

NEW METHOD FOR REACTIVE POWER PRICING IN IRAN'S NETWORK

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Abstract- Today, in view of the fact, that power industry is progressing towards competitiveness and restructuring or deregulation, the presence of algorithms to calculate price of energy and ancillary services in a network, is appreciated more necessary than before. The most important of these services, is reactive power supply in the power network because voltage profile and stability, system losses and secure transmission of power from production to consumption site, have direct relation to how reactive power is supplied in the network. Hence, using the appropriate pricing ways and algorithms for reactive power is of great importance. The main goal of this paper is showing a way on the basis of optimizing different functions used in optimal planning of reactive power to help calculate the cost of reactive power consumed in the network. The results of the proposed method have been given for a five bus sample network in different cases of the objective function.

Keywords- Independent System Operator, Reactive Power Pricing, power factor, Optimal Power Flow

1 Introduction

An efficient transmission network plays a crucial role in growing power markets around the world. In the last five years generating capacity grew enormously; however, transmission investment has been declining for many years. Many countries have already adopted competitive market programs where an Independent System Operator (ISO) or Regional Transmission Organization (RTO) is responsible for scheduling and dispatching generators on regional networks, implementing a market-based mechanism for allocating scarce transmission capacity [1].

The direct current (DC) system model is a common approximation for estimating spot market prices under a constrained network. The DC load model is insufficient since it ignores reactive power effects on the production of real power, line congestion and voltage constraints.

Hogan in Reference [2] created a separate price mechanism for reactive power in order to stimulate its production with a purpose of satisfying voltage constraints. Later, Kahn and Baldick in [3] demonstrated that although Hogan's pricing example for reactive power yielded a Pareto improving (more efficient) dispatch, it was not a solution of the formal optimal power flow problem. After 1994, the theoretical discussion of reactive power pricing shifted into the engineering literature, where it focused on how marginal reactive power should be determined and priced. Hao [4], [5] explored the technical and economic issues of determining reactive power structures, and

designed a practical solution for managing reactive power services. Reference [6] discussed auction design for ancillary services.

A great deal of engineering research centered on the technical side of the solution algorithm. Weber in [7] modified standard optimal power flow (OPF) analysis to simulate real and reactive power prices. Gil [8] proposed a theoretical approach of marginal cost pricing for reactive services. Alvarado [9] suggested marginal cost pricing for dynamic reactive power. These studies emphasize the important role of reactive power in the efficient production and distribution of electricity. They conclude first, that a DC approximation is not sufficient to mimic power flows in a congested network; and second, that reactive power output itself is costly and creates network congestion.

This paper presents an alternative pricing mechanism where the prices of real and reactive power are separated. In addition, separating real and reactive power bids in Iran's network is practical. In paper, a simple five bus network OPF solution is presented as a starting point. For OPF solution, four objective functions have been considered and new method has been presented for reactive power pricing in Iran's network.

2 Definition of objective functions in optimal reactive power planning

Optimal reactive power planning by means of capacitor placement in power systems, aims at three main objectives as follows:

- Voltage profile improvement
- Power loss decrease
- Reduction of reactive power compensation and compensation cost.

Therefore to mathematically express the issue of reactive power planning, we will deal with three quantities of real power losses (P_{Loss}), total absolute value of generated reactive power or compensators consumption (Q_{inj}) and total absolute value of voltage variations of buses from ideal values ($\Delta|V_i|$). Generally objective function can depend on one, two or three of mentioned quantities and considering the fact that reduction of energy loss is a very important factor in optimal control of reactive power, we will use the quantity of (P_{Loss}) for definition of all objective functions. So objective function can be expressed in one of the four following formulas:

$$F_1 = P_{loss} \quad (1)$$

$$F_2 = (\alpha_p \cdot P_{loss})^{\beta_p} + (\alpha_v \cdot \Delta|V|)^{\beta_v} \quad (2)$$

$$F_3 = (\alpha_p \cdot P_{loss})^{\beta_p} + (\alpha_q \cdot Q_{inj})^{\beta_q} \quad (3)$$

$$F_4 = (\alpha_p \cdot P_{loss})^{\beta_p} + (\alpha_q \cdot Q_{inj})^{\beta_q} + (\alpha_v \cdot \Delta|V|)^{\beta_v} \quad (4)$$

Coefficients of $\alpha_q, \alpha_v, \alpha_p$ are positive real numbers and $\beta_q, \beta_v, \beta_p$ are positive even numbers. These six coefficients determine the weighting factor of quantities to specify the value of objective function. For example if in objective function of F_2 , the values of β_v, α_v are, more than β_p, α_p , it means that voltage profile improvement is more important than system loss reduction. Also by equating coefficients of $\beta_q, \beta_v, \beta_p$ and changing coefficients of $\alpha_q, \alpha_v, \alpha_p$; we can make a kind of balance among quantities of P_{Loss} , $\Delta|V_i|$, Q_{inj} . For instance if the cost of 10 KVAR of capacitor placements is assumed approximately equivalent to 1 KW losses in the line, the objective function of $F_3 = (10P_{Loss})^2 + Q_{inj}^2$ can be used to reduce the losses and capacitor placement related costs.

Where,

$$P_{ij} = G_{ij}(V_i - V_j)^2 = G_{ij}[v_i^2 + v_j^2 - 2v_i v_j \cos(\delta_{ij})] \quad (5)$$

$$Q_{ij} = B_{ij}(V_i - V_j)^2 = B_{ij}[V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_{ij})] \quad (6)$$

$$P_{loss} = \sum \sum P_{ij}, Q_{loss} = \sum \sum Q_{ij} + \sum Y_i (V_i)^2 \quad (7)$$

$$\Delta|V| = \sum |(1 - V_i)| \quad i = 2, \dots, n \quad (8)$$

$$Q_{inj} = \sum (Injected Q(i)) \quad i = 2, \dots, n \quad (9)$$

P_{ij}, Q_{ij} are the active and reactive power losses between two buses of i and j ; V_i is voltage of bus i , Y_{ci} is related admittance for each bus; G_{ij}, B_{ij} are the matrix members of susceptance and conductivity; and n is the number of network buses. $\Delta|V_i|$ is voltage difference, Injected $Q(i)$ is injected VAR in i^{th} bus and Q_{inj} shows the total injected VAR into network buses. Injected $Q(i)$ is a discrete alternative, i.e. the VAR injection into i^{th} bus is accomplished through choosing from available values of capacitor banks.

3-Pricing of reactive power based on consumption power factor

As you know, the rate of reactive power consumed by a consumer is conversely related to its power factor and big consumers with low power factor cause to inject reactive power (positive or negative) into their own networks. So a considerable capacity of devices, transformers, cables and overhead transmission lines, is occupied by reactive power. Each country in order to force its consumers for keeping an allowed power factor, establishes a set of regulations to penalize those consumers having low power factor.

Both allowed power factor and the ways to calculate penalty, varies in different countries of the world. This different view arises from the fact that allowed power factor in each country is determined considering the network status including its technical and economic matters. That is reason that the ways to calculate penalties varies due to different conditions of the networks in different countries. Since attitudes towards consumers having power factor lower than

permitted level vary, as a result the reactive power pricing could be different in countries.

Suppose that we intend to price reactive power on the basis of active energy consumed.

In this case, reactive power price consumed by consumers who have power factor lower than the allowed power factor is determined as follows:

First, the bill of monthly active energy consumed by consumer is calculated through the below relation:

$$BIL = D * CD + E * CE \quad (10)$$

where, D is consumer demand (KW), CD is demand cost per unit (Rils/KW), E is monthly consumed electrical energy (KWh) and CE is average cost of electrical energy per unit (Rils/KWh). In such conditions, a bad consumer has to pay the reactive power cost equal to:

$$COST = BIL * \left(\frac{\cos \phi_p}{\cos \phi_a} - 1 \right) \quad (11)$$

where, $COST$ is cost of consumed reactive power, $\cos \phi_p$ is Allowed power factor and $\cos \phi_a$ is Average monthly power factor. In fact, in this kind of pricing, in order to encourage consumers to increase their own power factor to reach allowed level, only the reactive load consumed by consumers who have lower power factor than the allowed one, is included in their bills.

4-Suggested method for reactive power pricing

Assume that, reactive power pricing in a network is performed according to method introduced in the previous section. In the described method, pricing manner forces customer to increase its power factor to reach the allowed level so that reduction of reactive current in the lines, results in decrease of conductors losses in the network of that consumer and certainly buses voltage approaches unit.

Now suppose a customer whose power factor is lower than the allowed power factor. This customer in order to pay less reactive power cost or nothing at all; causes its power factor to reach to the allowed level by means of placing a specified capacitor. But it should be seen that whether Independent System Operator (ISO) who has the choice of control and operation of the transmission network, has achieved his goal through capacitor placement; that is minimizing the network lines losses and controlling the buses voltage or not? It is possible that the capacitor placed in the common bus with lower power factor, could not optimize the objective functions or cost introduced in the section 2.

In fact in the new method of pricing reactive power, the aim of capacitor placement in a bus with having power factor lower than the allowed level is optimization of objective functions not necessarily improve the common power factor to the allowed level. The reason is that optimization of an objective function, depending on which one it is; can contribute to obtain the best results in terms of losses(objective function number 1), losses and voltage of buses(objective function number 2), losses and compensation costs(objective function number 3), losses and voltage of buses also compensation costs(objective function number 4) throughout the network; besides reduction of lines losses and control of voltage of buses is now better realized in comparison with the time when capacitor placement is merely done for increasing common power factor. Considering the points mentioned above, the cost of consumed reactive power for each bus can be calculated by the following relation:

$$Cost = BIL * \left(\frac{Q_{\min F_i(x)} - Q_{\cos \phi_p}}{Q_{\min F_i(x)}} \right) \quad i = 1, \dots, 4 \quad (12)$$

where, $Q_{\min F_i(x)}$ is the capacitor placed in the related bus in order to optimize desired objective function and $Q_{\cos \phi_p}$ is the placed capacitor in the bus which helps common power factor reach to allowed level.

In this kind of pricing, depending on the network conditions and the point that which of the three parameters of lines losses, buses voltage and compensation costs in control and operation of transmission network is more important for independent system operator; any of the four objective functions already described can be used as a basis to calculate the cost of reactive power consumed. Further, it is feasible to use different objective functions in a particular network according to its conditions in different months or seasons of the year or the hours of the day to make different pricings, e.g. in peak load hours as a critical condition in the network, objective function number 2 can be considered that optimizes lines losses and bus voltages and at base load hours in the network, objective function number 4 could be used as the best among the four objective functions which yields the best results in terms of losses, bus voltage and compensation

costs. According to available information, with using the objective function number 4, the cost of 10 KVAR capacitor placements is approximately assumed equal to 1 KW of losses in the line. So in the discussed objective function, the expression related to losses has a 10 factor as compared with expression related to injected capacitor reactive power. By changing coefficient of $\Delta|V_i|$ i.e. α_v in objective function, the factor of 100 has led to the best result.

5 Case Study

In this section, results of pricing method suggested in the paper are shown on a sample network with 5 buses (Fig. 1), Tables 1 to 4 indicates parameters of load, lines and generators for the sample system in Fig1. Capacitor is placed on the bus 4. Here the cost of reactive power paid by load joined to the bus 4 has been studied.

In order to compare pricing results based on the allowed power factor and also the new method, two equations of 10 and 12 are respectively used. In these two equations, BIL value has been equally considered on perunit. For more examination, two cases are proposed for the network loads.

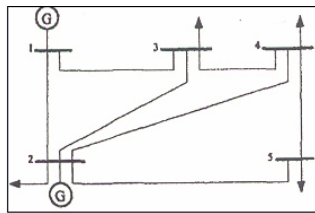


Fig 1: Five bus network

Table 1: Line parameters of 5-bus network

From	To	R	X	$Y_c / 2$
1	2	0.02	0.06	0.030
1	3	0.08	0.24	0.025
2	3	0.06	0.18	0.020
2	4	0.06	0.18	0.020
2	5	0.04	0.12	0.150
3	4	0.01	0.03	0.010
4	5	0.08	0.24	0.025

Table 2: Generators in formation

Gen.#	P_{max} (MW)	P_{min} (MW)
G_1	125	20
G_2	125	20

Table 3: Load information of each bus (Case 1)

Bus #	Active Load	Reactive Load
2	0.20	0.065
3	0.45	0.140
4	0.40	0.190
5	0.60	0.190

Table 4: Load information of each bus (Case 2)

Bus #	Active Load	Reactive Load
2	0.20	0.095
3	0.45	0.210
4	0.40	0.300
5	0.60	0.290

The first Case: The Power factor of all loads joined to buses is 0.95 but the load joined to bus 4 has a power factor of 0.9 and needs a capacitor with 5.853 MVAR capacity to improve its power factor to allowed level of 0.95.

The second case: The Power factor of all loads joined to buses is 0.9 but the load joined to bus 4 has a power factor of 0.8 and needs a capacitor with 11 MVAR capacity to improve power factor to allowed level of 0.9.

Information related to network loads in both cases has been respectively given in tables (3) and (4).

In new method pricing, any of the four objective functions referred to section 2 can be used as a base; using the software, determines the required capacitor in the bus 4 for optimizing each of the functions and accordingly the cost of reactive power consumed by the joined load to the bus 4 can be calculated through using two pricing methods. The summary of pricing results in two ways and both cases, also the needed capacitor values are included in tables (5), (6), (7), (8). Besides the percentage of losses reduction of the network in comparison with its first condition without any capacitor placed on the bus 4, has been mentioned too, in exchange for capacitor values placed on the bus 4 and as a result of optimization of each objective function. Also the load flow results for each case with different objective functions have been presented in tables (9) and (10).

6 Conclusion

In this paper a new method for reactive power pricing in Iran network, has been proposed. Also for the purpose of capacitor placement in the network, some appropriate objective functions introduced for being used in different working conditions of the system. Studies on a sample network show that reactive power pricing based on the new method provides better results in comparison with the power factor method which is currently utilized in Iran.

For the next studies, it is suggested that for reactive power pricing, first some relations found between active and reactive power and then active and reactive power pricing, done together.

7 References

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Table 5. Reactive power cost with PF method and suggested method (Case 1)

		Reactive power cost with PF method	Reactive power cost with new method				Reduction of Losses (%)
			F_1	F_2	F_3	F_4	
Amount of capacitor for optimizing objective function		5.853	36.887	49.748	6.870	49.748	-
Amount of capacitor at bus #4	0	0.0556	1	1	1	1	0
	5.853	0	0.8413	0.8823	0.1737	0.8823	1.83
	36.887	0.0407	0	0.2585	4.3693	0.2585	6.14
	49.748	0.1983	0.3486	0	6.2413	0	5.44
	6.870	0	0.8137	0.8619	0	0.8619	2.11
49.748	0.1983	0.3486	0	6.2413	0	5.44	

Table 6. Reactive power cost with PF method and suggested method (Case 2)

		Reactive power cost with PF method	Reactive power cost with new method				Reduction of Losses (%)
			F_1	F_2	F_3	F_4	
Amount of capacitor for optimizing objective function		11	56.996	69.791	11.637	69.791	-
Amount of capacitor at bus #4	0	0.125	1	1	1	1	0
	11	0	0.8070	0.8424	0.0574	0.8424	4.79
	56.996	0.0869	0	0.1833	3.8978	0.1833	13.35
	69.791	0.2695	0.2245	0	4.9973	0	12.74
	11.637	0	0.7958	0.8332	0	0.8332	5.03
69.791	0.2696	0.2245	0	4.9973	0	12.74	

Table 7. Value of objective functions with different cases of capacitors (Case1)

	Amount of capacitor	Value of objective function				P_{Loss} (KW)	Q_{Loss} (KVAR)
		F_1	F_2	F_3	F_4		
Without capacitor	0	0.2563	314.8112	0.25628	314.812	5062.45	893.41
With capacitor for PF improvement	5.853	0.2469	268.6525	0.2504	268.6559	4969.87	573.41
Amount of capacitor at bus #4	3.6887	0.2358	-	-	-	4751.63	-301.63
	49.748	-	43.7154	-	-	4787	-285.11
	6.870	-	-	0.2503	-	4955.53	-523.04
	49.748	-	-	-	268.6559	4787	-285.11
Amount of capacitor for optimizing objective function	-	3.6887	49.748	6.870	49.748	-	-

Table 8. Value of objective functions with different cases of capacitors (Case2)

	Amount of capacitor	Value of objective function				P_{Loss} (KW)	Q_{Loss} (KVAR)
		F_1	F_2	F_3	F_4		
Without capacitor	0	0.3238	592.0547	0.3238	592.0574	5690.46	2964.81
With capacitor for PF improvement	11	0.2935	471.8689	0.3056	471.8810	5417.87	2066.23
Amount of capacitor at bus #4	5.6996	0.2431	-	-	-	4930.74	276.69
	6.9791	-	71.9208	-	-	4965.61	292.62
	11.637	-	-	0.3056	-	5404.05	2020.13
	6.9791	-	-	-	72.4079	4965.61	292.62
Amount of capacitor for optimizing objective function	-	3.6887	49.748	6.870	49.748	-	-

Table 9: Load flow results for each objective function (Case 1)

Objective function	Bus No.	$ V $ (p.u.)	$\angle \theta$ (Degree)	Objective function	Bus No.	$ V $ (p.u.)	$\angle \theta$ (Degree)
F_1	1	1.05	0	F_3	1	1.05	0
	2	1	-0.42		2	1	-0.43
	3	0.9994	-3.54		3	0.9673	-3.19
	4	0.9920	-3.86		4	0.9623	-3.38
	5	0.9566	-4.01		5	0.9463	-3.89
F_2	1	1.05	0	F_4	1	1.05	0
	2	1	-0.42		2	1	-0.42
	3	0.9967	-3.64		3	0.9967	-3.64
	4	1	-3.99		4	1	-3.99
	5	0.9593	-4.04		5	0.9593	-4.04

Table 10: Load flow results for each objective function (Case 2)

Objective function	Bus No.	$ V $ (p.u.)	$\angle \theta$ (Degree)	Objective function	Bus No.	$ V $ (p.u.)	$\angle \theta$ (Degree)
F_1	1	1.05	0	F_3	1	1.05	0
	2	1	-0.41		2	1	-0.42
	3	0.9920	-3.56		3	0.9769	-3.33
	4	0.9919	-3.84		4	0.9724	-3.53
	5	0.9651	-4.14		5	0.9584	-4.06
F_2	1	1.05	0	F_4	1	1.05	0
	2	1	-0.41		2	1	-0.41
	3	0.9983	-3.66		3	0.9983	-3.66
	4	1	-3.97		4	1	-3.97
	5	0.9679	-4.17		5	0.9679	-4.17