on active power losses, exclusively. These κ_A factors are added to the MLCs in equation (5), so that the total losses to be equal with the corresponding results of the power flow. Thus, adding κ_A to MLCs related to the active power only, the following equation is extracted:

$$\sum_{i=1}^{N} \left(\tilde{\boldsymbol{\alpha}}_{P_i} + \boldsymbol{\kappa}_A \right) \cdot \left(\boldsymbol{P}_{g_i} - \boldsymbol{P}_{l_i} \right) = \boldsymbol{L} = \sum_{i=1}^{N} \boldsymbol{P}_{g_i} - \sum_{i=1}^{N} \boldsymbol{P}_{l_i} \quad (8)$$

Equation (5) regarding MLCs of active power injection can be represented as follow:

$$\sum_{i=1}^{N} \tilde{\boldsymbol{\alpha}}_{P_i} \cdot \left(\boldsymbol{P}_{g_i} - \boldsymbol{P}_{l_i} \right) \approx 2 \cdot \boldsymbol{L} = 2 \cdot \left(\sum_{i=1}^{N} \boldsymbol{P}_{g_i} - \sum_{i=1}^{N} \boldsymbol{P}_{l_i} \right) \quad (9)$$

Taking into account (8) κ_A factor is:

$$\boldsymbol{\kappa}_A = \frac{\left(\sum_{i=1}^{N} \boldsymbol{P}_{g_i} - \sum_{i=1}^{N} \boldsymbol{P}_{l_i} \right) - \left(\sum_{i=1}^{N} \tilde{\boldsymbol{\alpha}}_{P_i} \cdot \left(\boldsymbol{P}_{g_i} - \boldsymbol{P}_{l_i} \right) \right)}{\sum_{i=1}^{N} \left(\boldsymbol{P}_{g_i} - \boldsymbol{P}_{l_i} \right)} \quad (10)$$

Combining previous equations (9) and (10), the additive κ_A factor can be calculated as:

$$\boldsymbol{\kappa}_A = \frac{\left(\sum_{i=1}^{N} \boldsymbol{P}_{g_i} - \sum_{i=1}^{N} \boldsymbol{P}_{l_i} \right) - 2 \cdot \left(\sum_{i=1}^{N} \boldsymbol{P}_{g_i} - \sum_{i=1}^{N} \boldsymbol{P}_{l_i} \right)}{\sum_{i=1}^{N} \left(\boldsymbol{P}_{g_i} - \boldsymbol{P}_{l_i} \right)} = -1 \quad (11)$$

As it is clear from (11) the value of the additive reconciliation factor κ_A is approximately equal to the total (100%). The value of this factor is significant high due to the fact that MLCs is generally below 15%. Such a high additive reconciliation factor leads to high (positive or negative) payments by the network users correspondingly. In fact the prices can be so high almost equal to the energy production cost, so some users will pay double while others won't pay anything.

Although, the net payments for losses will be equal to the expected prices, the relatively high cash flow will cause practical failure of MLCs that are calculated with the additive reconciliation.

2.4 Constant Multiplier Reconciliation

The estimation of MLCs reconciliation vector is achieved by the initial calculation of multiplier reconciliation factor κ_M. As it is previously mentioned, reconciliation of MLCs by multiplier factor intents to normalize them. So as the sum of the reconciliation MLCs with the power injections in all buses to be equal with the total losses *L* that are calculated by the power flow. The scale factor κ_M is:

$$\boldsymbol{\kappa}_M = \frac{\boldsymbol{L}}{\sum_{i=1}^{N} \tilde{\boldsymbol{\alpha}}_{P_i} \cdot \left(\boldsymbol{P}_{g_i} - \boldsymbol{P}_{l_i} \right) + \sum_{\substack{i=1 \\ i \notin PV, ref}}^{N} \tilde{\boldsymbol{\alpha}}_{Q_i} \cdot \left(\boldsymbol{Q}_{g_i} - \boldsymbol{Q}_{l_i} \right)} \quad (12)$$

The value of κ_M factor is approximately equal to 0.5. MLCs vectors α_{PM} and α_{QM} that are with the constant factor κ_M are calculated as follow:

$$\tilde{\boldsymbol{\alpha}}_{PM} = \boldsymbol{\kappa}_M \cdot \tilde{\boldsymbol{\alpha}}_P \text{ και } \tilde{\boldsymbol{\alpha}}_{QM} = \boldsymbol{\kappa}_M \cdot \tilde{\boldsymbol{\alpha}}_Q \quad (13)$$

The reconciliation MLCs allocate the total losses to the several users of the network, as:

$$\sum_{i=1}^{N} \tilde{\boldsymbol{\alpha}}_{PM_i} \cdot \left(\boldsymbol{P}_{g_i} - \boldsymbol{P}_{l_i} \right) + \sum_{\substack{i=1 \\ i \notin PV, ref}}^{N} \tilde{\boldsymbol{\alpha}}_{QM_i} \cdot \left(\boldsymbol{Q}_{g_i} - \boldsymbol{Q}_{l_i} \right) \approx \boldsymbol{L} \quad (14)$$

However, the reconciliation by multiplier factors can lead to relegation of economical efficiency target, due to the fact that MLCs decrement weaken and eliminate the economic signals.

2.5 Generators/Loads Contribution to Losses

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 δ_P and δ_Q respectively a given generator loss contribution ratio can be achieved, as shown in [31].

The values of δ_P and δ_Q that are needed for the achievement of μ per unit contribution of losses allocated to generators can be correspondingly calculated by the equations (15) and (16), as follow:

$$\delta_P = \frac{\sum_{i=1}^{N}\tilde{\alpha}_{P_i}\cdot P_{g_i} + \sum_{\substack{i=1\\ i\notin PV,ref}}^{N}\tilde{\alpha}_{Q_i}\cdot Q_{g_i} - \mu\cdot L}{\left(\sum_{i=1}^{N}\left(P_{g_i}-P_{l_i}\right)\Big/\sum_{\substack{i=1\\ i\notin PV,ref}}^{N}\left(Q_{g_i}-Q_{l_i}\right)\right)\cdot\sum_{\substack{i=1\\ i\notin PV,ref}}^{N}Q_{g_i} - \sum_{i=1}^{N}P_{g_i}} \tag{15}$$

$$\delta_Q = -\left(\sum_{i=1}^{N}\left(P_{g_i}-P_{l_i}\right)\Big/\sum_{\substack{i=1\\ i\notin PV,ref}}^{N}\left(Q_{g_i}-Q_{l_i}\right)\right)\cdot\delta_P \tag{16}$$

where P_{li} and P_{gi} is the load and the generation of bus i correspondingly. The previous formulas are extracted by the following two equations:

$$\sum_{i=1}^{N}\left(\tilde{\alpha}_{P_i}+\delta_P\right)\cdot\left(P_{g_i}-P_{l_i}\right)+\sum_{\substack{i=1\\ i\notin PV,ref}}^{N}\left(\tilde{\alpha}_{Q_i}+\delta_Q\right)\cdot\left(Q_{g_i}-Q_{l_i}\right)=L \tag{17}$$

$$\mu = \frac{\sum_{i=1}^{N}\left(\tilde{\alpha}_{P_i}+\delta_P\right)\cdot P_{g_i} + \sum_{\substack{i=1\\ i\notin PV,ref}}^{N}\left(\tilde{\alpha}_{Q_i}+\delta_Q\right)\cdot Q_{g_i}}{L} \tag{18}$$

For equal overall division of losses between generation and losses a value of μ 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:

$$\sum_{i=1}^{N}\left(\tilde{\alpha}_{PM_i}+\delta_P\right)\cdot P_i + \sum_{\substack{i=1\\ i\notin PV,ref}}^{N}\left(\tilde{\alpha}_{QM_i}+\delta_Q\right)\cdot Q_i \approx P_L \tag{19}$$

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

$$MLC_{P_i} = \tilde{\alpha}_{PM_i} + \delta_P \tag{20}$$

$$MLC_{Q_i} = \tilde{\alpha}_{QM_i} + \delta_Q \tag{21}$$

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

$$AAV_i = \left(\tilde{\alpha}_{PM_I}+\delta_P\right)\cdot P_{g_i}\cdot\Pi_i = MLC_{P_i}\cdot P_{g_i}\cdot\Pi_i \tag{22}$$

$$REV_{P_{gi}} = \Pi_i\cdot P_{g_i}\cdot\left(1-MLC_{P_i}\right) = \Pi_i\cdot P_{g_i} - AAV_i \tag{23}$$

where Π_i is the price in €/kWh and P_g in MW. The difference of the revenues assessed before and after the MLC's appliance gives the revenue percentage change.

$$RPC_{P_{gi}} = 100\cdot\left[REV_{P_{gi}} - \Pi_i\cdot P_{g_i}\right]/\Pi_i\cdot P_{g_i} \tag{24}$$

2.7 Cost Allocation of losses Algorithm

Cost allocation of losses algorithm has been developed and implemented using MATLAB 5.3 [34-35]. The basic flow cart of the algorithm of the proposed problem is presented in Fig.1. The algorithm can use either its own power flow data or retrieved power flow data from different software for Marginal Losses Coefficients (MLC) or Direct Loss Coefficients (DLC) calculations. In this paper direct loss coefficient is not presented. Once power flow data of the investigated networks are inserted MLC or DLC calculation method is executed and the final coefficients are selected.

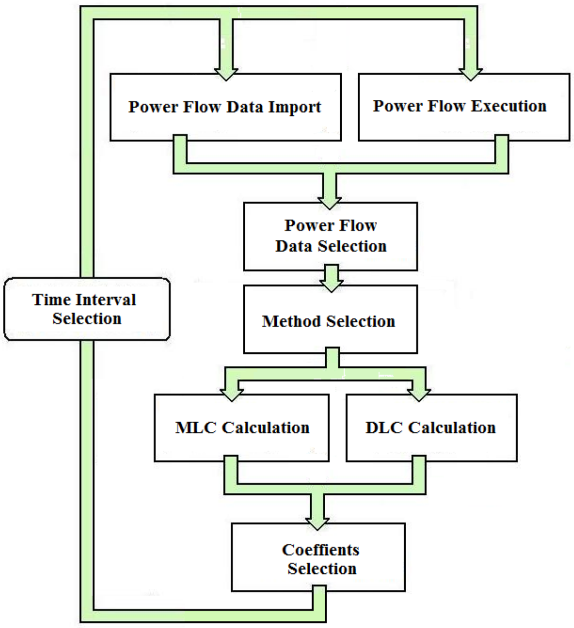

Fig.1 Flow chart of the algorithm for the calculation of MLC and DLC

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 [36-37] 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 Km^2 and one of the largest in Mediterranean region. Its population is more than 600,000 inhabitants that triple in summer period. Fig.2 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.

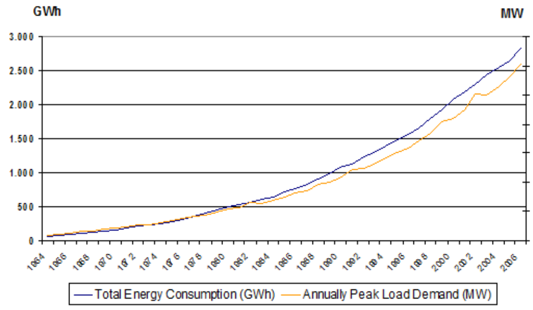

Fig.2 Load Demand and Energy Consumption Time Evolution

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 Fig. 3.

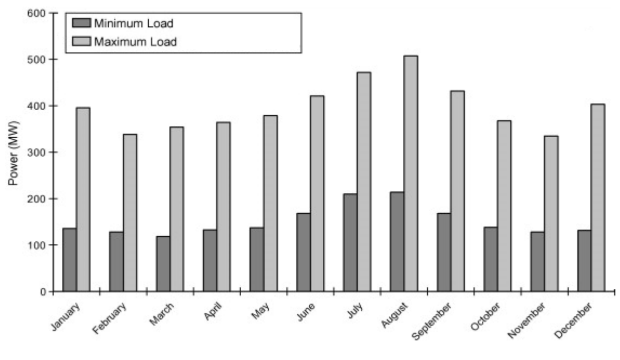

Fig. 3 Monthly variation of min and max load demand

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. 4. 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. Additionally, there are 25 wind parks installed with nominal power of 124,85MW in specific and appropriate regions of the island (Fig. 4). These WPs are connected to the grid through HV/MV substations of 20kV/150kV.

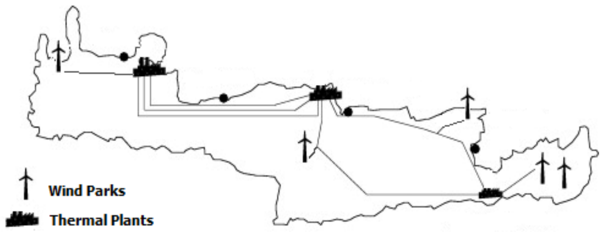

Fig. 4 Power plants and wind parks locations

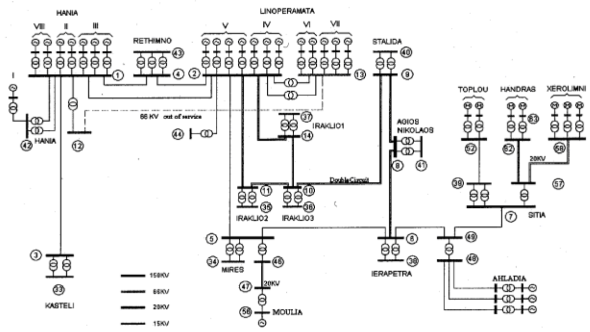

Fig. 5 One-line diagram of Crete's power system

One-line diagram shown in Fig.5 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.

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.

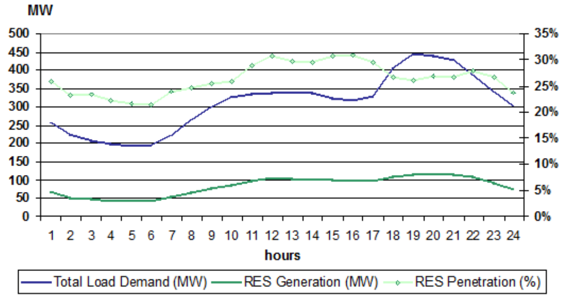

Fig. 6 Wind power penetration in power system of Crete

Table 1 Wind Parks in the island of Crete

ID	Location	Year	Power (MW)	T.V. P (MW)	T.V. Q (Mvar)
1	Toplou	1993	5,10	3,16	0,51
2	Toplou	1993	1,00	0,62	0,1
3	Toplou	1995	0,50	0,31	0,05
4	Xirolimni	2000	10,20	6,32	1,01
5	Mitato	1998	10,20	6,32	1,01
6	Chandras	1999	9,90	6,14	0,98
7	Meg. Vrisi	1999	4,95	3,07	0,49
8	Achladia	1999	10,00	6,2	0,99
9	Anemoessa	2000	5,00	3,1	0,5
10	Krya	2000	10,00	6,2	0,99
11	Plativolo	2000	2,50	1,55	0,25
12	Mare	1993	0,50	0,31	0,05
13	Vrouchas	2003	7,65	4,74	0,76
14	Xirolimni	2004	3,00	1,86	0,3
15	Plativolo	2004	3,00	1,86	0,3
16	Krousona	2004	5,95	3,69	0,59
17	Xirolimni	2005	3,00	1,86	0,3
18	Epanosifi	2005	6,30	3,91	0,62
19	Modi	2006	2,70	1,67	0,27
20	Ierapetra	2006	4,60	2,85	0,46
21	Mires	2007	5,20	3,22	0,52
22	Platanos	2007	3,30	2,05	0,33
23	Spatha	2007	4,60	2,85	0,46
24	Chonos	2008	4,50	2,79	0,45
25	Mare	2008	1,20	0,74	0,12

In Fig.6 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.

3.2 Wind Parks

It is known and widely accepted that Crete possesses very high wind power potential, while the wind energy exploitation activities started since mid eighties. As a result, a remarkable wind park installation activity has started since 1992, leading by 2008 to the existence of 25 wind power stations of rated power 124.85 MW. More precisely, Table 1 provides the installed capacity and typical values of each wind park active generation and reactive absorption.

3.3 PV Installation Prospects

Recently, a new Greek Legislation (L.3468/2006) promotes electricity production from RES and especially from PV. More precisely, the law foresees a PV program for the introduction of PV system in Greece for a total installed capacity of at least 500MW in the interconnected system and at least 200MW in autonomous island systems till the end of 2020. As a result, a great interest for PV plants integration of 104MW nominal capacity has been recorded. In the following Fig.7 the geographical diversion of the corresponding PV plants are depicted, leading to even greater power generation dispersal.

Assuming the previous mentioned wind parks and the prospect of many PV plants installation, Crete's power system deals even now with a significant dispersed generation and high RES penetration.

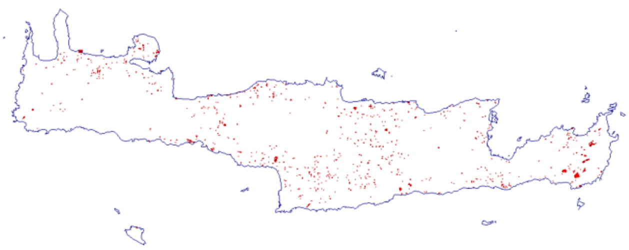

Fig. 7 Geographical dispersal of PV plants

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 24hours 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.

Furthermore, two new coefficients [Hat02b] have been introduced, payment factors PF_{Pg} of active power injection and payment factors PF_{Qg} of reactive power injection for the corresponding bus *i*:

$$PF_{P_{gi}} = \left(\tilde{\alpha}_{PM_I} + \delta_P\right)\cdot P_{g_i} \tag{24}$$

$$PF_{Q_{gi}} = \left(\tilde{\alpha}_{QM_I} + \delta_Q\right)\cdot Q_{g_i} \tag{25}$$

where equation (24) and (25) gives the results of the multiplication of the active and reactive power generation by the final coefficients MLC of the corresponding production bus.

The final profits assessment of the several independent producers after cost allocation of losses of the transmission networks are calculated by the following equation (26). This equation estimates only with the active power injection to the grid, while reactive power isn't under trade at the moment in Greek energy market.

$$REV_{P_{gi}} = C\cdot P_{g_i}\cdot\left(1-\left(\tilde{\alpha}_{PM_I} + \delta_P\right)\right) \tag{26}$$

where $C = €/kWh$ and P_g in *MW*.

The difference between final user incomes before and after of the cost allocation of losses through MLC is represented by Revenue Percentage Change ($RPC_{P_{gi}}$) and is calculated by the following equation:

$$RPC_{P_{gi}} = 100\cdot\left[REV_{P_{gi}} - C\cdot P_{g_i}\right]/C\cdot P_{g_i} \tag{27}$$

Fig. 8, 12, and 16 illustrated the load and the generation profiles of each day. It has to be mentioned that in Fig. 16 the wind power generation should be divided by 100 (as shown in figure caption). Fig. 9, 13, and 17 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. 10, 11, 14, 15, 18, and 19.

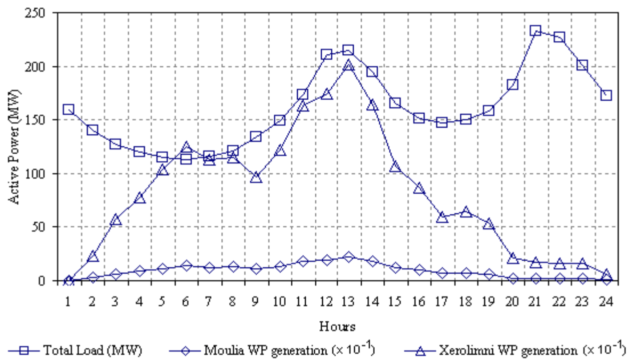

Fig. 8 System load profile and active power generation from Wind Parks for the 1st day

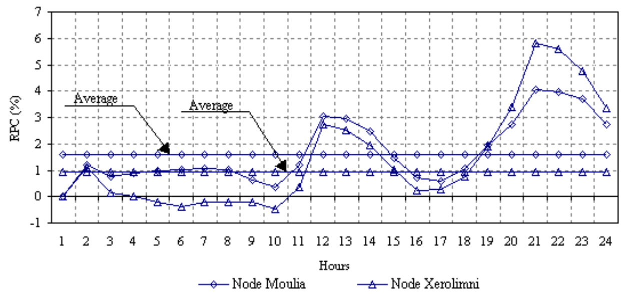

Fig. 9 Revenue percentage change (RPC) for the 1st day

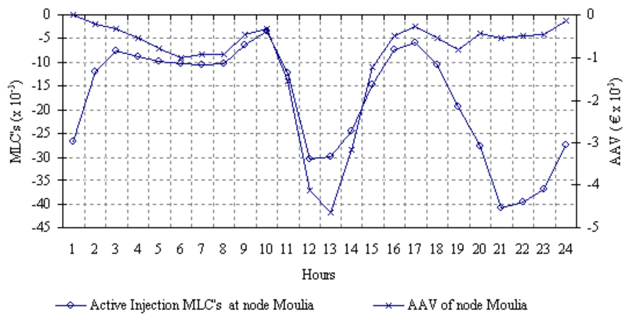

Fig. 10 MLCs related to active injections and AAVs at bus Moulia for the 1st day

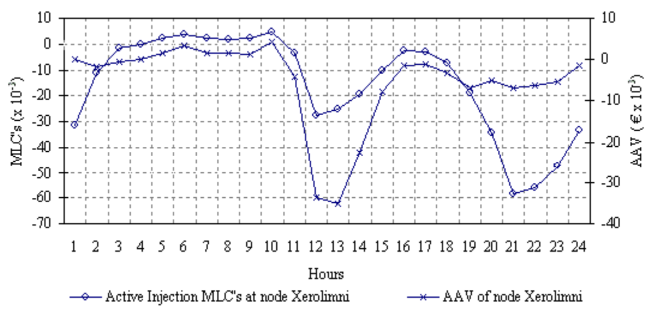

Fig. 11 MLCs related to active injections and AAVs at bus Xerolimni for the 1st day

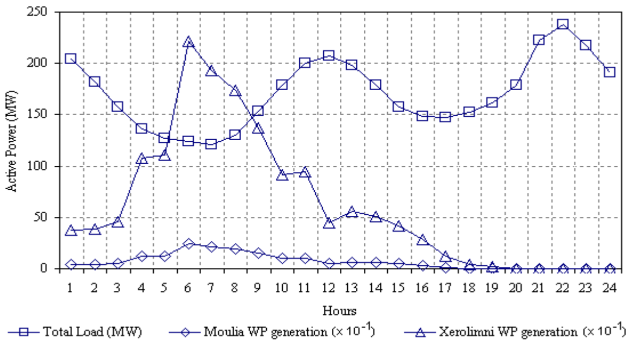

Fig. 12 System load profile and active power generation from Wind Parks for the 2nd day

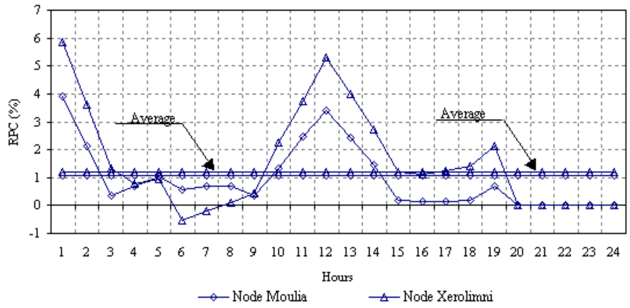

Fig.13 Revenue percentage change (RPC) for the 2nd day

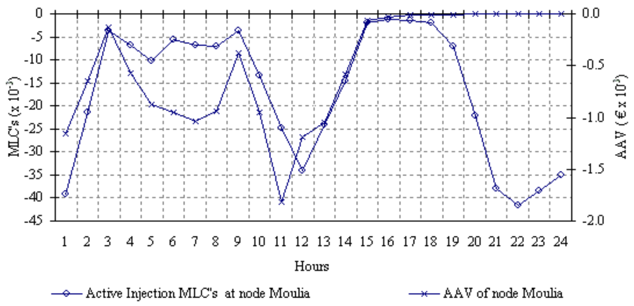

Fig. 14 MLCs related to active injections and AAVs at bus Moulia for the 2nd day

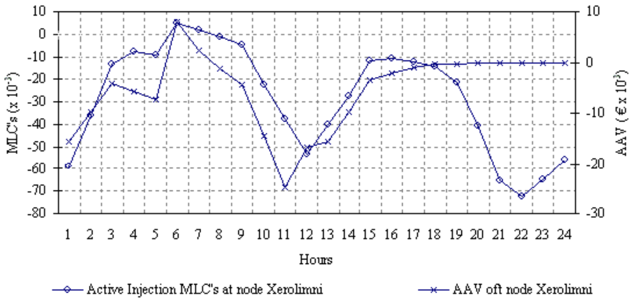

Fig. 15 MLCs related to active injections and AAVs at bus Xerolimni for the 2nd day

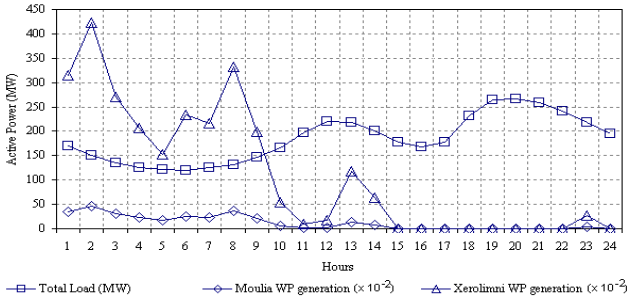

Fig. 16 System load profile and active power generation from Wind Parks for the 3rd day

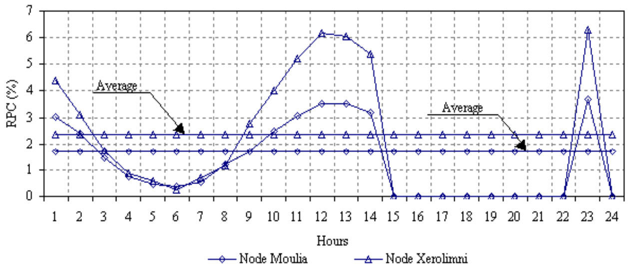

Fig. 17 Revenue percentage change (RPC) for the 3rd day

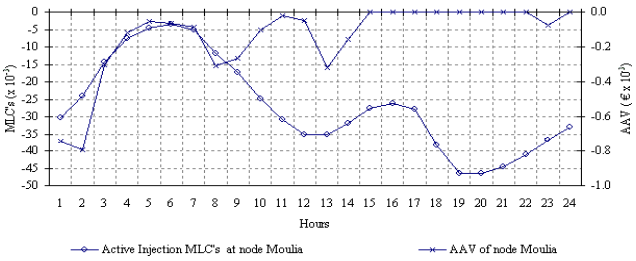

Fig. 18 MLCs related to active injections and AAVs at bus Moulia for the 3rd day

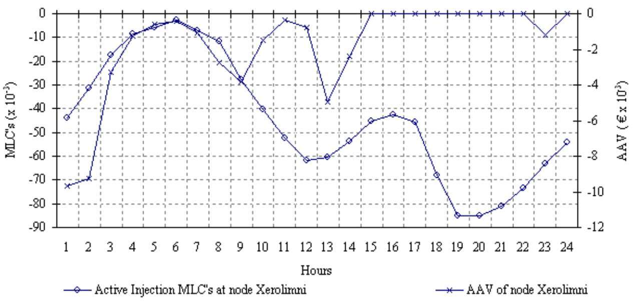

Fig. 19 MLCs related to active injections and AAVs at bus Xerolimni for the 3rd day

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 Fig. 9 and 15 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. 17 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 an additional 5% can be achieved.

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 investigates 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.

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