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Optimal Energy Trading Strategy for Proactive DISCO considering Demand Response Programs in the distribution networks

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SUMMARY

With the significant advances in renewable energy resources technology along with the considerable growing of energy markets in recent years, the distribution companies have been developed to deliver energy for the consumers in a reliable manner. Currently, the energy trading issue is considered as an effective tool in achieving the profit for all participants in the energy market environment. In this regard, various strategies are proposed and used for different goals such as maximizing the distribution company's (DISCO) profit in smart grid researches, which the maximum profit of the market participants is not simultaneously realized very well based on the strategies applied by a majority of them. Therefore, this paper proposes optimal energy trading strategy for minimizing the energy cost of proactive DISCO using demand response capabilities in the energy exchanging market. In this study, demand components including elastic and inelastic of them will be contributed in determining the demand response potential and capability. We will employ the wind turbine and PV panels as the distributed generation (DG) throughout the network for supporting the power imbalances between the DA and RT powers. Finally, standard IEEE 10 bus test system is chosen for proving the effectiveness of the proposed optimal strategy model.

KEYWORDS

Proactive distribution company (PDISCO), demand response (DR), renewable energy resources (RERs), energy trading strategies

INTRODUCTION

Until recently, conventional power plants are used as the main source of energy for meeting the consumer's energy demand in all over the worlds. Transmission lines with various foundations are structured for delivering energy to the consumers in remote areas. However, energy transmission to the small consumers is not possible due to the geographical restrictions in some cases and related plans usually have not the economic justifications in most cases. This issue has led to the introduction of new devices that are called distributed energy resources (DERs) and are used for energy generation in two categories: renewable and non-renewable energy resources. Due to the economic and environmental aspects, the DERs are considered for high level of operation in the distribution networks [1, 2]. In this regard, renewable energy resources (RERs) are adopted for clean energy production with increasing the environmental concerns about the harmful effects of gas-fired energy generation systems [3]. The volatility of RERs outputs has led to widely use of load control schemes such as demand response programs. With widespread utilization of DERs and demand response programs in the distribution networks, the opportunity of actively participation in the energy markets has been strongly realized for the distribution companies as the proactive participant [4]. Indeed, an effective contribution of proactive distribution companies (PDISCO) in the energy markets for delivering energy to the consumers has introduced new challenges, which majority of them are evaluated in recent literatures. One of the important of these challenges is that which strategy should be employed by the PDISCO in energy trading markets that led to its profit maximization. In this respect, many researches are accomplished considering the various conditions and optimization methods that concluded the best strategy for the PDISCOs in their interactions. For example, an energy exchanging based methodology is proposed in [5] for considering the trading strategies for the PDISCO in the transmission level markets. Bi-level model is applied for addressing the interactions between market and PDISCO as the mathematical formulation, which minimizing operation costs along with maximizing social welfare in the day-ahead (DA) and real time (RT) markets are considered as the objectives for the lower level (LL) problem while maximizing PDISCO’s profit is aimed to satisfy in the upper level (UL) problem. In [6], the bi-level model is used to formulate the energy trading strategy of active distribution networks with the aim of its cost minimization considering demand response programs in the UL problem. Moreover, DA market clearing as the objective function of LL problem is also presented along with the linearization techniques. Optimizing the PDISCO’s trading strategy is conducted in [7] by proposing the methodology integrated with demand response programs. In order to present the relationship between the real time market and PDISCO, the authors formulate the bi-level model, which PDISCO’s profit maximization and operation cost minimization are expressed as two objectives in the upper and lower level problems, respectively. In order to increase the trading efficiency in the distribution and transmission levels, the distribution company is considered as the proactive participation, while other important elements such as microgrids [8], distributed generation [9], and demand response programs [10] are taken to account as the flexibility providers [11]. In this regard, demand response plays a key role in balancing the supply and demand during the short term periods through providing the response capability for consumers to effectively react to the electricity price variations [12]. This capability has created the load reduction possibility and selling it to the wholesale electricity markets for consumer’s profit maximization [13]. Hence, demand response programs as the popular tools are used for balancing energy in the short term scheduling schemes, which widely addressed in recent literatures. For instance, the authors in [14] present the intra-day trading framework considering the grid operator (GO) points of view to use the demand response as a powerful tool for establishing power balance with the aim of cost minimization in providing the system requirements process. In [15], demand response has been exerted in the proposed novel strategy with the aim of ensuring the energy supply reliability along with reducing the operational cost of the multi microgrid systems. A pool based model for demand response exchange is proposed in [16] for dealing the uncertainties associated with the RERs to maximize social welfare issue. In addition, the demand response strategy is proposed in [17] for energy management within the residential households throughout the smart grid community. In this study, geometric programming technique is also used as the optimization method for balancing the power along with reducing the cost of grid energy consumption.

In mentioned references, some of them have considered the PDISCO profit maximization using different optimization techniques in the presence of various energy generation devices. On the other hands, some others have evaluated the impacts of demand response programs in controlling the energy consumption with various objectives especially PDISCO energy cost minimization. Despite the effective and valuable works are accomplished in this regard, but the role of flexibility of loads in demand response programs for minimizing the PDISCO costs is not reflected effectively in recent literatures. In addition, the behaviors of elastic and inelastic loads in the presence of numerous RERs such as wind turbines and PV panels are not well addressed, yet. Therefore, this paper presents the optimal energy trading strategy for PDISCO considering the demand response capability in the coordination of the behaviors of both elastic and inelastic loads with the aim of minimizing the PDISCO energy cost in the energy trading market. In this research, demand response not only is considered for minimizing the PDISCO costs, but also it is taken to account as the effective tool for mitigating the imbalances in power supply and demand. Moreover, the potential of wind speed and solar radiation in energy generation are used by installing the wind turbines and PV panels throughout the distribution network to meet a portion of energy demand without any fuel costs and environmental problems.

The reminder of this paper is organized as follows. Section II describes about the technical background of this paper. The problem formulation of the PDISCO energy cost minimization is presented in Section III. The numerical results of this optimization problem are represented in Section IV. Finally, Section V expresses the conclusion of this paper.

TECHNICAL BACKGROUND

A) PDISCO Energy Trading Architecture

In this paper, the PDISCO is targeted to meet the energy demand of consumers with the minimum operation costs. Due to this, PDISCO needs to make the proper decisions in its interactions with the real time and day ahead markets. Because the production of the RERs such as wind turbine is stochastic and unknown in the energy market, so applying the most effective and flexible techniques is essential for power balance in the network. In this study, optimal energy trading strategy along with the demand response program is proposed for the PDISCO to maximize its profit in the distribution networks. Indeed, optimal energy trading strategy provides suitable conditions for the PDISCO to adopt the best decision in the interactions with the main grid not only to maximize its profit, but also to dynamically meet its energy demand. In this research, it is assumed that the distribution network is operated by the PDISCO and is connected to the transmission grid through the one main substation. The real time energy trading framework for PDISCO is shown in Fig. 1. As seen in this figure, PDISCO not only can purchase a large portion of its energy demand in the DA market, but also it can provide the other portion of the energy demand from the production of stochastic DGs (wind turbine and PV panel) and demand response capability. Moreover, PDISCO can sell the surplus energy to the main grid for cost minimization or buy energy for power balancing from the real time market.

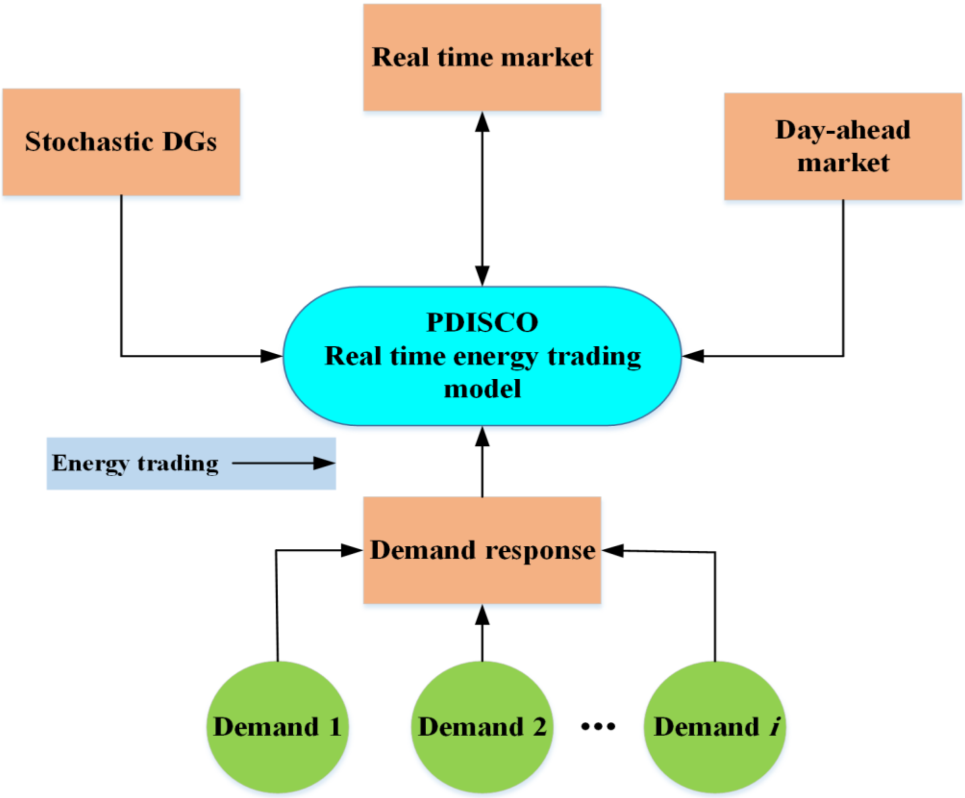

Fig. 1. Real time energy trading framework of PDISCO.

B) *Demand Response*

In this research, a demand is considered as the summation of elastic and inelastic portions. In the DA market, PDISCO purchases energy based on the amount of elastic and inelastic demands (P_{it}^{DAE} and P_{it}^{DAI}). In the RT market, the real time inelastic portion P_{it}^{RTI} has the same amount with P_{it}^{DAI} and is considered as the indispensable consumption of demand at bus i. The definition of demand response in the real time energy trading market is demonstrated in Fig. 2. As obvious from this figure, elastic portion can be divided into two parts and considered as ΛP_{it}^{DAE} $(\Lambda \geq 1)$. The first part $m_{it} P_{it}^{DAE}$ presents the shifting flexibility of demand in the real time and is named as the actual energy consumption of elastic portion (ACEP). Indeed, this part of the elastic portion states the shifting capability of demand response. The second part of elastic portion represents the shavable demand and is considered as the virtual generation of elastic portion (VGEP), which can be sold to the PDISCO. Hence, the summation of P_{it}^{RTI} and $m_{it} P_{it}^{DAE}$ makes up the total amount of active power consumption.

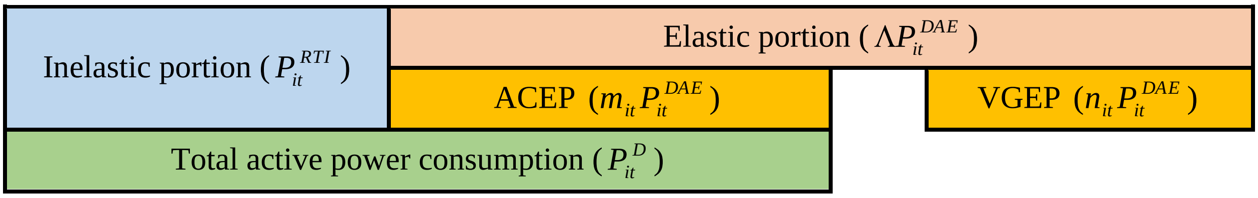

Fig. 2. Demand response definition in the real time energy trading market.

PROBLEM FORMULATION

A) *Objective function*

Based on the energy trading model of PDISCO illustrated in Fig. 1, the objective function of it can be defined as follows:

$$\text{Min} \ \sum_{t} \rho_t^{RT}.P_t^{RT} + \sum_{t} \rho_t^{DA}.P_t^{DA} + \sum_{i,t} \rho_t^{LS}.P_{it}^{LS} - \sum_{i,t} \rho^{Sell}.P_{it}^{D} \tag{1}$$

where, ρ_t^{RT} and ρ_t^{DA} are the electricity purchasing prices in RT and DA markets, respectively. P_t^{RT} and P_t^{DA} are the active power purchased from RT and DA markets, respectively. P_{it}^{LS} and ρ_t^{LS} are the amount and cost of load shedding at bus *i* at time *t*, respectively. ρ^{Sell} and P_{it}^{D} are the electricity selling price and the amount of load at bus *i* at time *t*, respectively. In (1), the first term presents the cost of energy purchasing from the DA market. Second term represents the cost (revenue) of energy purchasing (selling) from (to) the RT market. Finally, the two last terms of objective function state the cost of load shedding and revenue of selling energy to the consumers, respectively.

B) Constraints

In minimizing the energy cost of PDISCO process, the set of constraints should be satisfied during the optimization problem, which are formulated as follows.

$$0 \le m_{it} + n_{it} \le \Lambda \ , \forall i,t \tag{2}$$

$$P_{it}^{D} = P_{it}^{RTI} + m_{it} P_{it}^{DAE} \ , \forall i,t \tag{3}$$

$$P_{it}^{RTI} = P_{it}^{DAI} \ , \forall i,t \tag{4}$$

where, m_{it} and n_{it} are the consumption and virtual generation of elastic portion of demand at bus *i* at time *t*, respectively. Λ denotes the elasticity limit of demand in the real time market. P_{it}^{DAE} and P_{it}^{DAI} are the amount of active power purchased in the DA market for elastic and inelastic portions of demand at time *t* at bus *i*, respectively. P_{it}^{RTI} is the real time inelastic portion of demand at time *t* at bus *i*. For the main substation, which is known as the reference bus, we have the following constraints:

$$P_t^{RT} + P_t^{DA} + P_{1t}^{LS} + n_{1t} P_{1t}^{DAE} - P_{1t}^{D} = \sum_{1j, j \ne 1} P_{1jt}^{F} \ , \forall t \tag{5}$$

$$Q_t^{RT} + Q_t^{DA} + Q_{1t}^{LS} + Q_t^{VG} + Q_{1t}^{C} - Q_{1t}^{D} = \sum_{1j, j \ne 1} Q_{1jt}^{F} \ , \forall t \tag{6}$$

$$\text{V}_{1t} = 0, \tag{7}$$

$$\delta_{1t} = 0, \tag{8}$$

$$(P_t^{RT} + P_t^{DA})^2 + (Q_t^{RT} + Q_t^{DA})^2 \le S^2 \ , \forall t \tag{9}$$

where, Q_t^{RT} and Q_t^{DA} state the amount of reactive power purchased in RT and DA markets. Q_{it}^{LS} denotes the amount of reactive power of load shedding at bus *i* at time *t*. Q_t^{VG} and Q_{it}^{C} state the reactive power provided from virtual generation of demand and shunt compensator at bus *i* at time *t*, respectively. Q_{it}^{D} denotes the total amount of reactive demand at bus *i* at time *t*. P_{ijt}^{F} and Q_{ijt}^{F} are the active and reactive power flow between *i-j* at time *t*. δ_{it} and V_{it} present the phase angle and voltage magnitude at time *t* at bus *i*. *S* states the capacity limit for the reference bus. Equations (5) and (6) express the AC power balance for the main substation and constraints related to the amount of voltage and phase angle for this bus are also represented in (7) and (8), respectively. The constraint (9) specifies the capacity limit of reference bus. For the other buses, the set of constraints can be formulated as follows.

$$P_{it}^{LS} + n_{it} P_{it}^{DAE} - P_{it}^{D} = \sum_{ij, j \neq i} P_{ijt}^{F} \quad , \forall i, t \tag{10}$$

$$Q_{it}^{LS} + Q_{t}^{VG} + Q_{it}^{C} - Q_{it}^{D} = \sum_{ij, j \neq i} Q_{ijt}^{F} \quad , \forall i, t \tag{11}$$

$$P_{ijt}^{F} = -\upsilon_i G_{ij} V_{it}^{2} + V_{it} V_{jt} [G_{ij} \cos(\delta_{it} - \delta_{jt}) + B_{ij} \sin(\delta_{it} - \delta_{jt})] \quad , \forall i, j, t \tag{12}$$

$$Q_{ijt}^{F} = \upsilon_i B_{ij} V_{it}^{2} - 0.5\beta_{ij} + V_{it} V_{jt} [G_{ij} \sin(\delta_{it} - \delta_{jt}) - B_{ij} \cos(\delta_{it} - \delta_{jt})] \quad , \forall i, j, t \tag{13}$$

$$V_{i}^{Down} \leq V_{it} \leq V_{i}^{UP} \quad , \forall i, t \tag{14}$$

$$\delta_{i}^{Down} \leq \delta_{it} \leq \delta_{i}^{UP} \quad , \forall i, t \tag{15}$$

$$(P_{ijt}^{F})^2 + (Q_{ijt}^{F})^2 \leq (S_{ij})^2 \quad , \forall i, j, t \tag{16}$$

$$Q_{i}^{C,Down} \leq Q_{it}^{C} \leq Q_{i}^{C,UP} \quad , \forall i, t \tag{17}$$

$$0 \leq P_{it}^{LS} \leq P_{it}^{D} \quad , \forall i, t \tag{18}$$

$$0 \leq Q_{t}^{VG} \leq Q_{t}^{DAE} \quad , \forall i, t \tag{19}$$

$$P_{it}^{LS} Q_{it}^{D} = Q_{it}^{LS} P_{it}^{D} \quad , \forall i, t \tag{20}$$

$$n_{it} P_{it}^{DAE} Q_{it}^{D} = Q_{it}^{DE} P_{it}^{D} \quad , \forall i, t \tag{21}$$

$$\sum_{i,t} P_{it}^{D} - \sum_{i,t} P_{it}^{LS} \geq \tau^{\min} \sum_{i,t} P_{t}^{DA} \tag{22}$$

$$\sum_{i,t} P_{it}^{D} - \sum_{i,t} P_{it}^{LS} \leq \tau^{\max} \sum_{i,t} P_{t}^{DA} \tag{23}$$

where, B_{ij}, G_{ij}, and β_{ij} are the susceptance, conductance, and charging susceptance of feeder *i-j*, respectively. υ_i is the transformer tap ratio. V_i^{UP} and V_i^{Down} present the up and down amount of voltage at bus *i*. δ_i^{UP} and δ_i^{Down} denote the up and down limits for the phase angle at bus *i*. $Q_i^{C,UP}$ and $Q_i^{C,Down}$ state the up and down limits for the reactive power of shunt compensator. S_{ij} denotes the capacity limit of feeder *i-j*. Q_t^{DAE} is the reactive power purchased for elastic portion of demand from the DA market at time *t*. $\tau^{\min}$ and $\tau^{\max}$ present the consumption control factor limits. Equations (10) to (13) express the AC power flow formulations for feeder *i-j*. Constraints (14) and (15) identify the voltage magnitude limits and angel bounds for the other buses. Constraint (16) presents the capacity limits individually. Constraint (17) expresses the capacity limits for each compensator. The limits related to the amount of load shedding and elastic reactive power for each load are capped with the constraints (18) and (19), respectively. In order to keep the amount of power factor in constant, constraints (20) and (21) is applied to the problem formulation. Finally, constraints (22) and (23) describes the consumption control with the bounds $\tau^{\min/\max}$.

SIMULATION RESULTS

In this paper, IEEE 10 bus radial system shown in Fig. 3 [18] is selected for validating the presented energy trading model for the PDISCO. Capacity of each feeder S_{ij} and main substation *S* are imposed to 15 and 20 MVA, respectively. The voltage magnitude and its phase angle are 1 p.u. and 0 for the reference bus. For the other buses, the voltage limit is considered between 0.9 and 1.1 p.u. For each transformer, tap ratio υ_i is set to 1. The output of each compensator is limited to 0-500 kVar. Inelasticity control factor φ is applied to allocate this portion for each demand i.e., $P_{it}^{DAI}=\varphi P_t^{DA}$, $P_{it}^{DAE}=(1-\varphi)P_t^{DA}$. The DA, RT, and load shedding prices can be fully found from [19]. Demand purchase price ρ^{Sell} is fixed to 0.6 €/kW. The initial amount for elasticity limit Λ is 1.2 and control factor for daily consumption is set to 1 ($\tau^{\min}=\tau^{\max}=1$).

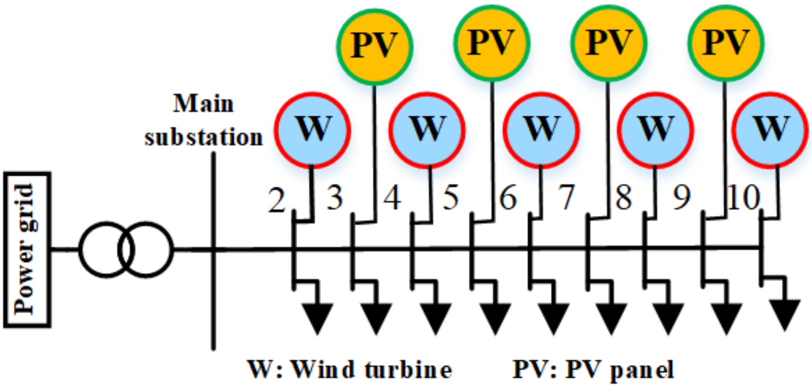

Fig. 3. The diagram of IEEE 10-bus with DGs.

The amount of demand in DA and RT markets along with energy trading for PDISCO are shown in Fig. 4. As seen in this figure, in the time intervals that the demand in RT is greater than DA one (2-4, 7-8, 16-18, and 22-24 hours), the PDISCO purchases energy from the RT market to meet the its energy demand and establish balance between the amount of demand and supply. However, during the noon hours (10-13), although energy demand is larger in RT in comparison with DA, but PDISCO uses the potential of wind turbines and PV panels not only to provide the peak times demand, but also to sell surplus energy produced by DGs to the main grid for maximizing its profit. On the other hands, PDISCO sells the surplus of energy purchased from the DA market to the power grid to minimize its energy cost when the amount of demand in RT market is less than DA one such as 18-21 hours.

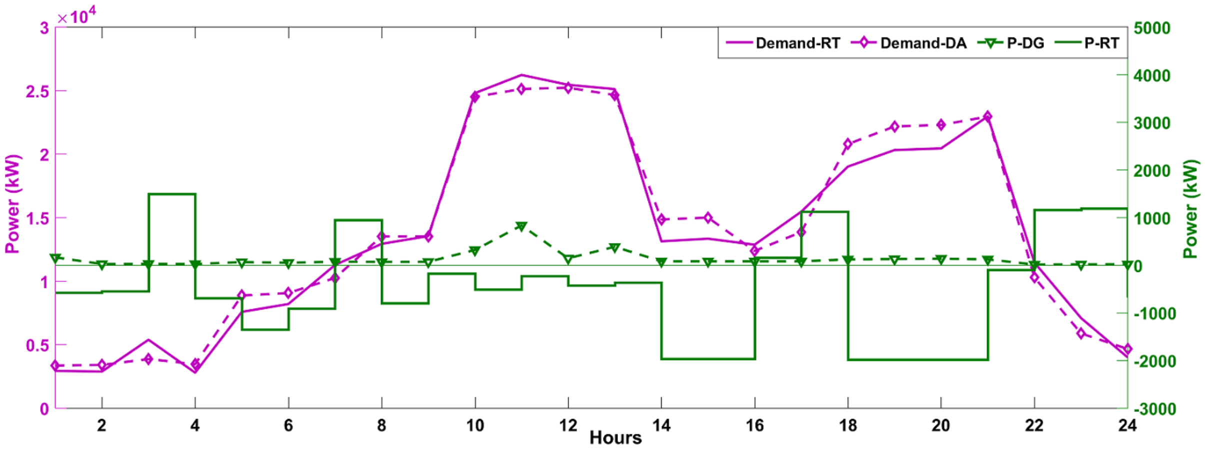

Fig. 4. The results for PDISCO in DA and RT markets.

In this research, the impacts of some key parameters variation on PDISCO cost and revenue are also analyzed carefully. All of these evaluations are performed with assuming that the other parameters are kept unchanged. In the first step, the impact of inelasticity control factor φ on the PDISCO's cost and revenue is illustrated in Fig. 5. As obvious from this figure, with increasing the magnitude of φ, the possibility of energy trading between the participants is limited due to the elasticity reduction. This is also led to increasing PDISCO's cost as well as reducing its revenue.

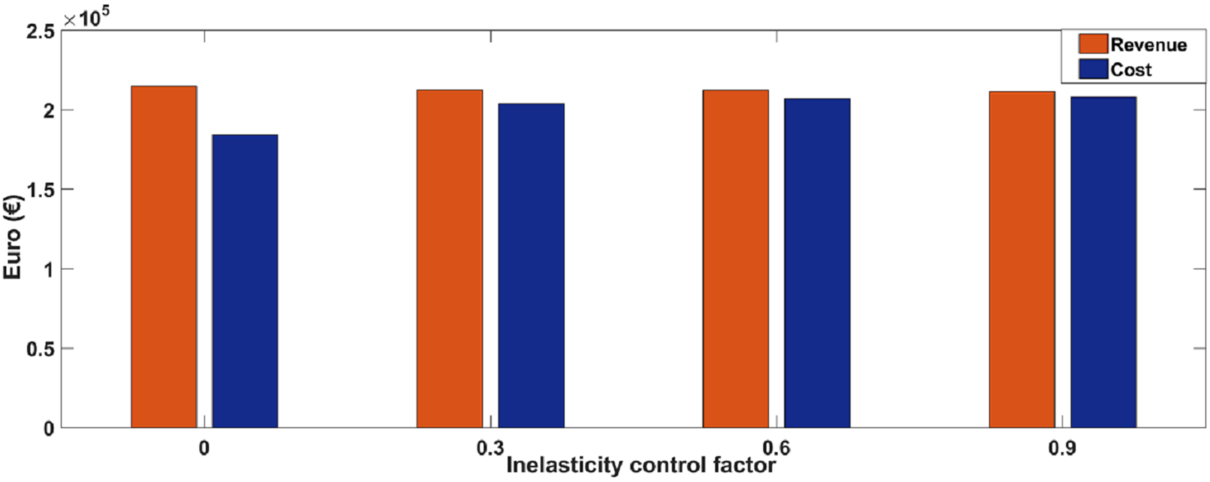

Fig. 5. Impact of inelasticity control factor on the PDISCO cost.

In the second step, the impact of the elasticity limit Λ on the PDISCO's cost and revenue is demonstrated in Fig. 6. The amount of the elasticity limit impacting the revenue of demand, PDISCO decisions, and RT energy consumption. Because of load shedding imposes the extra-large cost for PDISCO, the amount of variable n_{it} related to the shavable demands is less than m_{it} during most times that led to a more energy demand in RT market. With increasing the amount of this factor, as seen in Fig. 6, the amount of PDISCO's cost is also increased given to increasing the amount of purchased energy from RT market.

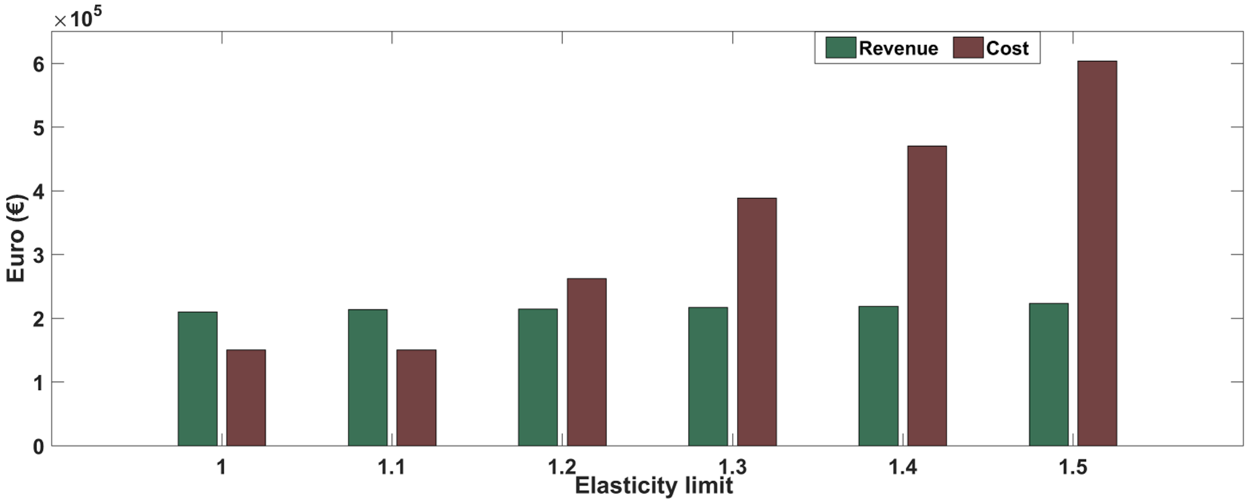

Fig. 6. Impact of elasticity limit on the PDISCO cost.

In the third step, the impact of consumption control factor is evaluated and the behaviors in PDISCO's cost and revenue are also presented in Fig. 7 with variating this factor. Equations (22) and (23) present the related constraints for the consumption control factor. Given these constraints, the amount of load shedding is approximately zero to avoid the imposing extra costs for the PDISCO. As seen in Fig. 7, with decreasing the bounds of control factor, the energy cost of PDISCO is also increased. This is because that, when the control factor is set to the smaller bounds, it enforces that the amount of energy demand should be within a limited range. This issue can lead to the smaller quantities for the variable m_{it} or a larger amount of n_{it}. The larger amount for virtual generation of elastic portion can be realized with load shedding in some cases, which led to an increase of energy costs for PDISCO in the time intervals with small amount of consumption control factor.

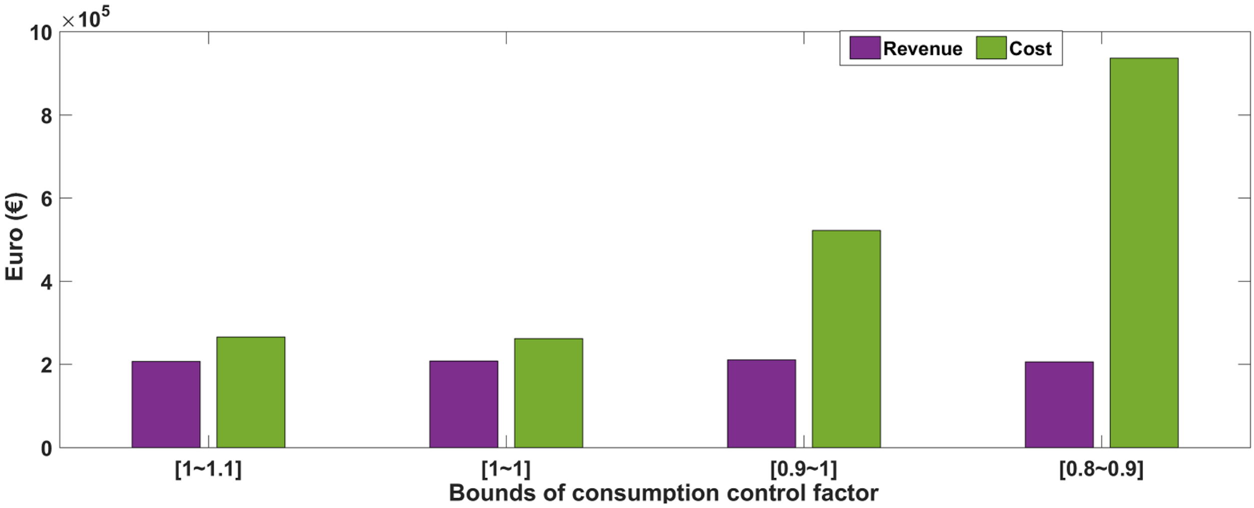

Fig. 7. Impact of consumption control factor on the PDISCO cost.

In sum up, the maximum profit of the market participants is not simultaneously realized very well based on the current solutions and strategies and the system reliability is also not considered effectively. Therefore, this paper not only proposes the optimal energy trading strategy for maximizing the profit of the PDISCO, but also it employs demand response program to maximize the reliability of meeting the electricity demand in the presence of high penetration of RERs. Because the proposed method has satisfied all the constraints of the problem specially networked constrains and due to the existence of enough potential in distribution networks for installing clean energy resources similar with a state that is done in the considered test system of this study, so the proposed method can well be implemented on the practical distribution networks.

CONCLUSION

This paper proposes the optimal energy trading strategy with the aim of minimizing the energy cost of PDISCO. In addition to the energy exchanging in DA and RT markets, it is provided that PDISCO can meet a portion of its demand through stochastic DGs includes wind turbines and PV panels. Moreover, load shedding possibility as the last option for PDISCO is considered to establish the energy balance in the emergency conditions. For this research, IEEE 10 bus system equipped with stochastic DGs is selected for analyzing the effectiveness of the proposed strategy. The simulation results evaluation indicated that PDISCO can minimize its energy cost even can maximize its profit through working based on the proposed energy trading strategy. For careful assessment of the problem, the impacts of inelasticity control factor, elasticity limit, and consumption control factor as the sensitive parameters on the PDISCO energy cost and revenue are evaluated under the different conditions.

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