Optimal reactive power pricing with transformer variable taps using genetic algorithm

Ahmad Kor[1], Hossein Zeynal[2], Zuhaina Zakaria[3], Seyed Hamid Hosseini[4]
[1]Tehran Farayand Dena Engineering Co., Tehran, Iran
[2]Department of Electrical and Computer Engineering, Buein Zahra Technical University, Qazvin, Iran
[3]School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia
[4]Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

Ancillary services in interconnected networks are crucial to secure real power transfers, maintaining network reliability, improving power quality as well as network stability. Reactive power has always been of special importance as one of the most substantial ancillary services required to control the voltage in power grid. This paper presents a fresh reactive power pricing approach by embedding variable transformer taps into voltage ampere reactive (var) pricing method. To carry out the resultant optimization problem with a set of complicating constraints, the genetic algorithm takes part and guarantees the global optimal solution. The simulation results show that when transformer tap works as a control variable, the total cost of reactive power can be decreased. However, the incorporation of transformer taps in the pricing model can slightly complicates voltage profiles as the sensitivity of bus voltages to the reactive power variations in the system is increased. Further, the findings reiterate that by optimal position of transformer taps, technically, the security index of the system can be enhanced while the var price for end-users (lowest purchase cost for independent system operator) being more reasonable. To simulate the proposed reactive pricing method, the standard IEEE 30-bus system is employed to analyze the proposed method.

Corresponding Author:

Zuhaina Zakaria
School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA
40450 Shah Alam, Malaysia
Email: zuhainaz@uitm.edu.my

1. INTRODUCTION

In the last two decades, the electricity industry in some countries of the world has undergone various changes. Recently, it has been found that creating competition in the electricity industry is one of the most important factors to make the best use of the power system. This has turned the electricity industry into a competitive market in which different companies compete with each other in terms of generation, distribution and sales [1]–[5].

More than a century has passed since the birth of the first power system. Since the inception of these systems, the government or one or more quasi-governmental bodies have been responsible for generation, transmission, distribution and selling electricity. The term "electricity industry" is used for such systems. At present, in many countries of the world such as Iran, the operation mechanism of power system is still traditional [5], [6].

The world electricity industry, for various economic and technological reasons, has undergone changes in the way it is managed and operated. These changes are referred to as "restructuring". Restructuring in the electricity industry implies a change in the structure of regulations and economic activities that the government sets to better control and operate the electricity industry [6], [7]. Depending on the objectives, in the restructured electricity industry, the restructuring can be varied. In any case, the transmission system is unique and often remains in the hands of the government, and control and operation of the transmission system is vested in the independent system operator. The independent system operator is required to provide and price the ancillary transmission services in the performance of its power transmission functions. One of the most important of these services is the provision of reactive power in the power grid [8]–[10]. The profile and the stability of the voltage and the reliable transfer of power from the point of production to the point of consumption are directly related to how the reactive power is supplied in the network [11].

Regarding electricity pricing, various researches and practical works have been done in the world, which are divided into a general category of long-term pricing and short-term pricing. This research has been done mainly in the traditional electricity industry. In long-term pricing, it is neglected due to the low cost of reactive power versus active power [1], [2]. On the other hand, in [12] it is shown that the real-time price of active and reactive power, depending on the operating conditions of the system, can be compared with each other. With the expansion of interconnected transmission networks and the possibility of connecting adjacent networks with each other, the issue of electricity pricing has become more important. In different countries, depending on the structure of the electricity industry, different methods have been used in the pricing of reactive power [13].

Electricity supply is competitively generated by electricity markets. The need for such markets is the existence of services called ancillary services with the help of which the network operator can meet the problems and technical needs of the system. Reactive power as one of the most important of these services plays an important role in controlling network voltage and reducing transmission system losses [14], [15].

In a general classification, energy pricing methods are divided into "short-term" methods and "long-term" methods. Economic calculations conducted in these methods are performed using "marginal costs", "comprehensive costs" or "incremental costs" [1]. In short-term methods, point pricing theory is used [2]. In this type of pricing methods, there is a close relationship with the type and location of customers and their consumption, so that in this type of price, the price determined in certain time periods, is regularly informed to the customer and the customer may, depending on the price, change its consumption. Based on time periods, in practice, short-term methods are divided into two categories:

- 5-minute point pricing: This pricing is done every five minutes and new quantities are notified to the customer.
- 24-hour point pricing: This price changes every hour, so that based on a specific daily pattern, these changes are obtained and the customer is informed at specific times of each day.

In long-term methods, costs are calculated based on inclusive costs or incremental costs. Inclusive costs are the revenue required to pay for all existing equipment in the system plus the cost of all new equipment that is added to the system during the contract period. The incremental cost indicates the revenue required to pay for all new equipment added to the transmission network. In long-term methods, the price of reactive power is omitted due to the low cost of reactive power utilization compared to the cost of electrical power utilization.

In the field of reactive power pricing, studies have been done by some researchers, each of which has advantages and disadvantages. Based on the final cost theory introduced in [16], Jiang *et al.* [12] formulated equations for an optimal power flow (OPF) problem that calculates reactive power pricing simultaneously using active power balance equations. In this sense, two optimization sub-problems were built [12] so as to price active and reactive power, where the objective function is to price reactive power in premise of minimizing active power generation [16]. In the above cases, the objective function is formed solely on the basis of active power cost and reactive power costs are encompassed within it.

As an alternative, Chattopadhyay *et al.* [17] proposed an objective function for reactive power pricing, which calculates the investment costs of new equipment to compensate for reactive power. To calculate reactive power, further, a quadratic and linear function is reported [18] to model the reactive power cost of each generator within the problem of minimizing reactive power generation, without clearly defining reactive power cost curves [18]. In any case, the fundamentals of the theory and analysis of real-time pricing of active and reactive power is based on the studies presented in [2], [16]. Further, Caramanis *et al.* [16] extended the idea by supplementing parlances about real-time pricing of real power in the traditional electricity industry.

According to the definition of incremental cost which is represented as the rate of change in the optimization objective function due to the change of specific optimization variable [16], [19], [20]. Based on the explanations given for real-time pricing, the Lagrange function represents the total cost of production in fulfilling International Organization for Standardization (ISO) obligations and power transactions according to contracts at a desirable level of profile and voltage stability. Following the definition of incremental costs, the Lagrangian function calculates the incremental cost of reactive power supply in particular bus of the system based on the calculation of the generation cost variation in exchange for a small change in the reactive power of the aforementioned bus. In this paper, the concept of incremental costs is used to price real-time reactive power service.

2. METHOD

In this section, the costs of active and reactive power generation in the objective function are considered for optimization. OPF is used to dispatch active and reactive power at the same time. Genetic algorithm is employed to solve the OPF problem [21]. The results of the active and reactive power pricing problem for the standard 30-bus IEEE system are discussed below.

In this method, it is assumed that reactive and active power demand are obtained from load forecasting, and are considered constant during the OPF steps. The purpose of this method is to minimize the generation costs of reactive power for generator. Network management and system maintenance costs are assumed to be fixed and given in the objective function. Therefore, the objective function is considered as relation (1).

$$C = \sum_{i \in G} \left[C_{gP_i}(P_{Gi}) + C_{gqi}(Q_{Gi}) \right] \tag{1}$$

where *G* is the number of generators and the active power cost function for the generator at bus *i* is the function of reactive power cost at bus *i*.

The cost of generating active power used in (1) is approximated by (2).

$$C_{gpi}(P_{Gi}) = a + bP_{Gi} + cP_{Gi}^2 \tag{2}$$

Reactive power generation reduces the ability to generate more active power with respect to the power (capability) curve of the generator Figure 1.

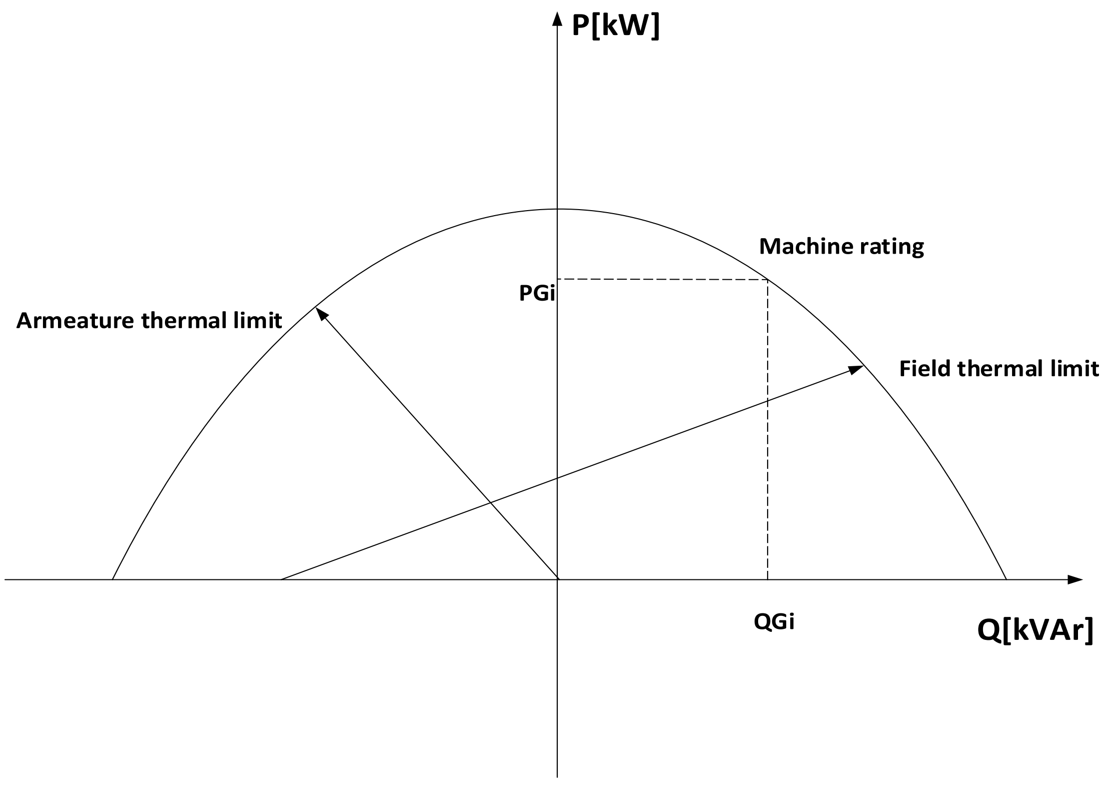

Figure 1. Generator capability curve

The cost of modeled reactive power generation takes into account the financial loss when reactive power generation is generated (opportunity cost) [22]. An approximation for the cost of reactive power generation can be expressed as in (3).

$$C_i(Q_{gi}) = \left[C_i(\sqrt{P_{gi}^2 + Q_{gi}^2}) - C_i(P_{gi})\right] \quad (3)$$

According to the generator load diagram, the reactive output power may reduce the active output power capacity of the generator [23]. In practice, opportunity cost depends on the simultaneous balance between production and market demand; Therefore, it is difficult to determine its true value. In the simplest case, the opportunity cost of the generator is considered as in (4).

$$C_{gqi}(Q_{Gi}) \left[C_{gpi}\left(S_{Gi,max}\right) - C_{gpi}(\sqrt{S_{Gi,max}^2 - Q_{Gi}^2})\right] K \quad (4)$$

where,
$S_{Gi, max}$: Maximum apparent rated power of the generator at bus *i*
Q_{Gi} : Reactive power of generator output in bus *i*
K : Reactive power rate (usually between 5 and 10%).

2.1. Problem formulation

The load flow equations are expressed as in (5) and (6):

$$P_{gi} - P_{di} - \sum_{j=1}^{nb} |V_i||V_j|\,|Y_{ij}| Cos(\theta_{ij} + \delta_j - \delta_i) = 0 \quad (5)$$

$$Q_{gi} - Q_{di} - \sum_{j=1}^{nb} |V_i||V_j|\,|Y_{ij}| Sin(\theta_{ij} + \delta_j - \delta_i) = 0 \quad (6)$$

The mathematical expressions expressed in (5) and (6) represent the active and reactive balance power dispatch. The *nb* is the number of buses. The active power generation capacity for each generator is limited by its maximum and minimum limits in (7).

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad (7)$$

The flow capacity of the active power, which is limited by the thermal constraints of the transmission lines is given in (8).

$$P_{ij} \le P_{ij}^{max} \quad (8)$$

The reactive power generated at bus i must be in the range of maximum and minimum reactive power generated by the generator stated in (9).

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \quad (9)$$

Technical and operating conditions limit the voltage range of all buses to the acceptable range defined for each bus, as described in (10).

$$V_i^{min} \le V_i \le V_i^{max} \quad (10)$$

Definition of active and reactive power pricing. According to the definition of marginal costs, the limit cost of active and reactive power in bus *i* is as relation (11) and (12).

$$CM_{pgi} = \frac{\partial L}{\partial P_{di}} \quad (11)$$

$$CM_{Qgi} = \frac{\partial L}{\partial Q_{di}} \quad (12)$$

The Lagrangian function corresponding to (11) and (12) for this optimization problem will then be as in (13):

$$L = \sum_{i \in G} \left[C_{Pgi}(P_{Gi}) + C_{Qgi}(Q_{Gi}) \ \right] -$$
$$\sum_{i \in N} \lambda_{pi} \left[P_{Gi} - P_{Di} - \sum_{i \in N} |V_i||V_j||Y_{ij}| Cos(\theta_{ij} + \delta_j - \delta_i) \right]$$
$$- \sum_{i \in N} \lambda_{qi} \left[Q_{Gi} - Q_{Di} - \sum_{i \in N} |V_i||V_j||Y_{ij}| Sin(\theta_{ij} + \delta_j - \delta_i) \right]$$
$$+ \sum_{i \in G} \mu_{Pi,\min} (P_{Gi,\min} - P_{Gi}) + \sum_{i \in G} \mu_{Pi,\max} (P_{Gi,\max} - P_{Gi,\max})$$
$$- \sum_{i \in S} \mu_{Si} (P_{Gi}^2 + Q_{Gi}^2 - S_{Gi,\max}^2)$$
$$+ \sum_{i \in N} \sum_{j \in N} \eta_{ij} (|P_{ij}| - P_{ij,\max}) + \sum_{i \in N} \gamma_{i,\min} (V_{i,\min} - |V_i|)$$
$$+ \sum_{\mathrm{i} \in \mathrm{N}} \gamma_{\mathrm{i,max}} (|\mathrm{V_i}| - \mathrm{V_{i,miax}}) \quad (13)$$

Qgi, Pgi	: Generation of active and reactive power at i^{th} bus
Qdi, Pdi	: Active and reactive power demand at i^{th} bus
δ_i, v_i	: Magnitude and angle of voltage at i^{th} bus
θ_{ij}, Y_{ij}	: Amplitude and phase of ij^{th} bus and admittance matrix
N, G, S	: Set of bus, generator and lines respectively
$P_{gi}^{min}, P_{gi}^{max}$	: Maximum and minimum active output power produced in the bus
$Q_{gi}^{min}, Q_{gi}^{max}$	: Maximum and minimum reactive output power produced in the bus
P_{ij}^{max}, P_{ij}	: Active power flow of the transmission line and its maximum
V_i^{min}, V_i^{max}	: Maximum and minimum voltage at bus *i*
CM_{Qgi}, CM_{pgi}	: Lagrange coefficients for active and reactive bus power which are equal to the $\lambda_{qi}, \lambda_{pi}$
C_i	: The cost function of the generation unit in the bus
$\eta, \gamma, \mu, \lambda$	: Lagrange coefficients for active and reactive power limits, bus voltages and active power flow

According to the definition of marginal costs, the final price for active and reactive power at bus *i*, $\lambda_{qi}, \lambda_{pi}$ will be in Lagrangian function, respectively.

2.2. Genetic algorithm

Genetic algorithm is that of search methods employed in this work to handle all the nonlinearity and optimization process which works based on natural genetics that developed using the imitation of processes observed in natural evolution. Genetic algorithm only needs information about the quality of the responses generated by each set of parameters [24], [25].

The algorithm begins by defining a chromosome or a set of optimization parameters. For example, if the chromosome contains a parameter with N_{Par} number (an optimization problem with N_{Par} dimension), then the chromosome can be shown as [26].

$$Chromosome = [P1\ P2 \ldots PN_{Par}\ ]$$

P_{Npar}.... *P2, P1* are optimization parameters that have real numerical values in the genetic algorithm. Therefore, in order to optimize, each of the optimization parameters carries a cost in the objective function and we obtain a cost for each of the parameters, which will be a benchmark for the convergence of the algorithm.

$$Cost = f\ (chromosome) = F\ (P1, P2 \ldots\ PNpar)$$

Thus, there will be a cost for each chromosome. And this is the measurement cost for the survival or non-survival of a chromosome to generate and extend the characteristics of that chromosome. In optimization problems, the goal is usually to minimize the cost function. The forms of (14) and (15) are expressed

$$SSE = \sum_{i=1}^{n} (F_{actuali} - F_{estimatedi}) \quad (14)$$

$$\%RSSE = \frac{SSE}{\sum_{i=1}^{n} F_{actuali}^2} \times 100 \quad (15)$$

F_{actual} is the actual value of the signal and $F_{estimated}$ is the estimated value of the signal based on the optimization parameters specified by the genetic algorithm. Usually, the sum of squares errors less than 0.0001 or the sum of squares of relative error 0.01 is promoted as the convergence criterion.

3. SIMULATION RESULTS

To demonstrate the benefits of the proposed reactive pricing in presence of transformer variable taps, the standard IEEE 30-bus power system is studied. To end this, we first price the active and reactive power by assuming all the transformer taps in the network are fixed, and then the transformer taps between the 6 and 10 buses are considered as a control variable and its effect on the objective function is evaluated. In this system, 6 generators are connected to buses 1, 2, 13, 22, 23 and 27. Bus 1 is considered as the Slack bus. The base power will be 100 MVA throughout the system and voltage range for each bus is 0.95<Vi<1.05.

First case: by assuming the fixed tap for all transformers in the pricing study for active and reactive power, the cost function of the active power of the generators along with the opportunity cost function are considered as the objective function. Considering Table 1 and Figure 2, the amount of cost obtained for the case where the transformer tap is assumed to be unchanged led to 595.3041$/hr. If the tap of the transformers is accounted as a control variable, therefore the final cost ought to be less than the amount obtained earlier, which will be studied below. Optimal values obtained by control variables that include power and voltage of photovoltaics (PV) buses and Slack bus voltage are presented in Table 2. Table 1 shows the optimal values of the control variables obtained from the OPF solution taking into account fixed transformer tap changers.

Table 1. Optimal values of control variables

	Active Power					Voltage Magnitude					Reactive Power	
Control variable	P2	P22	P27	P23	P13	V1	V2	V22	V27	V23	V13	Q4	Q24
Optimal value	56	36.8	17	17.2	23	1.03	1	0.98	0.998	0.998	1.01	12	2.6

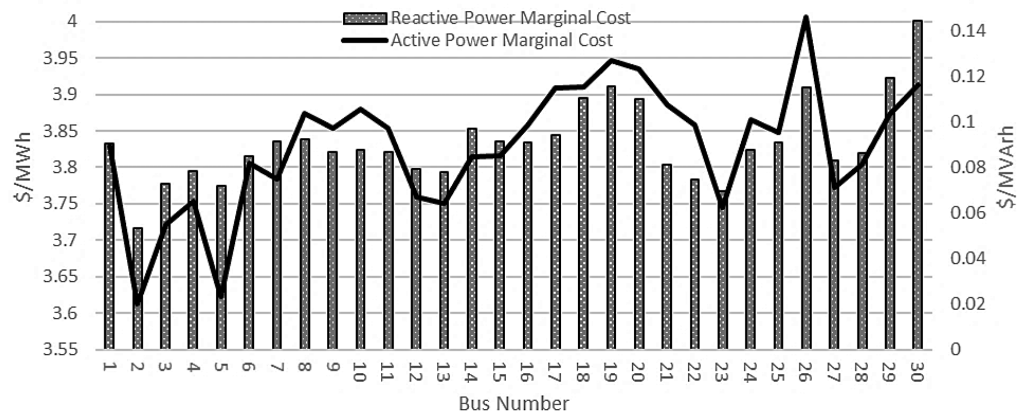

Figure 2. Active and reactive price for 30-bus system with fixed transformer taps

As a result, the amount of marginal cost at each bus is calculated according to values given in Table 1. As can be seen in Table 1, all the control variables in terms of active/reactive generation and voltage magnitudes are in a pre-specified acceptable range of operation, which, on the other hand, states that all the unequal constraints in the Lagrange function are satisfied. To obtain the Lagrangian coefficients, which according to the definition are the marginal cost of active and reactive power in the buses, the calculated control values will be plugged into the Lagrangian function. As a result, the value of λ_P and λ_Q can be obtained for all buses which are shown in Figures 2 and 3.

Second case: In this case, the transformer taps between bus number 6 and 10 will be treated as a decision variable in the optimization problem. That is, transformer taps are considered as chromosomes in the genetic algorithm solution mechanism. In this regard, the transformer tap is set between 0.98 and 1.02 in a discrete manner with 0.01 steps so as to find the optimal tap (the amount in which the cost function meets its lowest value). As a part of genetic algorithm, the initial population of 3000 is taken to end computations. Further, to price active and reactive power, the cost function of generator's active power along with the opportunity cost function is considered as the objective function.

The amount of cost obtained in the second case where the transformer taps are treated as a variable found to be 594.8272$/hr, which is less than the amount obtained in the previous case. In this sense, the optimal values for control variables including power and voltage of PV buses and Slack bus voltage and values of reactive generation by capacitors are stated in Table 2.

Table 2. Optimal values of control variables with variable transformer taps

	Active Power					Voltage Magnitude						Reactive Power		Tap
Control variable	P2	P22	P27	P23	P13	V1	V2	V22	V27	V23	V13	Q4	Q24	TP6-10
Optimal value	57.4	34.6	18.5	17	22.4	1.03	1.019	0.978	0.994	0.989	1.012	12.8	2	0.99

However, much optimal operating points for control variables can tend to the total cost reduction that is a priority for many utilities around the globe. In this approach of reactive pricing, the cost of purchasing active and reactive power for ISO is minimized. To prevent customer's financial loss who buy power from ISO, the selling price is multiplied by a coefficient called the penalty coefficient, which is the ratio of the total purchase price to the total selling price. Figure 3 shows the simulation results in the case where the transformer taps between 6 and 10 is variable.

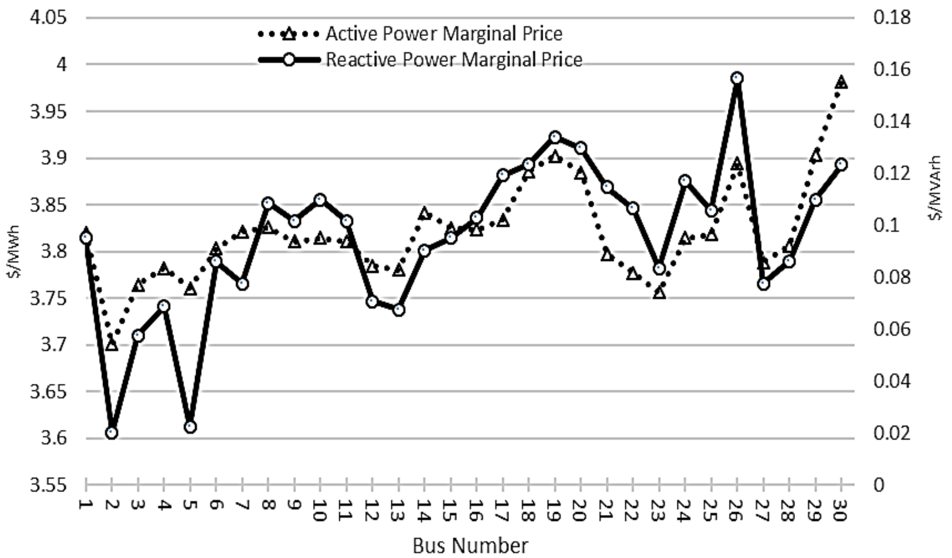

Figure 3. Active and reactive price for 30-bus system with variable transformer taps

4. CONCLUSION

Since the power pricing aims at, as described in this work, considering all the different possibilities for power variations, however, it should be noted that if the above constraints are satisfied, the real-time marginal cost of active and reactive power will be the same as their balance coefficients. That is, if an active power unit is increased by one unit, there is no possibility of power plant being shut down and the lines are within the allowable power transfer range and also the maximum and minimum power production by generators is met within this range due to the active power balance coefficient. The same can be said for reactive power. If the transformer taps are considered as a control variable, during optimization process, the total cost is reduced by obtaining more suitable optimal points. However, due to the fact that the transformer taps are involved in voltage control, the voltage buses become more sensitive to reactive power changes.

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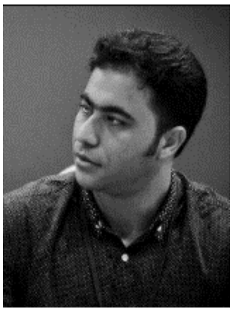
BIOGRAPHIES OF AUTHORS

Ahmad Kor received M.Eng (2004) from Sharif University of Technology, Tehran, Iran in electrical power engineering. He currently holds the head discipline in Tehran Farayand Dena Engineering Co., Tehran, Iran. He is also a Managing Director at Ravaj Niroo Golestan company, Gorgan, Golestan, Iran. He can be contacted at email: ahmad_ko@yahoo.com.



Hossein Zeynal received his Ph.D. degree from University Technology of Malaysia (UTM), Skudai, Malaysia in 2013 in electrical power engineering. Presently He is an Assistant Professor in Department of Electrical and Computer Engineering, Buein Zahra Technical University, Qazvin, Iran. He can be contacted at email: hzeynal@gmail.com.

Zuhaina Zakaria received her Ph.D. degree in Power System from University of Strathclyde in Glasgow, UK in 2005. She is currently a Full Professor in the Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia. She can be contacted at email: zuhainaz@uitm.edu.my.

Seyed Hamid Hosseini received his Ph.D. degree in electrical engineering from the Iowa State University, Ames, IA, USA, in 1988. He is currently a Full Professor at the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. He can be contacted at email: hosseini@sharif.edu.