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Plug in hybrid electric vehicles (PHEVs) as a player in Energy market and Reactive power market and coupled market

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ABSTRACT: In this research work, Plug in Hybrid Electric Vehicle (PHEV) is studied how to participate in the energy market, reactive power market and coupled energy and reactive power market. The PHEV capability curve is identified which have been recently presented in the related work in the area. The concept Lost Opportunity Cost (LOC) is explained based on the capability of PHEV and its application is fully taken into consideration. Then PHEV is included in energy, reactive and coupled market. This require to determine objective functions in each market. Finally a 17-node microgrid is taken as case study in which some of PHEVs are placed to take part in these markets.

Keywords**:** energy market, reactive power market, coupled energy and reactive power market, Plug in Hybrid Electric Vehicle (PHEV), Expected Payment Function (EPF), Total Payment Function (TPF), Lost Opportunity Cost (LOC).

INTRODUCTION

Plug-in hybrid electric vehicle is a environmentally clean technology that decrease greenhouse gas emissions and air pollution (Niknam et al., 2011). Such electric vehicles (EVs) can change the load-shaping increasing the utilization of installed generation capacity (DeForest et al., 2009). Reference (W Su et al., 2012) completely surveys the electrification of transportation in a smart grid environment. In fact PHEVs/PEVs include a lot of promise such as higher energy efficiency, lower carbon emissions, energy independency, and environmental responsibility. The impact of different levels of PEV penetration on the distribution network’s investment and incremental energy losses is studied by (L P F nde et al., 2011). Also, (J A P Lopes et al., 2011), assessed the integration of EVs into power systems from the aspect of technical operation electricity market. In (Kempton and Tomi´c, 2005) , a formulation is presented to calculate the capacity for grid power from vehicle fleets to be used in four electric markets, i.e., base-load power, peak power, spinning reserves, and regulation market. The other papers (Andersson et al., 2010 and Kisacikoglu et al., 2010), are devoted to the study of PHEVs integration in the energy and reserve market and also to use the PEHVs in the other power system operation problem such as Unit Commitment (UC).

It is important to note that, the reactive power compensation of V2G does not degrade the battery life of vehicle as compared with the peak power shaving by V2G for the reason that the reactive power can be provided by DC link capacitor and the battery does not have any role in reactive power transfer (Kisacikoglu et al., 2010). Therefore, the owners of PHEVs can participate in both energy and reactive power market in the form of coupled energy and reactive power market.

Reactive power has a significant effect on system security (Bhattacharya and Zhong, 2001 and Rabiee et al., 2009).(Bhattacharya et al., 2001; Zhong, 2006 and Zhong et al., 2004) presents a competitive reactive power market. In (Zhong et al., 2004), a localized reactive power market is proposed to mitigate market power of generators. Since the localized reactive power market limit the market power of each generator to its area and it no longer affects the reactive power prices of the other zones.

In deregulated environment, when talking about electricity markets, one usually refers to energy market paying less attention to reactive power market. Active and reactive powers are however coupled with together through the AC power flow equations and branch loading limits as well as the synchronous generators capability curve. However, the sequential approach for energy and reactive power markets cannot present the optimal solution due to interactions between these markets. For instance, clearing of reactive power market can change the active power dispatch (e.g., due to change of transmission system losses and capability curve limitation), which can lead to degradation of the energy market clearing point. In (Rabiee et al., 2009) coupled active and reactive power market is cleared. Inspire by paper (Rabiee et al., 2009), in this paper a coupled energy and reactive power market is in which the integrated PHEVs are participated in both energy and reactive power market.

Decoupled energy market

In the energy market, the ISOs generally use an auction mechanism that minimizes the total offer cost to select generating units and their capacity levels for energy market and then use a market clearing price settlement mechanism (Pay-at-MCP) to determine the corresponding payments for the selected generating units in the market settlement. Accordingly, the objective function of the energy market, considering the system demand is given, can be written as follows:

$$Minimize \ \sum_{i=1}^{NB}\left(\rho_e^i . \tilde{P}_G^i\right) \qquad (1)$$

Where, ρ_e^i is bid price for the i^{th} unit and $\tilde{P}_G^i$ is the energy output unit in i^{th} bus in the energy market; *NB* is the number of system buses.

Decoupled reactive power market

The reactive power capability curve of a generator is shown in Figure 1 (Kisacikoglu et al., 2010). Q_{base} is the reactive power required by the generator for its auxiliary equipment. If the operating point lies inside the limiting curve, e.g. (P_A , Q_{base}), then the unit can increase its reactive generation from Q_{base} to Q_A without requiring the adjustment of P_A.

Accordingly, the EPF can be determined in any operating condition of synchronous generator. The EPF of a generator as a function of the amount of generator reactive power production is illustrated in Figure 2 (M. C. Kisacikoglu*, et al, 2010*). According to the classification of reactive power production cost, an offer structure is formulated mathematically in (M. C. Kisacikoglu*, et al, 2010*) as the following equation:

$$EPF_G^i = a_0^i + \int_{Q_{Min}}^{0} m_1^i \ dQ_G^i + \int_{Q_{base}}^{Q_A} m_2^i \ dQ_G^i + \int_{Q_A}^{Q_B} m_3^i Q_G^i \ dQ_G^i \qquad (2)$$

The coefficients in (2) represent the various components of reactive power cost incurred by the i^{th} needed to be offered in the reactive power market, where a_0^i is the availability price offer in dollars,

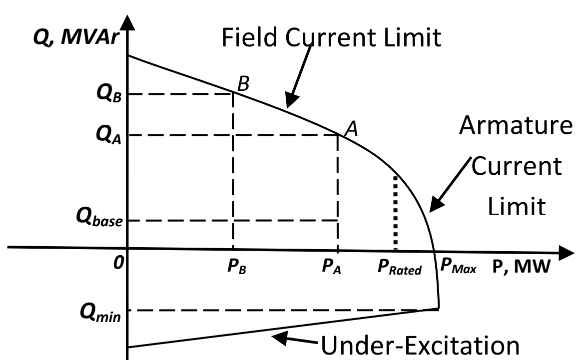

Figure 1. Synchronous generator capability curve.

m_1^i is cost of loss price offer for operating in under excited mode ($Q_{min} < Q \le 0$) in \$/MVAr-h, m_2^i is cost of loss price offer for operating in region ($Q_{base} \le Q \le Q_A$) in \$/MVAr-h and m_3^i is opportunity price offer for operating in region ($Q_A \le Q \le Q_B$) in \$/MVAr-h/MVAr-h (Fig. 2). As shown in Fig. 2, the opportunity cost is a quadratic function of *Q*.

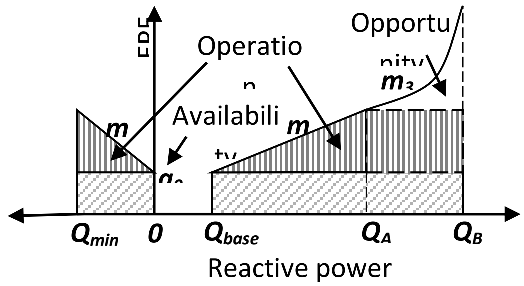

Figure 2. Reactive power offer structure of provider.

The capability curve of PHEV

A typical circuit for PHEV structure is considered which consists of three parts: AC/DC converter (rectifier and inverter), DC/DC converter (buck and boost converter) and battery. AC/DC converter operates as rectifier in charging mode and as inverter in discharging mode. The DC/DC converter operates as a buck converter in charging mode and boost converter in discharging mode.

In the charging/discharging mode, PHEV can absorb/inject active power from/to the grid. At the same time, PHEV can inject/absorb reactive power to/from the grid. In other words, the PHEV owners can be considered as a participant of reactive power market and regulate grid voltage in the form of reactive power ancillary service. For this approach it is needed that the PHEV owners offer in the reactive power market. Therefore, the PHEV owners, like synchronous generators and other participants of reactive power market should offer their price offer components based on the EPF of PHEV. The capability curve of PHEV is presented (Feshki Farahani et al., 2012) that in this paper it is used.

Expected Payment Function (EPF) of PHEV

To obtain the EPF curve for PHEV, the losses of typical PHEV is considered and discussed. Using PHEV capability curve in Fig. 3, the PHEV losses are a quadratic function of its reactive power output in both charging and discharging mode. However, the losses in the discharging mode are greater than that of charging mode which is mainly due to inverter switching losses.

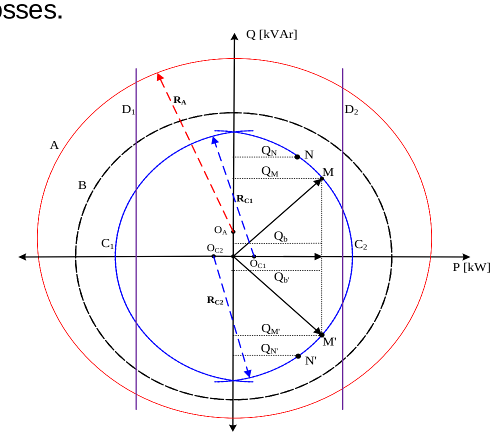

Figure 3. The capability curve of PHEV.

Based on Fig. 3, five operating regions for a PHEV on the reactive power coordinate can be defined as shown in Fig. 4. In the boundary ($Q_{b'}$ to Q_b), the PHEV should operated based on the requirement of system and the ISO decision without any operating payment. A PHEV operated in this boundary, is paid only the availability payment. Accordingly the PHEV EPF in this region is:

EPF_0 = *availability cost* = a_0 (3)

where, α_0 is availability price offer in dollars.

In region I ($Q_{b'}$ to $Q_{M'}$) and region II (Q_b to Q_M) because of generating/absorbing reactive power, the losses of PHEV increase and therefore, it can expect to be paid for its service. Thus, the EPF of PHEV, besides availability component, will contain the cost of loss component. It is noted that the losses of region II is different from those of region I. This matter is discussed with more details in appendix. The losses of PHEV in regions I, II are a quadratic function of PHEV reactive power generation/absorption which is shown in Fig. 4. Accordingly, the losses cost in region I and II are considered as (m_1Q) and (m_2Q), respectively. Therefore, the EPF of PHEV in these regions is:

EPF_I = *availability cost + losses cost*

$$= a_0 + \int_{Q_{b'}}^{Q_{M'}} (m_1.Q).dQ \qquad (4)$$

EPF_{II} = *availability cost + losses cost*

$$= a_0 + \int_{Q_b}^{Q_M} (m_2.Q).dQ \qquad (5)$$

m_1 is cost of losses price offer for operating in reactive power absorption in region I ($Q_{b'} \le Q \le Q_{M'}$) in \$/kVAr–h/kVAr–h, m_2 is cost of loss price offer for operating in reactive power injection in region II ($Q_b \le Q \le Q_M$) in \$/kVAr–h/kVAr–h . According to Figure 4, the loss offer is a function of reactive power output, and hence, the corresponding EPF component will be a quadratic function of Q

In region III (Q_M to Q_N), and region IV ($Q_{M'}$ to $Q_{N'}$) the PHEV is managed to reduce its active power to generate the required reactive power. Thus, the PHEV incurs loss of revenue cost and consequently, the EPF will contain all components of cost (i.e. availability cost, cost of loss and opportunity cost). As shown in Fig. 4, the LOC of PHEV is a quadratic function of its reactive power generation/absorption. Accordingly, the EPF of PHEV in this region will be as follows:

EPF_{III} = *availability cost + losses cost + LOC cost*

$$= a_0 + \int_{Q_b}^{Q_M} (m_2.Q).dQ + \int_{Q_M}^{Q_N} (m_3.Q).dQ \qquad (6)$$

EPF_{IV} = *availability cost + losses cost + LOC cost*

$$= a_0 + \int_{Q_{b'}}^{Q_{M'}} (m_1.Q).dQ + \int_{Q_{M'}}^{Q_{N'}} (m_4.Q).dQ \qquad (7)$$

Where, m_3 is opportunity price offer for operating in region ($Q_M \le Q \le Q_N$) in \$/kVAr–h/kVAr–h and m_4 is opportunity price offer for operating in region ($Q_{M'} \le Q \le Q_{N'}$) in \$/kVAr–h/kVAr–h. Similar to cost of loss price, the opportunity offer is a function of reactive power output, therefore, the corresponding EPF component will be a quadratic function of Q which is shown in Fig. 4. According to the classification of reactive power production cost, an offer structure is formulated mathematically as (Zhong and Bhattacharya, 2002; Feshki Farahani et al., 2012):

$$EPF_j = a_{0j} + \int_{Q_{b'}}^{Q_{M'}} (m_{1j}.Q_j).dQ_j + \int_{Q_b}^{Q_M} (m_{2j}.Q_j).dQ_j + \int_{Q_M}^{Q_N} (m_{3j}.Q_j).dQ_j + \int_{Q_{M'}}^{Q_{N'}} (m_{4j}.Q_j).dQ_j \qquad (8)$$

Where a_{0j}, m_{1j}, m_{2j}, , m_{3j} and m_{4j} are the bid values of the j^{th} provider for the reactive power market. As shown in Figure 4, the cost of loss and also the opportunity cost are a quadratic function of Q.

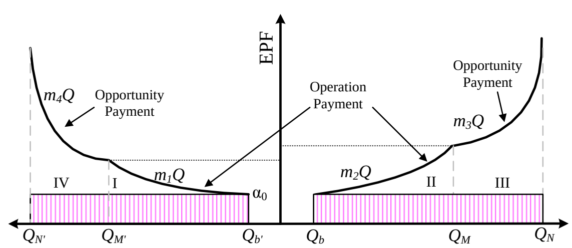

Figure 4. Reactive power offer structure of PHEV.

Reactive Power Market Clearing

The reactive power is settled based on the minimization of total payment function (TPF) paid to the participants of reactive power market. In other words, the objective function of this minimization problem is the EPF of PHEVs plus the EPF of synchronous generators that should be minimized. Therefore, the total payment will depend on the market price of the five components of the bid prices offered by the PHEVs and four components of the bid prices offered by synchronous generators. The total payment function (TPF) is formulated as Where ρ_0, ρ_1, ρ_2, ρ_3, and ρ_4

are the market clearing prices (MCPs) of offer prices of market participants for a_0, m_1, m_2, m_3 and m_4 respectively which are accepted in the reactive power market. The discussion for TPF_i is the same as (Zhong and Bhattacharya, 2002; Rabiee et al., 2009). However TPF_j deserves more explanation. According to (18), the PHEV owner is paid for losses payment as it enter region I, IV for reactive power absorption, and region II, III for reactive power production.

$$
\begin{aligned}
TPF &= TPF_i + TPF_j \\
&= \sum_{i\in gen}\left[\begin{array}{l} \rho_0.W_0^i - \rho_1.W_1^i.Q_{1G}^i + \rho_2.W_2^i.\left(Q_{2G}^i - Q_{G\,base}^i\right) \\ + \rho_2.W_3^i.\left(Q_{3G}^i - Q_{G\,base}^i\right) + \frac{1}{2}\rho_3.W_3^i.\left[\left(Q_{3G}^i\right)^2 - \left(Q_{G\,base}^i\right)^2\right] \end{array}\right] \\
&+ \sum_{j\in PHEV}\left[\begin{array}{l} \rho_0.W_{0j} \\ + \overbrace{\frac{1}{2}\rho_1.W_{1j}.\left(Q_{1j}^2 - Q_{b'j}^2\right) + \frac{1}{2}\rho_1.W_{4j}.\left(Q_{4j}^2 - Q_{b'j}^2\right)}^{Losses\ \ Payment\ \ regions\ I,IV} \\ + \overbrace{\frac{1}{2}\rho_4.W_{4j}.\left(Q_{4j}^2 - Q_{M'j}^2\right)}^{LOC\ Payment\ \ region\ IV} \\ + \overbrace{\frac{1}{2}\rho_2.W_{2j}.\left(Q_{2j}^2 - Q_{bj}^2\right) + \frac{1}{2}\rho_2.W_{3j}.\left(Q_{3j}^2 - Q_{b'j}^2\right)}^{Losses\ Payment\ \ regions\ II,III} \\ + \overbrace{\frac{1}{2}\rho_3.W_{3j}.\left(Q_{3j}^2 - Q_{Mj}^2\right)}^{LOC\ Payment\ \ region\ III} \end{array}\right]
\end{aligned}
\tag{9}
$$

Despite the synchronous generator (which is a linear function), the losses payment of PHEV is quadratic function of PHEV reactive power output (Feshki Farahaniet al., 2012). The LOC payment of PHEV is similar to that of synchronous generator which is a quadratic function of its reactive power output (Zhong and Bhattacharya, 2002 and Rabiee et al., 2009). The objective function is subjected to equality and inequality constraints. It is noted that:

$$W_{0,i}, W_{1,i}, W_{2,i}, W_{3,i} \in \{0,1\};\ \ i \in the\, generator\ \ index \tag{10}$$

LOC consideration in decoupled and coupled markets

In decoupled reactive power market, if a generator is needed to decrease its active power output determined earlier in the energy market to meet system reactive power requirement, it is paid for LOC payment. According to equation (3), the LOC payment is a quadratic function of produced reactive power. In the coupled market, same as decoupled reactive power market, a generator will be paid for LOC if its active power output in the coupled market is less than that of energy-only market. However, the LOC payment in the proposed coupled market is formulated in a different way compared with that of decoupled reactive power market. The quadratic term of TPF in decoupled reactive power market, i.e. the last term in the large parentheses of (3), is related to LOC payment. On the other hand, in the coupled market, the LOC of a generating unit is calculated based on the MCP of energy-only market as well as its bid price in the energy-only market.

Hence, in the proposed coupled market, the quadratic term of TPF related to the LOC payment is removed and substituted by the new formulation described in (4) and (5). So, the TPF for reactive power compensation in the coupled market only includes availability and operation payments as follows:

$$
\begin{aligned}
TPF &= TPF_i + TPF_j \\
&= \sum_{i\in gen}\left[\begin{array}{l} \rho_0.W_0^i - \rho_1.W_1^i.Q_{1G}^i + \rho_2.W_2^i.\left(Q_{2G}^i - Q_{G\,base}^i\right) \\ + \rho_2.W_3^i.\left(Q_{3G}^i - Q_{G\,base}^i\right) \end{array}\right] \\
&+ \sum_{j\in PHEV}\left[\begin{array}{l} \rho_0.W_{0j} \\ + \overbrace{\frac{1}{2}\rho_1.W_{1j}.\left(Q_{1j}^2 - Q_{b'j}^2\right) + \frac{1}{2}\rho_1.W_{4j}.\left(Q_{4j}^2 - Q_{b'j}^2\right)}^{Losses\ Payment\ \ regions\,I,IV} \\ + \overbrace{\frac{1}{2}\rho_4.W_{4j}.\left(Q_{4j}^2 - Q_{M'j}^2\right)}^{LOC\,Payment\ \ region\,IV} \\ + \overbrace{\frac{1}{2}\rho_2.W_{2j}.\left(Q_{2j}^2 - Q_{bj}^2\right) + \frac{1}{2}\rho_2.W_{3j}.\left(Q_{3j}^2 - Q_{b'j}^2\right)}^{Losses\,Payment\ \ regions\,II,III} \end{array}\right]
\end{aligned}
\tag{11}
$$

The two regions (Q_{base} to Q_A) and (Q_A to Q_B) are merged in (6) compared with (3), since both regions have the same operation payment (the quadratic term of the region (Q_A to Q_B) has been eliminated).

Coupled energy and reactive power markets

The objective function of the coupled energy and reactive power market is composed of offer cost of generating units for their active power production, TPF of units for their reactive power compensation, and the LOC payment of units:

$$Minimize \begin{cases} \sum_{i\in gen}\rho_e^i.P_G^i + \sum_{j\in PHEV}\rho_e^j.P_{PHEV}^j + \sum_{i\in gen}\begin{bmatrix}\rho_0.W_0^i - \rho_1.W_1^i.Q_{1G}^i + \rho_2.W_2^i.\left(Q_{2G}^i - Q_{Gbase}^i\right) \\ + \rho_2.W_3^i.\left(Q_{3G}^i - Q_{Gbase}^i\right)\end{bmatrix} \\ \quad + \sum_{j\in PHEV}\begin{bmatrix}\rho_0.W_0^j - \rho_1.W_1^j.Q_{1G}^j + \rho_2.W_2^j.\left(Q_{2G}^j - Q_{PHEV\,base}^j\right) \\ + \rho_2.W_3^j.\left(Q_{3PHEV}^j - Q_{PHEV}^j\right)\end{bmatrix} \\ \quad + \sum_{i\in gen}\left[LOC_G^i\right] + \sum_{j\in PHEV}\left[LOC_{PHEV}^j\right] \end{cases} \tag{12}$$

Subject to the equality and inequality constraints.

Case Study

The coupled energy and reactive power market is studied based on a 17-node LV network presented in (Papathanassiou et al., 2005) is which is shown in Fig. 5. The network comprises three feeders: One feeder serves residential area, the other one is industrial feeder, and the last feeder includes commercial consumers. The power factor of all loads is assumed to be equal to 0.85 lagging. This network is modified by adding some PHEVs to the network and eliminating the DGs such as micro turbines (MTs), small wind turbines (WTs) and photovoltaic (PVs) from the first version of the network used in (Papathanassiou et al., 2005).

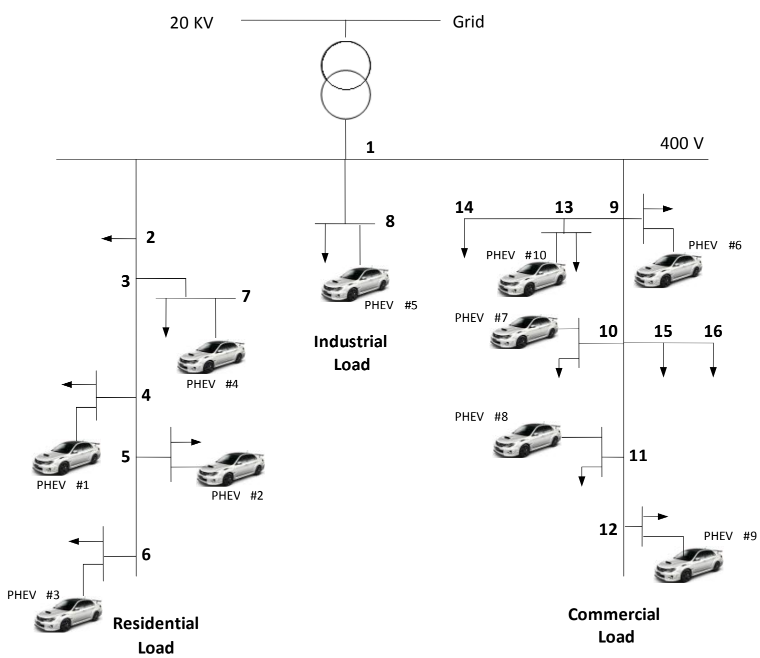

Figure 5. The modified version of 17-node LV network.

The required data of this network can be found in (Papathanassiou et al., 2005). Chargers and associated cords fall into three categories by voltage and power levels which in the level-3 charging, the maximum output power is equal up to 16.8 kW (240V, 70A) (Su et al., 2012 and Kisacikoglu et al., 2010). The maximum transferable reactive power between grid and PHEV is considered about 10 kVAr (level-3 charging). The grid is considered as a synchronous generator which submits its four-component price offers, i. e. a_0, m_1, m_2, and m_3 in order to participate in the reactive power market. The owners of PHEVs should also offer their five-component offer prices which are a_0, m_1, m_2, m_3, and m_4. In this study a coupled energy and reactive power market is considered by the ISO.

Therefore the output of synchronous generator and PHEVs in the energy market is the boundary of participant wherein they entered to LOC region and should be paid for the LOC payment by the ISO if they are accepted in the reactive power market and operated in the LOC region. In other words, the (P_A, Q_A) of synchronous generator (Zhong and Bhattacharya, 2002 and Rabiee et al., 2009) and (P_M, Q_M) of PHEVs are determined based on their output in the energy market cleared previously.

Table 1. Reactive power offer prices of participant PHEVs and Synchronous Generator (SG)

Bus No.	PHEV No.	Components of offer prices m_4	m_1	a_0	m_2	m_3
4	1	0.772	0.609	0.069	0.603	0.722
5	2	0.869	0.811	0.048	0.726	0.743
6	3	0.672	0.483	0.067	0.551	0.717
7	4	0.708	0.602	0.052	0.518	0.683
8	5	0.898	0.537	0.063	0.459	0.858
9	6	0.641	0.396	0.06	0.492	0.8
10	7	0.814	0.624	0.068	0.564	0.683
11	8	0.769	0.433	0.066	0.368	0.663
12	9	0.675	0.707	0.075	0.629	0.627
13	10	0.685	0.895	0.073	0.765	0.702
1 Syn Gen (Grid)	-	-	0.281	0.1	0.32	0.35

However, for the sake of simplicity, in our study it is assumed that $Q_A = 0.6 \times Q_B$ and $Q_M = 0.7 \times Q_N$. The price offers of reactive power market participants are taken in Table 1. The buses voltage ranges are 0.95 to 1.05 pu. It is assumed that all PHEVs are injecting 5kW to the grid and are remunerated based on the system MCP of energy market. The results of decupled energy and decupled reactive power market and coupled market are obtained. It can be observed that the result of coupled market is better than that of decoupled markets. In the coupled market the ISO will pay less money (i.e. 362.76$) to the participants of energy and reactive power markets in comparison with decoupled energy and reactive power market (i.e. 366.27$).

CONCULSION

This paper incorporates PHEVs in the coupled active and reactive power market. The presence of PHEV in the reactive power market, increase the participants market which in turn lead to increase the competition level in the active and reactive power market. Furthermore, the PHEV participation in the coupled market can help the ISO to procure active and reactive power from local resource, decreasing transmission losses. On the other hand, the owner of PHEVs participates in the coupled market with enough economic incentive because they are remunerated by the ISO for their active and reactive power compensation.

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