Reactive Power Management and Economic Assessment of Power System Markets

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Abstract— Power industry is under great pressure to provide reactive power or Var support. Although it is generally known that there are technical benefits for utilities and industrial customers to provide local reactive power support, a thorough quantitative investigation of the economic benefit is greatly needed. In this paper, we have discussed about various issues associated with the management of reactive power and also about the optimal power flow in the power system markets. We have conducted various experiments and tests to justify our results. A comparison of the methods is also presented in this paper.

Key words: Reactive Power Management, Economic Dispatch, Genetic Algorithm, Particle Swarm Optimization

I. Introduction

Reactive power management is one of the most important issues in the power system. It is essential in order to maintain the power system healthy and also to supply reliable and secure power to the end users. Insufficient reactive power may lead to serious issues like complete system blackout, voltage instability or complete voltage collapse. The US-Canada power system outage was a consequence of the reactive power insufficiency [1]. With deregulation, the management of reactive power and charges for it are separately maintained. It also stated that reactive power from capacitors and FACTS controllers, installed as a part of the transmission system, is not a separate ancillary service [2]. However, there are recent recommendations for considering reactive power provision from these sources and to recognize them as ancillary services that are eligible for financial compensation [3]. FERC Order 2003 [4] further states that a reactive power provider should not be financially compensated when operating within a power factor range of 0.95 lagging and 0.95 leading, but an Independent System Operator (ISO) may change this range at its discretion.

The Economic Dispatch (ED) is an optimization problem. It is meant to allocate powers to the generating units in such a way that the all constraints of the power system are met at the minimum cost. This problem of determining the outputs of the generating units at the minimum cost is known as the Optimal Power Flow (OPF) problem. Production cost of a given generator unit can be defined by its fuel cost coefficients (a, b, and c of $a+bP+cP^2$). Economic dispatch is also defined as the coordination of the production costs of all the participating units in supplying the total load. The purpose of economic dispatch is to determine the optimal power generation of the units participating in supplying the load. The sum of the total power generation should equal the load demand at the station.

II. Reactive Power Management in Competitive Electricity Markets

There is no generalized reactive power management structure or design yet suggested due to variation of its concepts from one electricity market to another. In main countries like USA, UK, Australia, for procurement of reactive power services, the ISO enters into contracts with the reactive power providers. These contracts are usually traditional practices or bilateral agreements as per ISO experience for reactive power support. In the California, provision of reactive power services is based on long-term contracts between CaISO and reliable mustrun generators. In Canada, the Independent Electric System Operator (IESO) of Ontario requires generators to operate within a power factor range of 0.9 lag to 0.95 lead and within a +/-5% range of its rated terminal voltage. The IESO sign's contracts with generators for reactive power support and voltage control, and generators are paid for the incremental cost of energy loss in the windings due to the increased reactive power generation. The generators are also paid an opportunity cost if they are required to generate reactive power levels by reduction of their real power dispatch. The generator receives payment at the market clearing price.

A. Reactive Power Procurement and Dispatch

Reactive power provisions can also be framed as two classes of a problem in the context of deregulated electricity markets, namely,

- Reactive power procurement and
- Reactive power dispatch.

Reactive power procurement is basically a long-term issue, i.e., a seasonal problem; in this case, the ISO obtains optimal reactive power “allocations” from possible suppliers that would be best suited to its needs and constraints in a given season. This optimal set would be determined based on forecasts of the demand and system conditions expected over the planning horizon. The criterion for such procurement could be varied, but would essentially consider the cost/price offers of reactive power provision. This long term procurement can be done assuming like 60 days ahead on a season basis. The second level in the proposed approach to a reactive power provision is the short-term management function, which takes place one to half hour ahead of real-time.

Reactive power dispatch is the second level in the proposed hierarchical approach to reactive power management. It is the short-term management function, which takes place one to half hour ahead of real-time. The real-time dispatch of reactive power only takes into account the current operating conditions, with the ISO arriving at the optimal dispatch via an OPF. Based on actual usage and

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actually dispatch requested, cumulative payment to a supplier is calculated post real time operation.

B. Lost Opportunity Cost

It is well accepted that the principal function of a synchronous generator is to generate real power to meet the demand of the system. Under certain circumstances, usually arising from critical system conditions, the ISO may request or instruct a generator to increase its reactive power output, which may require a reduction in its active power output, thereby affecting market conditions. The real and reactive power output from a synchronous generator is usually limited by the capability of its prime mover. When real power and terminal voltage are fixed, the armature and field winding heating limits determine the reactive power capability of a generator.

C. Reactive Power Market Power

One of the primary barriers to the implementation of a full auction-based competitive market for reactive power is the possibility of market power arising from a limited number of providers in the system. Furthermore, reactive power is a “local” service, i.e. it must be procured and provided as close to the demand buses as possible, because of the technical issues associated with transporting reactive power over long distances. Hence, in a reactive power market, it is certainly plausible that some “well-located” suppliers may try to game the price offers by submitting excessively high price offers, or withholding reactive power supply in an attempt to increase the reactive power market price to their advantage.

III. ECONOMIC LOAD DISPATCH

The ED problem is to define the production level of each plant so that the total cost of generation and transmission is minimum for a prescribed schedule of load. It may also be defined as the process of allocating generation levels to the generating units in the mix, so that the system load may be supplied entirely and most economically.

B. H. Chaudhary and Saifur Rahman has done a review of advances in economic dispatch in 1990 in which four very important and related areas of economic dispatch are identified and papers published in the general area of economic dispatch are classified into these [5]. These areas are:

- Optimal power flow,
- Economic dispatch in relation to AGC,
- Dynamic dispatch and
- Economic dispatch with non-conventional generation sources.

Various analytical techniques have been developed for the economic dispatch of the generation to meet system load. J. S. Luo has proposed an approach to economic dispatch with the bus incremental cost as the key variable which offers a possibility to get an insight into the ED mechanism. This approach to derive and promote some novel concepts showing how incremental costs can be viewed as a “potential” in the dispatch analog of the power systems, such that basic electrical network solution techniques can be readily applied to solve the ED problem [6]. Some of the Artificial Intelligence techniques like Hopfield Neural Networks are used to solve economic dispatch problem with transmission capacity constraints [7], [8].

Genetic Algorithms are adaptive metaheuristic search algorithm. Its source of inspiration is the process of natural selection, according to which, the competition among the individuals over limited resources results in fitter ones dominating over the weaker ones. It is based on bio-inspired operators like mutation, crossover, and selection. As compared to another popular method, called Simulated Annealing (SA), GA gives faster results due to its parallel search techniques. In GAs, a population of points at each iteration is generated. Among all these points, the best point converges towards the optimal solution. GA has been used for various types of optimization problems of power systems like feeder reconfiguration and placement of capacitors in the distribution system [5], [9]-[11]. In [9], Walters and Sheble make use of a GA-based algorithm to solve an ED problem for valve point discontinuities. Yalcinoz et al. use a neural network based approach for solving the ED problem under constrained transmission conditions [8]. Chen and Chang present a GA based approach for solving the ED problem in a large-scale system [12]. Through numerical results, they show that their proposed method is faster than the lambda-iteration method in a large-scale system. Fung et al. make use of Simulated Annealing (SA) and Tabu Search (TS) techniques in an integrated parallel Genetic Algorithm to solve the ED problem [13].

IV. NUMERICAL EXAMPLES AND RESULTS

The PSO and the GA method are used to solve an Economic Dispatch (ED) problem and the results obtained are discussed and compared. Three different systems, having six, fifteen and forty generators, are taken as the test system. For simplicity, the losses, ramp rate limits and the prohibited zones are not considered. Under the same evaluation function and individual definition, we perform 50 trials using the two methods and the quality of the solution is observed.

A. PSO Method

- Population size = 100
- Generations = 200
- Inertia weight factor: w_{max} = 0.9 and w_{min} = 0.4
- Acceleration constants: C_1 =2 and C_2 =2.

B. GA Method

- Population size = 100
- Generations = 200
- Crossover rate, P_c =0.8
- Mute rate, P_m = 0.01

V. CASE STUDY

A. Example 1: Six-Unit system

The system consists of six generators and the total load demand on the system is 1263 MW. The power outputs of the six generators are represented by P_1, P_2, P_3, P_4, P_5 and P_6. These values are randomly generated. The best solution obtained by applying these methods is shown in table 1.

Unit Power Output	PSO method	GA method
P_1(MW)	447.9250	445.8835
P_2(MW)	170.6501	170.3555
P_3(MW)	264.7467	267.1309
P_4(MW)	120.3847	120.6641
P_5(MW)	170.8557	170.3184

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P_6 (MW)	88.4368	88.6466
Total Power output (MW)	1263	1263
Total Generation cost ($/hr)	15,276	15,276

Table 1: Best solution of 15- unit system (Best individual)

	Generation cost ($)	
	Max	Min
PSO	15298	15276
GA	15277	15276

Table 2: Comparison between both methods (50 trials)

B. Example 2: Fifteen-Unit System

The system consists of fifteen generators and the total load demand on the system is 2630 MW. The experimental results are shown in Tables 3 and 4. These results are found to satisfy the system constraints.

Unit Power Output	PSO method	GA method
P_1(MW)	343.9627	270.8264
P_2(MW)	452.0160	268.2754
P_3(MW)	112.8241	118.1084
P_4(MW)	127.3678	119.0828
P_5(MW)	260.6972	460.6699
P_6(MW)	402.4683	459.2369
P_7(MW)	436.8479	269.2358
P_8(MW)	125.3228	78.4970
P_9(MW)	65.0803	149.0780
P_{10}(MW)	30.5095	147.0860
P_{11}(MW)	68.2176	67.5806
P_{12}(MW)	61.9314	68.0805
P_{13}(MW)	67.8161	71.3302
P_{14}(MW)	40.8083	41.0806
P_{15}(MW)	34.1232	41.8306
Total Power output (MW)	2630	2630
Total Generation cost($/hr)	32,604	32,844

Table 3: Best solution of 15- unit system (Best individual)

	Generation cost ($)	
	Max	Min
PSO	32803	32604
GA	33054	32844

Table 4: Comparison between both methods (50 trials)

C. Example 3: Forty-Unit System

The system consists of forty generators and the total load demand on the system is 7550 MW. These results are found to satisfy the system constraints.

Unit Power Output	PSO method	GA method
P_1(MW)	51.6495	69.899
P_2(MW)	106.4366	115.095
P_3(MW)	146.4114	184.555
P_4(MW)	33.1208	37.332
P_5(MW)	26.3967	36.099
P_6(MW)	133.1878	137.12
P_7(MW)	202.4194	248.282
P_8(MW)	225.0944	245.118
P_9(MW)	235.1695	246.857
P_{10}(MW)	229.7413	249.619
P_{11}(MW)	185.3917	321.446
P_{12}(MW)	136.9803	254.599
P_{13}(MW)	271.3692	244.791
P_{14}(MW)	318.5009	252.566
P_{15}(MW)	181.9445	255.925
P_{16}(MW)	231.3118	249.32
P_{17}(MW)	278.4898	250.376
P_{18}(MW)	318.7897	281.582
P_{19}(MW)	399.5334	388.831
P_{20}(MW)	420.4946	411.776
P_{21}(MW)	434.0356	312.837
P_{22}(MW)	427.1164	319.096
P_{23}(MW)	433.4655	314.376
P_{24}(MW)	391.3355	314.82
P_{25}(MW)	423.9103	315.192
P_{26}(MW)	411.3608	334.909
P_{27}(MW)	447.4497	323.329
P_{28}(MW)	28.8625	101.964
P_{29}(MW)	21.0774	34.159
P_{30}(MW)	32.5027	118.372
P_{31}(MW)	43.2138	63.28
P_{32}(MW)	45.0267	63.669
P_{33}(MW)	35.4292	64.589
P_{34}(MW)	22.5218	62.689
P_{35}(MW)	20.8390	53.239
P_{36}(MW)	38.5331	54.849
P_{37}(MW)	27.0108	53.643
P_{38}(MW)	43.3273	54.003
P_{39}(MW)	46.9845	55.095
P_{40}(MW)	43.1169	54.700
Total Power output (MW)	7550	7550
Total Generation cost($/hr)	110820	129665

Table 5: Best solution of 40- unit system (Best individual)

	Generation cost ($)	
	Max	Min
PSO	115730	110820
GA	148187	129665

Table 6: Comparison between both methods (50 trials)

D. Paired T-Test

The paired sample t-test, sometimes called the dependent sample t-test, is a statistical procedure used to determine whether the mean difference between two sets of observations is zero. In a paired sample t-test, each subject or entity is measured twice, resulting in pairs of observations. Common applications of the paired sample t-test include case-control studies or repeated-measures designs.

1) Comparison of outputs of GA and PSO

The power outputs obtained from the experiments conducted on the six, fifteen and forty generator system is subjected to the paired T-test with confidence interval of 90%. The results obtained are shown in the table 7.

S. No.	System	C. I. = 90%	T-Value	P-Value	Significance
1	6-GEN	$-1.511 < \mu < 0.694$	-0.79	0.474	No (But approaching)
2	15-GEN	$-44.4 < \mu < 44.4$	0.00	1.000	No
3	40-GEN	$-16.45 < \mu < 16.43$	0.00	0.999	No

Table 7: Output of PSO versus GA

From the results obtained, we can infer that there is no much difference in the two methods. Both the methods are quite similar as far as the power outputs are considered.

2) Comparison of costs of GA and PSO

The costs obtained from the experiments conducted on the six, fifteen and forty generator system is subjected to the paired T-test with confidence interval of 90%. The results obtained are shown in the table Ⅷ

S. No.	System	C.I. = 90%	T-Value	P-Value	Significance
1	6-GEN	-55.8< μ < 76.8	1.0	0.500	No
2	15-GEN	-280.23 < μ < -210.77	-44.64	0.014	Yes
3	40-GEN	-68622 < μ < 17320	-3.77	0.165	No (But closely approaching)

Table 8: Cost Comparison of PSO and GA

From the t-test conducted on the costs obtained from the two methods, there in significant cost difference for a six-generator system. But it comes out to be significant when we consider the case of a fifteen-generator system as the p-value is less than 0.1 or 10%. In the case of forty-generator system, it is out of the confidence interval but it is quite close to being significant. So, we can say that the there is significant difference in the costs obtained from the two methods.

VI. Conclusion

In this paper, a discussion about the reactive power management is done. Also, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) have been successfully implemented to solve the Economic Dispatch problem with generator constraints. For simplicity, some of the nonlinear characteristics of the generator like ramp rate limits and valve point zones have not been considered. For the testing of the above two methods, a six-generator system, a fifteen-generator system and a forty- generator system have been used. The results obtained show that PSO gives higher better solution than the GA. This is confirmed by the t-tests. From the time taken in the execution of the programs of the two methos, GA comes out to be a better choice over PSO.

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