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A New AHP-Based Reactive Power Valuation Method

S. Fattahi, S. Afsharnia, M. H. Javidi

***Abstract*--Payment for reactive power services is a part of generator revenue in most established electricity markets today. However such payments do not have a sound technical basis, the critical role that dynamic sources of reactive power play in maintaining voltage stability of the power system must be taken into account. This paper proposes a new method for valuation of Reactive power in restructured power system. This method uses four important factors to determine the importance of Reactive power compensation from one source in network and then calculates payments to the sources according to their importance in power system. These four important factors are: Voltages Sensitivities, Voltage Adequacy and Stability, Equivalent Reactive Compensation (ERC) and Back-up generation. In this paper we use AHP method to classify the Reactive power sources according to their importance in power system. The effectiveness of the proposed method is verified under IEEE 9-bus system.**

***Keywords*-- AHP , Back-up generation ,Voltages Sensitivities, Voltage Adequacy and Stability, Equivalent Reactive Compensation (ERC)**

I. [1]NOMENCLATURE

Q_G : Generator Reactive Power

S_L : System Loss

$\sum VS_{Li}$: sensitivity of each load to all generators

$\sum VS_{Gi}$: sensitivity of each generator to the marginal change of all loads

QLS_{Gi} : Q losses sensitivities of the generators

QLS_{Li} : active power loss sensitivity to Reactive power changes

Q_{ERC} : Equivalent Reactive Compensation

$Q_{S,I}$: Reactive power of synchronous condensers

$Q_{G\min,i}$: the lowest permissible reactive power output of the source

$Q_{ERC,i}$: the compensation curve for the reactive power source

CI: The consistency index of a hierarchy ranking

Lmax: the maximal eigenvalue of the judgment matrix

N: the dimension of the judgment matrix

RI: a set of given average stochastic consistency indices

CR: the stochastic consistency ratio

F: the total real power generation cost

PGi: real power of generator

VGi: the voltage magnitude at generator bus i

QGi:VAr generation of generator i

VDk: voltage magnitude at load bus k

PDk: real power load at load bus k

QDk: reactive power load at load bus k

Pij: real power flow through transmission line ij

QL: system reactive power loss

PL: system real power loss.

II. INTRODUCTION

With deregulation of electricity sector each electric power service should be economically valued and the fair rules for evaluation and compensation should be established. Reactive power service is one of the key ancillary services and its trading is becoming a reality for deregulated electricity markets [1-7]. Reactive power support plays an important role in implementation of power transactions. In electricity markets, reactive power supply is classified as a part of ancillary service of electricity. It is realized that establishing accurate prices of reactive power can not only recover the costs of reactive power production, but also provide useful information related to the urgency of reactive power supply and system voltage support [10].

Traditionally, transmission customers are charged for reactive power support service based only on the costs of transmission equipment or power factor penalties. In an open access environment, the transmission system operator will continue to be responsible for coordinating the generation and transmission systems for the reactive power service and control based on a new price mechanism which can reflect the embedded costs incurred by the utilities for wholesale transactions [8].

Therefore, real-time reactive power pricing addresses the important issue of providing information to both the utility and consumers about the true burden on the system [9]. Existing reactive power pricing policy based on power factor penalties. Baughman and Siddiqui [11] proposed a real-time reactive power pricing scheme which is similar to real power pricing scheme proposed by Scheweppe et al. [12]. Real-time reactive

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power pricing has been shown to perform better than the power factor penalty scheme in terms of providing incentives to all customers to reduce their reactive power consumption irrespective of their power factor [8–12].

In this paper we use AHP method (Multi Attribute Decision Making) to classify the Reactive power sources according to their importance in power system by using four factors mentioned earlier. AHP method is used for comparing several options that are available for a certain objective function. In fact, when we use this method for Reactive Power Valuation, we are going to classify our options for Reactive power production in our network. Finally when we finished classification of Reactive Power sources, we can calculate each source portion from total payment for reactive power services. Since in most electricity markets there is no real competitive Reactive Power market, establishing a fair Payment mechanism is very important. For this reason we must use the method to classification of Reactive sources. In our study we use four important factors to take our Reactive sources into account. These factors are Voltages Sensitivities, Voltage Adequacy and Stability, Equivalent Reactive Compensation (ERC) and Back-up generation. The first two factors present the reaction of each source to loads variations, and others show the response of system to variations of different source changes. In section III, we introduce all of these factors.Because the nature of voltage control- local control- the location of each source in power system is very important in Reactive power valuation. The four described factors help us to determine the value of each VAR source by consideration of their location in power system.

III. Reactive power valuation

Which reactive power source is the most important to the system? What is the criterionfor defining that?For evaluation of source's reactive power to system security and voltage stability many methods can be used. In our investigation we'll try the most promising candidates. Those are Voltage Sensitivity (VS), PV curves, Back-up generation and Equivalent Reactive Compensation (ERC) methods. For testing these methods we used MAT Power software and it's built in capabilities.

3.1. Voltage Sensitivity (VS) based Method

Besides of ranking the system sources according to reactive power supply capabilities, this method also answers the question: What does 1 MVar from one or other source do to system losses?

We will try to set the value for the reactive power of all test system generators in one case. Voltages Sensitivities (VS) show the effect that an additional injection of real or reactive power at a bus has on real or reactive, or complex power flow on a particular line or interface. Mathematically it is:

$$\frac{dQ_G}{dS_L} = \left(\frac{\sum dQ_{Gi}}{dV} \right) . \left(\frac{dS_L}{dV} \right)^{-1} \qquad (1)$$

The numbers could be obtained from the Jacobian matrix. An additional marginal load increase in 1 MVA at one load bus requires generators capabilities of more than 1 MVar, to keep the voltage constant. We want to find which Generator has the greatest influence in this case. We calculate the portion of each generator to supply 1 additional MVAR and repeat it for all loads. We also calculate ∑VSLi which represents the sensitivity of each load to all generators MVar output and ∑VSGi that represents the sensitivity of each generator in MVar to the marginal change of all loads. We can find out from ∑VSGi , which generator is the most valuable in regulating the voltage in the system and reacting to the load and from ∑VSLi, we find out which load requires more system reactive power resources than other loads. To determine sensitivity of loss to marginal increase in Reactive power, we use QLS as the active power loss sensitivity to Reactive power changes. It is used to calculate the sensitivity of a real power loss function, P losses, to bus reactive power injections. Stated mathematically, it calculates dPlosses/dQL, where QL are the reactive power injections at the load bus. It indicates how losses would change if one more MVar of power were injected at the load bus. Q losses sensitivities QLSGi of the generators have been calculated as follows:

$$QLS_{Gi} = \sum \frac{VS_{Gi}}{\sum S_{Li}} .QLS_{Li} \qquad (2)$$

This means that we find the each generator contribution to the losses sensitivities at load buses. It depends on the network configuration and location of the source in the system.

3.2. PV curves Method

It is performed by increasing the load at the selected buses of the system and getting the response of the sources until the system reaches the limits and crashes. So the answer to this question can be found: What does 1 MVar mean to transfer capacity? The procedure of this method is as follows:

1. Select the load or the group of loads in the area or whole system you want to vary. It is possible to increase only the active load or keep the power factor constant. In our case, power factor was kept constant.

2. Select the generator or the group of generators to meet the system demand. Only generators with AGC (generators responding to load level) could be varied, while others are used for reactive power supply.

3- Determine the step size of the transfer. In our case the initial step size is 1MW.

4. Pick up the quantities you want to monitor. Voltage, power flows of generators', loads' buses, transmission lines and other quantities can be selected.

5. Perform the simulation until system reaches its limits and collapse margin is obtained. Variation of the selected quantities can be viewed graphically.

6. Sensitivity coefficients of the curves for all generators could be established. It was made using Curve Expert software to linearize the curves and get sensitivity coefficients in the range from zero to Pmax of generators total active power output.

3.3. Equivalent Reactive Compensation (ERC) Method

According to the authors of this method (W. Xu, 2000) the basic form of the idea is as follows: if a Var source changes its output, the network voltage profile and stability levels will change. To maintain a same degree of network security, Var compensations can be added (at all load buses). The total amount of fictitious compensation added is a direct measure of the value of the missing Var output from the source. The fictitious injected reactive power is termed as Equivalent Reactive Compensation. The procedure of this method used for our system model is like this:

1. Add fictitious synchronous condensers *QS,i* (generators with zero active power output) to each load bus . There are no reactive power limits for the condensers.

In further research the fictitious condensers can be placed in a given zone or area of a system, instead of all over the system. Reactive output limits could be added to the fictitious condensers. The Var limits could be set in proportion to the size of bus MVA load.

2. The reactive power output of generators is kept at the base case level, that is almost zero, and AVR is turned off. So generators are represented as PQ buses.

3. For the dynamic reactive power source to be studied, we increase its reactive power output QG,i from the QGmin to QGmax. QERCs are calculated in the process as reactive power output of all fictitious condensers:

$$Q_{ERC} = \sum_{i=L} Q_{S,I} \qquad (3)$$

4. QERC as a function of QG,i, the output of the study source, can be plotted.

5. QERC curves for each reactive power source can be transformed into the value curves.

$$V(Q_{G,i}) = Q_{ERC,i}(Q_{G\min,i}) - Q_{ERC,i}(Q_{G,i}) \qquad (4)$$

QERC,i(.) – the compensation curve for the reactive power source;

QGmin,i – the lowest permissible reactive power output of the source or QERC at the zero reactive power output of the generator.

The value curve represents the system-wide reactive power savings that one can achieve if the output of any dynamic Var source is increased. More savings a generator can give to the system implies more efficient it is to support system security.

6. Sensitivity coefficients of the value curves for all generators could be established.

Curve Expert software was used to linearize the curves and get sensitivity coefficients in the range from zero to Qmax of generators reactive power output.

Generator with lowest sensitivity value is the most efficient to the system security and dynamic reactive power supply.

3.4. Back-up generation Method

In this case we'll try to answer this question: How much MVar from other sources would be needed to replace Q from the selected source?

To evaluate generators' reactive power support capabilities we'll decrease marginally the output of reactive power of one generator and track the response to this from the others.

Sensitivity coefficients of the value curves for all generators could be established.

These coefficients mean that the shortage of 1 MVar from one generator requires how much MVar from other reactive power sources to keep the system at the same voltage and security level.

IV. Principle of AHP [13, 14]

In the analytic hierarchical process, first a structural model of the analytic hierarchy is established through analysis of the complex system. Then the complex problem is transformed into the problem of ranking calculation within the hierarchical structure. In the ranking calculation, the ranking in each hierarchy can also be converted into the judgment and comparison of a series of pairs of factors. This implies that a judgment matrix is needed to reflect these judgments and comparisons. The judgment matrix can be formed according to the quantified judgment of pairs of factors using some ratio scale methods [13, 14]. Consequently, the value of the weighting coefficient of all factors can be obtained through calculating the maximal eigenvalue and the corresponding eigenvector of the judgment matrix. Obviously, the purpose of ranking the elements of the eigenvector corresponding to the maximal eigenvalue is simply to obtain the weighting of each factor among the different kinds of factors.

The steps of the AHP algorithm may be written as follows [14]:

Step 1: Set up a hierarchy model.

Step 2: Form a judgment matrix.

The value of elements in the judgment matrix reflects the user's knowledge about the relative importance between every pair of factors.

Step 3: Calculate the maximal eigenvalue and the corresponding eigenvector of the judgment matrix.

Step 4: Check hierarchical rank and consistency of results.

We can perform the hierarchical rank according to the value of elements in the eigenvector, which represents the relative importance of the corresponding factor.

The consistency index of a hierarchy ranking CI is defined as CI_(lmax_n):(n_1) where, lmax is the maximal eigenvalue of the judgment matrix, n is the dimension of the judgment matrix. The stochastic consistency ratio is defined as: CR_CI:RI where RI is a set of given average stochastic consistency indices and CR is the stochastic consistency ratio.

It is possible to precisely calculate the eigenvalue and the corresponding eigenvector of a matrix. However, this would be time-consuming. Moreover, it is not necessary to precisely compute the eigenvalue and the corresponding eigenvector of the judgment matrix. The reason is that the judgment matrix, which is formed by the subjective judgment of the user, itself, has some range of error. Therefore, the approximate approaches, which were presented in [14], are adopted in this paper to compute the maximal eigenvalue and the corresponding eigenvector. Figure .1 shows graphically four factors to classification of Reactive sources.

V. OPF formulation

In this paper, an OPF formulation in which the objective function is the total cost of generation operation, has been used. Considering the 'generation cost' objective function, somewhat higher losses would be incurred since cheaper

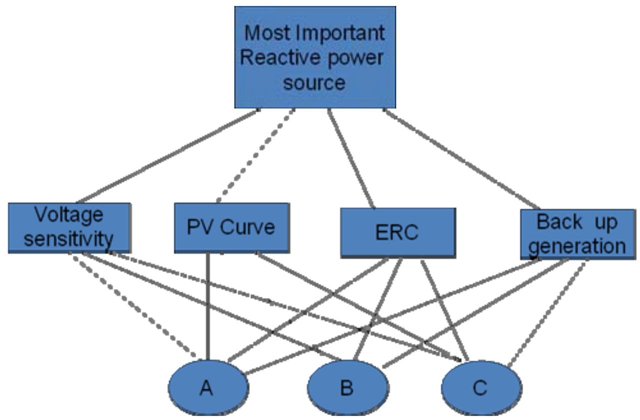

Figure . 1 . Hierarchical model of VAR source rank

generating sources, generally located away from load center, would be predominantly used to meet the demands. Since we want to evaluate Reactive power in restructured power system, we must run OPF for calculate of four described factors.

The OPF formulation can be expressed as follows:

(1) Objective function

$$MINF = \sum_{i=1}^{NG} f_i(P_{Gi}) \qquad (5)$$

Where F, the total real power generation cost;
PGi, real power of generator i; the total number of generators; According to engineering economics [15], whenever there are different investment schemes, technical and economic quantitative analysis should be performed and economic assessment should be provided in order to select the optimal scheme. The static assessment method and dynamic assessment method are two kinds of frequently used economic assessment means. The time value of the capital is not considered in Eq. (5).This assessment of the economic effects in engineering project investment is called static assessment. The static assessment method is simple and direct. However, it is difficult to consider the change in gains and cost during the service time of the engineering project and especially the time effect of capital.

(2) Constraints

$$\sum_{i=1}^{NG} P_{Gi} = \sum_{k=1}^{ND} P_{DK} + P_L$$

$$\sum_{i=1}^{NG} Q_{Gi} + \sum_{i \in NC} Q_{Ci} = \sum_{k=1}^{ND} Q_{DK} + Q_L$$

$$P_{Gi\min} \le P_{Gi} \le P_{Gi\max} \qquad i = 1,2,\dots,NG$$

$$Q_{Gi\min} \le Q_{Gi} \le Q_{Gi\max} \qquad i = 1,2,\dots,NG \qquad (6)$$

$$V_{DK\min} \le V_{DK} \le V_{DK\max} \qquad i = 1,2,\dots,NC$$

$$|V_{Gi}| = cons\tan t \qquad i = 1,2,\dots,NG$$

$$P_{ij\min} \le P_{ij} \le P_{ij\max} \qquad i = 1,2,\dots,NT$$

The subscripts 'min' and 'max' stand for the lower and upper bounds of a constraint, respectively.

VI. Test results

The proposed approach was tested on the IEEE 9 bus system. The parameters of the system are taken from [16]. Figures.2 shows this system.

Voltage Sensitivity: We run OPF in our test case like OPF formulation in previous section. Then for calculation of voltage Sensitivity coefficients, we change the loads in bus 5-9 one by one. For this investigation we'll use MAT Power software, which allows us to find different sensitivity values. Our simulation result is shown in Table1.

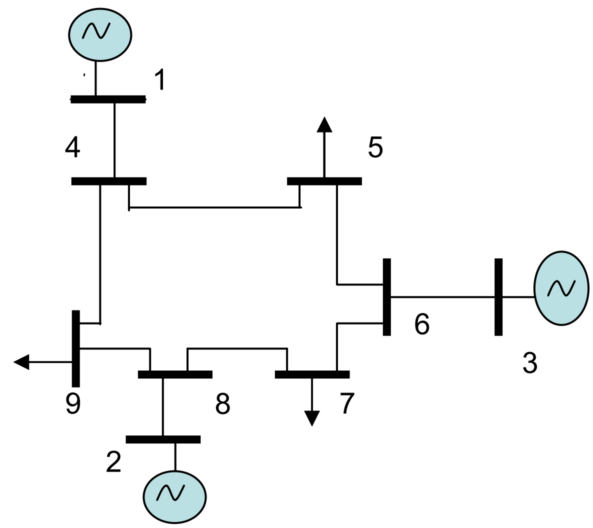

Figure . 2 . Test system model scheme

For example, an additional marginal load increase in 1 MVA at load bus L5 requires generators capabilities of 1.06 MVar, as shown on the first column, to keep the voltage constant. Generator G1 has the greatest influence in this case.

TABLE I
Sensitivity values of sources and loads

	VSL5,Gi, MVar	VSL7,Gi, MVar	L9VSL9,Gi, MVar	Sum, ∑VSGi, MVar
G1 VSG1,Li, MVar	0.48	0	0.49	0.97
G2 VSG2,Li, MVar	0.12	0.6	0.48	1.2
G3 VSGs1,Li, MVar	0.46	0.41	0.1	0.97
Sum, ∑VSLi; MVar	1.06	1.01	1.07	
QLSLi, MW	0.001	0.003	0.001	

As we see from the Sum ∑VSGi generator G2 is the most valuable in regulating the voltage in the system and reacting to the load variation. And the marginal increase of load L9, as we see from Sum ∑VSLi, requires more system reactive power resources than other loads.

In the last row, the Bus Marginal Loss Sensitivities QLS is shown. As we see in Table 1, the marginal increasing load in bus 7 has most effect on system loss than other loads. So in the table 2 we set the reactive power value of each generator according to the data obtained from the Table 1. So generator G2 produces the highest marginal losses. This depends on the network configuration and location of the source in the system.

TABLE 2
VS method voltage and losses sensitivities of the sources

	VSGi	QLSGi,MW
G1	0.97	0.000910774
G2	1.2	0.002343984
G3	0.97	0.001745242

PV curves:

By using the steps that described in section 3.2, we implied the PV curves method in our test system. Collapse margin in this case is 469 MW, because generator G1 reaches active power output limits of 250 MW and becomes unable to support the active power demand of the loads in the system. Figure 3 illustrates the result of PV curves simulation.

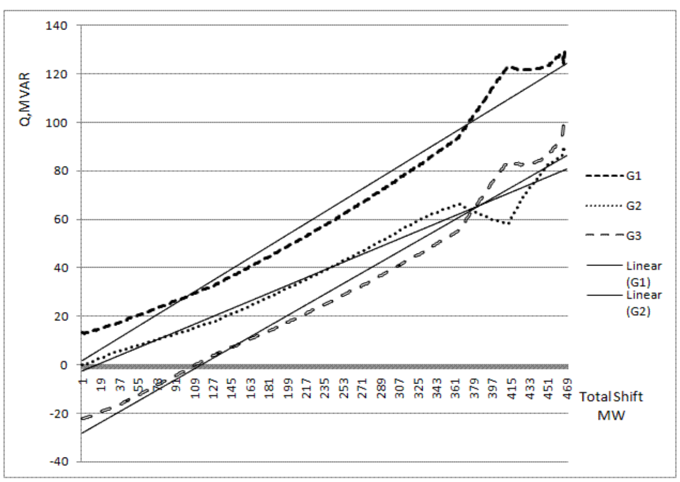

Figure. 3 . Generators' reactive power output versus total load shift

Linearization of PV curves using Curve Expert software is shown in figure 3. The line slope shows the sensitivity coefficient of each generator. Higher sensitivity coefficient means more importance in system security and voltage stability. Table 3 shows these coefficients for each generator. As we see in table 3, G1 is the most important Reactive source in system.

TABLE 3
Sensitivity Coefficient By PV Curves Method

Generator	sensitivity
G1	0.26
G2	0.176
G3	0.244

Equivalent Reactive Compensation (ERC):

Like the procedure introduced in section 2-3, we can apply this method in our test system. We install a synchronous condenser in load buses and change the generators Reactive output one by one. Figure 4, shows simulation results.

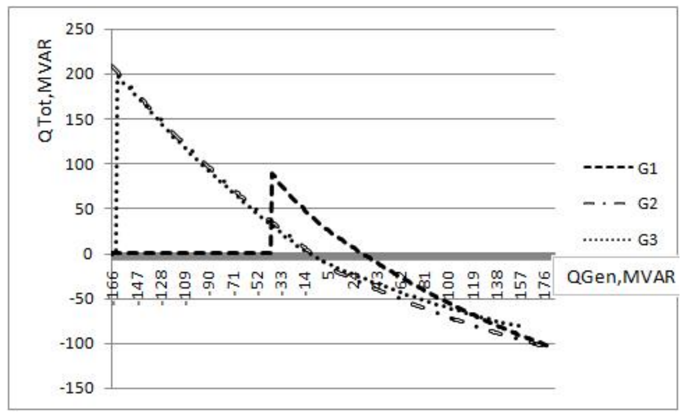

Figure. 4 . Q_{ERC} as a function of $Q_{G,i}$

By using the following equation, we can draw the value curve for sensitivity coefficients calculation:

$$V(Q_{G,i}) = Q_{ERC,i}(Q_{G\min i}) - Q_{ERC,i}(Q_{G,i}) \qquad (7)$$

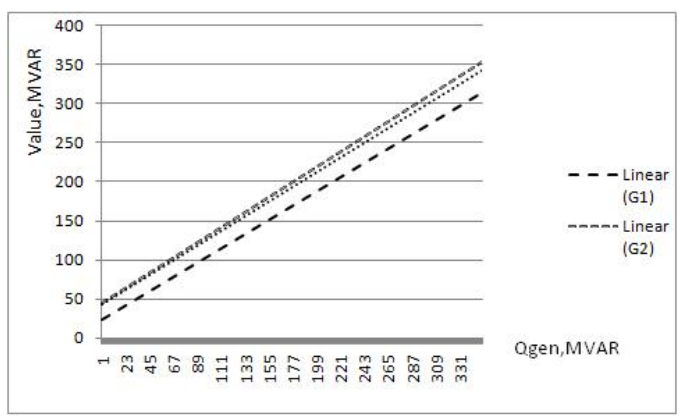

Figure. 5 . Value curves

Figure 5 presents linear Value curve. From this curve we can obtain sensitivity coefficients. Table 4 shows these coefficients. As we see in this table, reactive power output from G1 is less expensive to the system – so that generator is the most efficient to our test system in supporting system security. G1 has the lowest sensitivity value and is the most efficient to the system security.

TABLE 4
ERC method sensitivities of the generators

generator	sensitivity
G1	0.829
G2	0.883
G3	0.854

Back-up generation Method

To evaluate generators' reactive power support capabilities we'll decrease marginally the output of reactive power of one generator and track the response to this from the others.

The decrease by 1 MVar gives the following results:

TABLE 5
Back-up method sensitivities of the generators

generator	sensitivity
G1	1.14
G2	1.19
G3	1.21

This means that the shortage of 1 MVar from G1 requires 1.14 MVar from other reactive power sources to keep the system at the same voltage and security level.

Classification of generators:

For classification of generators using AHP method, we use the following judgment matrix. This matrix shows the relation between our four factors. The relation between generators for each factor is shown in it's judgment matrix. for similar analysis we normalized the results by dividing them on maximum element in each group.

TABLE 5
Judgment Matrix

	VS	PV	ERC	B U G
VS	1	1	2	2
PV	1	1	2	2
ERC	1/2	1/2	1	1
B U G	1/2	1/2	1	1

And by using AHP method, these results are obtained. As we see in table , G1 is the most important generator in our system, and then G3 and the last generator is G2.now,we know which generator in our system has most important role in our system. The fair mechanism that can cover the generators costs to produce reactive power will be reported in separate paper.

TABLE 6
Classification of generators

Generator	Total Index
G1	0.3414
G2	0.3235
G3	0.3352

VII. Conclusions

A new approach for reactive power valuation and reactive source classification was developed in the paper. The analysis was based on OPF, different methods of power system analysis and analytic hierarchical process (AHP). The value of reactive power support was determined based on the following factors: Voltages Sensitivities, Voltage Adequacy and Stability, Equivalent Reactive Compensation (ERC) and Back-up generation. Voltages Sensitivities, Voltage Adequacy and Stability present the behavior of Reactive source to load changes. Equivalent Reactive Compensation (ERC) and Back-up generation show the system response to reactive source. AHP method helped us to classify Reactive sources. We considered four factors to reactive power valuation and by using judgment matrix and their relationships. The proposed approach was tested on an IEEE 9 bus system. The results have shown the feasibility and effectiveness of our approach. Different methods have different results, but consideration of different methods together can help us to get to a better result. The additional work on comparison of different methods of Reactive Power pricing with new AHP-based method will be reported in a separate paper.

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IX. BIOGRAPHIES

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