Combined Real and Reactive Power Economic Dispatch using Multi-Objective Reinforced Learning with Optimized Losses

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Abstract- Most of the economic dispatch (ED) works so far deal with real power dispatch only. With the integration of renewable energy into the grid, reactive power dispatch cannot be ignored any longer due to its importance in providing security and reliability in power system planning, operation and control. This paper deals with the formulation of combined real and reactive economic dispatch (CRRED) subject to equality, inequality and stochastic constraints. An effective algorithm that uses a hybrid of distributed slack bus (DSB) formulated using combined participation factors (PF) and multi objective reinforcement learning (MORL) is proposed in this paper. The IEEE 14 Bus was used to validate the effectiveness of the proposed CRRED formulation and Hybrid method .The numerical results obtained show that combining real and reactive power results in a 0.95% decrease in the overall generation cost as compared to a case in which only real power is considered. Further, when the losses are distributed in the entire network using the DSB, then the overall generation cost is reduced by 29.6% due to the reduced losses in DSB model.

Index Terms- *Combined Real and Reactive Economic Dispatch (CRRED), Distributed Slack Bus (DSB), Participation Factors (PF), Reinforcement Learning (RL)*

I. INTRODUCTION

Reactive power production is highly dependent on the real power output. However, reactive power production by a generator reduces its capability to produce active power. Hence the production of reactive power by generator will result in reduction of its active power production. In addition Renewable power systems generate and absorb reactive power at the same time,leading to a stochastic reactive power scenario. Thus the place of reactive power in the modern power system cannot be ignored any longer. The objectives of reactive power (VAR) optimization, which include Reactive Power ED (RPED), are to improve the voltage profile, to minimize system active power losses, and to determine optimal VAR compensation placement under various operating conditions. To achieve these objectives, power system operators utilize control options such as adjusting generator excitation, transformer tap changing, shunt capacitors, and SVC. There has been a growing interest in VAR optimization problems over the last decade. Solving Optimal RPED (ORPED) is gaining more importance due to their effectiveness in handling the inequality constraints and discrete values using hybrid methods as compared to the deterministic and heuristic methods. Thus better method are needed to handle the more complex problems where stochastic reactive power from wind and solar generators are involved.

II. REVIEW OF REACTIVE POWER ECONOMIC DISPATCH (RPED)

Various aspects of reactive power have been considered in past researches. Deterministic methods have been used in past researches to handle problems related with reactive power optimal flow .These include Unified Method (UM) by Lee, K.Y, Park Y.M, and Ortiz, J. L, 1985 [1] ,Linear Programming (LP) and Quadratic Programming (QP) by Serrano, B. R. Vargas, 2001 [2],Mean-Variance Mapping Optimization (MVMO) by Worawat Nakawiro et al, 2011 [3],Superiority of Feasible solutions (SF), Self-adaptive Penalty (SP), εε-constraint (EC), Stochastic Ranking (SR), and the Ensemble of Constraint Handling Techniques (ECHT) by R. Mallipeddi et al,2012 [4] and Second Stochastic Chance-Constrained Model (SSCCM) by Lopez, J.C. et al, 2012 [5].Heuristic methods such as Adaptive Genetic Algorithm (AGA) has also been considered by Q.H. Wu, Y.J. Cao, J.Y. Wen, 1998 [6].In all these works, the Cost function for the reactive power economic dispatch not formulated and further only Static reactive power has been considered .Thus, there is need to formulate the reactive power cost function, determine the cost coefficients and finally come up with a method in which the real and reactive costs can be combined. It can also be noted that only pure methods have been employed in this problem. These methods are strong and weak at the same time, thus there is need to use a hybrid methods which exalts the strengths and suppresses the weaknesses.

In previous studies different techniques have been suggested to determine the reactive power pricing [15-23]. For example, Niknam et al., 2004[21], utilized various search techniques such as genetic algorithm (GA) and ant colony algorithms (ACO) for pricing and Chung et al. 2004[23] proposed a coupled market framework for energy and reactive power. Further, Bialek and Kattuman,2004 [22] developed an integrated method to calculate both real and reactive power spot price and to decompose them into the prices of selected ancillary services.

III. PROBLEM FORMULATION

In order to obtain a more accurate cost function, the reactive power cost is to be included in the active power cost function. The total cost is given by combining the active and reactive power cost by a weighting function,giving the active power more weight than the reactive power.

Real Power Dynamic Economic Dispatch

For real power,dynamic economic dispatch (DED) considers change-related costs. The DED takes the ramp rate limits, valve points and prohibited operating zone of the generating units into consideration. The general form of DED was formulated by **Yusuf Somez, 2013[7]** as is given by

$$F(P_{ij}) = \left\{ a_{0,i} + \sum_{j=1}^{L=N_G} a_{ji} P_{t,i}^{j} + r_i \right\} + \left| e_i \sin f_i (P_i^{min} - P_i) \right| \qquad (1)$$

where $a_{0,i,}a_{j,i}, e_i$ and f_i are the cost coefficients of the i^{th} unit, $P_i^{min}$is the lower generation bound for the i^{th} unit and $r_i$is the error associated with the i^{th} equation. The problem is solved subject to the following constraints:

$$\sum_{i=1}^{NG} P_{gi} = P_D + P_L \qquad (2)$$

$$P_i^{min} \leq P_i \leq P_i^{max} \qquad (3)$$

$$P_{ij} - P_{ij-1} \leq UR_i \qquad (4)$$

$$P_{ij-1} - P_{ij} \leq DR_i \qquad (5)$$

$$-P_l^{max} \leq P_{lj} \leq P_l^{max} \; l = 1,2,3 \ldots\ldots . L \quad (6)$$

$$P_i \leq P^{PZ,LOW} \qquad (7)$$

$$P_i \geq P^{PZ,HIGH} \qquad (8)$$

Reactive Power Economic Dispatch

According to Hasanpour, S., et al 2009[15] the fuel cost function for the reactive power output can be expressed as

$$F(Q_{gi}) = a_{q,o} + \sum_{j=1}^{L=N_G} a_{qi} Q_{g,i}^{j} \qquad (9)$$

Where $a_{q,o}$ and a_{qi} are the reactive power cost coefficients calculated using a curve fitting method, Q_{gi} is the reactive power generated by generator i and n is the order of the fuel cost function . This equation has been extracted from the reactive power cost function of the generator.It is simple,realistic and can therefore provide realistic results in reactive power pricing[15]. The problem is solved subject to the following constraints:

Power balance constraints

$$P_i - V_i \sum_{j=1}^{N_B} V_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) = 0 \qquad (10)$$

$$i = 1,2,3 \ldots \ldots N_B - 1$$

$$Q_i - V_i \sum_{j=1}^{N_{PQ}} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) = 0 \; (11)$$

$$i = 1,2,3 \ldots \ldots N_{PQ}$$

Continuous control variable (Generator Bus Voltage)

$$V_i^{min} \le V_i \le V_i^{max} \; i \in N_B \qquad (12)$$

Discrete control variable (Transformer Tap Settings)

$$t_k^{min} \le t_k \le t_k^{max} \; i \in N_T \qquad (13)$$

Where t_k is the tap setting of transformer at branch k

State variables

$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max} \; i \in N_C \qquad (14)$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \; i \in N_G \qquad (15)$$

$$|S_i| \le S_i^{max} \qquad i \in N_i \qquad (16)$$

Reactive power balance

$$\sum_{i=1}^{N_G} Q_{Gi} + \sum_{j=1}^{N_G} Q_{cj} = \sum_{k=1}^{N_D} Q_{dk} + Q_L \qquad \mathbf{(17)}$$

In these constraints, Q_{Ci} is the reactive power generated by the i^{th} capacitor bank, Q_{gi} is the reactive power generated at bus i, S_i is the apparent power flow through the ith branch, N_B is the total number of buses, $N_T is$ the number of tap setting transformer branches, N_C is the number of capacitor banks and N_g is the number of generator buses, Q_{Gi} Reactive power generated by generator i, Q_{cj} Reactive power generated and absorbed by VAR compensation device j such as capacitors,SVC,Wind Based Doubly Fed Induction Generators s(DFIGs), and PV generators, Q_{dk} Reactive power load at load bus k and Q_L Power system reactive power power loss and absorption .Further , V_i is the voltage magnitude at bus i , V_j is the voltage magnitude at bus j, P_i, Q_i is the real and reactive powers injected at bus i, G_{ij}, B_{ij} is the mutual conductance and suspectance between bus i and j , $N_B - 1$ is the total number of buses excluding the slack bus, N_{PQ} is the number of PQ buses and θ_{ij} is the voltage angle difference between bus i and bus j.

Combined Real and Reactive Economic Dispatch (CRRED)

In order to obtain a more accurate optimal cost, the reactive power cost is to be included in the active power cost function. The total cost is given by combining the active and reactive power cost, giving the active power more weight than the reactive power.The CRRED objective function for dynamic reactive power is formulated as

$$Minimize\ F_{Total} = \sum_{i=1}^{NG} WF\left(F_{gi}\right) + (1-W)F(Q_{gi}) \qquad (18)$$

Where W is the weight attached to the real power.

IV. MULTI OBJECTIVE REINFORCED LEARNING (MORL) WITH DISTRIBUTED SLACK BUS (DSB) [MORL-DSB]

In the past researches, heuristic and deterministic methods haven been widely used in the real power economic dispatch[1-6,15-23] due to their ability to solve such optimization problems with speed and accuracy. Musau et al,2015 [24] did a detailed review of the methods that have been used so far in solving the Multi Objective Dynamic Economic Dispatch (MODED). A more recent trend for solving MODED is the two-method and three-method hybrids formulation in which all the weaknesses of the base methods (that is, deterministic and heuristic methods) are suppressed and the strengths exalted. This leads to increased accuracy and speed in handling higher order cost functions with more objectives. However, hybrid methods have not been applied to CRRRED problems. This paper utilizes a hybrid of MORL and DSB for the first time.

a) Multi Objective Reinforced Learning[MORL]

The RL used in this case has been suggested by, E. A. Jasmin et al, 2011[13].The solution consists of two phases: *learning phase* and *retrieval phase*.To carry out the learning task, one issue is regarding how to select an action from the action space. The two commonly used action selection methods are **ε-greedy** and **pursuit**. In this paper, ε-greedy strategy of exploring action space is used.For solving this multi-stage multi-objective problem using RL, first step is fixing of state space χ and action space $\mathcal{A}$ precisely. The different units can be considered arbitrarily as corresponding to the different stages. The modification is that a MORL which can incorporate both real and reactive power is proposed. RL has the merits of faster computing speed and simplicity,it can effectively handle stochastic cost functions especially in RE environment .Also the method can also handle a great number of the Constraints. The flow chart of MORL is as shown in Figure 1.o

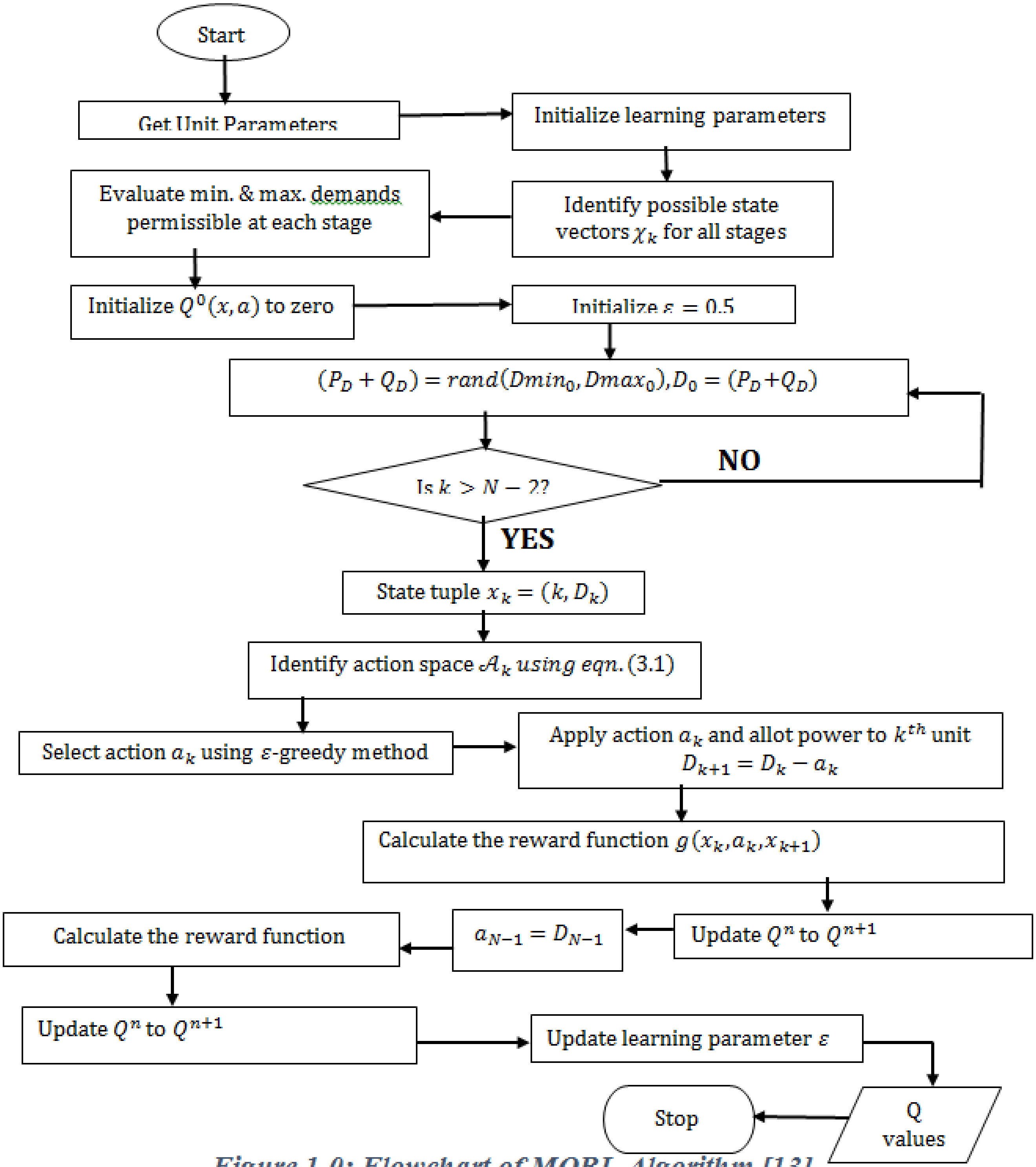

Figure 1.0: Flowchart of MORL Algorithm [13]

b)DSB with MORL (DSB-MORL)

Tong and K.Miu [8-11] formulated a real power DSB using the Newton Raphson Method. In this case real power participation factors (PF) were utilized to model the losses. Musau et al,**2012**[12] developed reactive power DSB then applied the results in [8-11] to come up with combined DSB which can handle both real and reactive power. In this paper, this combined DSB has been used to optimize the real and reactive losses, which is, compared to the Single Slack Bus (SSB) model. DSB results in reduced real and reactive power losses .MORL is then utilized to handle the CRRED in which the losses have been optimized by the DSB.

V. RESULTS AND ANALYSIS

Simulations were carried out on an Intel Core i3, 2.10 GHz, 4-GB RAM processor. The coding is written in MATLAB 2013a version. A hybrid of RL-DSB algorithm was used for solving the CRRED problem. The IEEE-14 bus system used to validate the method consists of 14 buses, 5 generators and 20 lines.The results consists of four parts,a load flow for the DSB and SSB,MORL, MORL-DSB and a comparison with other methods in the existing literature.

a) SSB and DSB Load flows

A load flow for the IEEE 14 Bus system was performed to illustrate the need for DSB,and the corresponding participation factors in CRRED problem. From tables 1.0-4.0,it is evident that DSB leads to reduced combined losses as compared to the SSB.The integration of the reactive power participation factor(RPPF) reduces the real losses to a great extent.

Table 1.0: Output Data with Single Slack Bus (SSB)

Bus No.	**V (pu)**	**Angle**	**P_G**	**Q_G**	**P_L**	**Q_L**	**P_I**	**Q_I**
1	1.0600	0.0000	232.593	-15.233	0.000	0.000	232.593	-15.233
2	1.0450	-4.989	40.000	47.928	21.700	12.700	18.300	35.228
3	1.0100	-12.7487	0.000	27.758	94.200	19.000	-94.200	8.758
4	1.0133	-10.2429	0.000	0.000	47.800	-3.900	-47.800	3.900
5	1.0166	-8.7606	0.000	0.000	7.600	1.600	-7.600	-1.600
6	1.0700	-14.447	0.000	0.000	11.200	7.500	-11.200	15.526
7	1.0457	-13.2375	0.000	23.026	0.000	0.000	0.000	0.000
8	1.0800	-13.2375	0.000	0.000	0.000	0.000	0.000	21.030
9	1.0306	-14.8207	0.000	21.030	29.500	16.600	-29.500	-16.600
10	1.0299	-15.0365	0.000	0.000	9.000	5.800	-9.000	-5.800
11	1.0461	-14.8584	0.000	0.000	3.500	1.800	-3.500	-1.800
12	1.0533	-15.2974	0.000	0.000	6.100	1.600	-6.100	-1.600
13	1.0466	-14.2814	0.000	0.000	13.500	5.800	-13.500	-5.800
14	1.0193	-16.0721	0.000	0.000	14.900	5.000	-14.900	-5.000
	TOTAL		**272.593**	**104.509**	**259.000**	**73.500**	**13.593**	**31.009**

Table 2. 0 :Line Flows and Losses with Single Slack Bus(SSB)

From-To	**P(MW)**	**Q(Mvar)**	**From-To**	**P(MW)**	**Q(Mvar)**	**Loss (MW)**	**Loss(Mvars)**
1-2	157.080	-17.484	2-1	-152.772	30.369	4.309	13.155
1-5	75.513	7.981	5-1	72.740	3.464	2.773	11.455
2-3	73.396	5.936	3-2	71.063	3.894	2.333	9.830
2-4	55.943	2.935	4-2	54.273	2.132	1.670	5.067
2-5	41.733	4.738	5-2	40.813	-1.929	0.920	2.890
3-4	-23.137	7.752	4-3	23.528	-6.753	0.391	0.998
4-5	-59.585	11.574	5-4	60.064	-10.063	0.479	1.511
4-7	27.066	-15.396	7-4	-27.066	17.372	0.000	1.932
4-9	15.464	-2.640	9-4	15.464	3.932	0.000	1.292
5-6	45.889	-20.843	6-5	-45.889	26.617	0.000	5.774
6-11	8.287	8.898	11-6	-8.165	-8.641	0.123	0.257
6-12	8.064	3.176	12-6	-7.9485	-3.008	0.081	0.168
6-13	18.337	9.981	13-6	-18.085	-9.485	0.252	0.496
7-8	0.000	-20.362	8-7	0.000	21.030	0.000	0.668
7-9	27.066	14.798	9-7	-27.066	-13.840	0.000	0.957
9-10	4.393	-0.904	10-9	-4.387	0.920	0.006	0.016

9-14	8.637	0.321	14-9	-8.547	-0.131	0.089	0.190
10-11	-4.613	-6.720	11-10	4.665	6.841	0.051	0.120
12-13	1.884	1.408	13-12	-1.873	-1.398	0.011	0.010
13-14	6.458	5.083	14-13	-6.353	-4.869	0.105	0.215
TOTAL LOSS						**13.593**	**56.910**

Table 3. 0: Output Data with Distributed Slack Bus (DSB) using Real Power PF

Bus No.	V (pu)	Angle	P_G	Q_G	P_L	Q_L	P_I	Q_I
1	1.0700	11.8713	232.408	6.325	0.000	0.000	232.408	6.325
2	1.0450	7.1139	40.001	27.802	21.700	12.700	18.301	15.102
3	1.0100	-0.6377	0.000	27.037	94.200	19.000	-94.200	8.037
4	1.0144	1.8474	0.000	0.000	47.800	-3.900	-47.800	3.900
5	1.0186	3.3143	0.000	0.000	7.600	1.600	-7.600	-1.600
6	1.0700	-2.3537	0.000	21.944	11.200	7.500	-11.200	14.444
7	1.0462	-1.1461	0.000	0.000	0.000	0.000	0.000	0.000
8	1.0800	--1.1461	0.000	20.695	0.000	0.000	0.000	20.695
9	1.0311	-2.7297	0.000	0.000	29.250	16.600	-29.500	-16.600
10	1.0304	-2.9452	0.000	0.000	9.000	5.800	-9.000	-5.800
11	1.0464	-2.7663	0.000	0.000	3.500	1.800	-3.500	-1.800
12	1.0533	-3.2039	0.000	0.000	6.100	1.600	-6.100	-1.600
13	1.0467	-3.2385	0.000	0.000	13.500	5.800	-13.500	-5.800
14	1.0196	-3.9797	0.000	0.000	14.900	5.000	-14.900	-5.000
	TOTAL		**272.409**	**103.803**	**259.000**	**73.500**	**13.409**	**30.303**

Table 4.0: Line Flows and Losses with Distributed Slack Bus(DSB) using Real Power PF

From-To	P(MW)	P(MW)	From-To	P(MW)	P(MW)	Loss (MW)	Loss(Mvars)
1~2	156.840	0.349	2~1	-152.677	12.364	4.164	12.713
2~3	75.567	11.815	3~2	-72.807	-0.419	2.761	11.397
2~4	73.320	5.944	4~2	-70.991	3.866	2.328	9.810
1~5	55.924	2.243	5~1	-54.257	2.815	1.667	5.058
2~5	41.735	3.572	5~2	-40.820	-0.778	0.915	2.794
3~4	-23.209	7.058	4~3	23.595	-6.071	0.387	0.987
4~5	-59.725	9.739	5~4	60.200	-8.241	0.475	1.499
5~6	27.100	-15.087	6~5	-27.100	16.999	0.000	1.912
4~7	15.487	-2.515	7~4	-15.487	3.804	0.000	1.289
7~8	45.827	-20.042	8~7	-45.827	25.706	0.000	5.664
4~9	8.253	8.793	9~4	-8.132	-8.541	0.121	0.253
7~9	8.057	3.163	9~7	-7.976	-2.996	0.080	0.167
9~10	18.317	9.927	10~9	-18.066	-9.433	0.251	0.494
6~11	0.000	-20.049	11~6	0.000	20.695	0.000	0.647
6~12	27.100	14.825	12~6	-27.100	-13.866	0.000	0.959
6~13	4.424	-0.807	13~6	-4.418	0.823	0.006	0.016
9~14	8.662	0.384	14~9	-8.572	-0.192	0.090	0.191
10~11	-4.582	-6.623	11~10	4.632	6.741	0.050	0.117
12~13	1.876	1.396	13~12	-1.865	-1.386	0.011	0.010
13~14	6.432	5.019	14~13	-6.328	-4.808	0.104	0.211
TOTAL LOSS					**13.409**	**56.187**	**56.188**

Table 5.0:Line Flows and Losses with Distributed Slack Bus using Reactive Power PF

Bus No.	V (pu)	Angle	P_G	Q_G	P_L	Q_L	P_I	Q_I
1	1.0500	12.0665	223.861	-35.774	0.000	0.000	223.861	-35.774
2	1.0450	7.0834	46.150	57.193	21.700	12.700	24.450	44.493
3	1.0200	-0.6686	2.287	37.215	94.200	19.000	-91.913	18.215
4	1.0142	1.8161	-1.790	-5.224	47.800	-3.900	-49.590	-1.324
5	1.0172	3.3072	2.114	-0.211	7.600	1.600	-5.486	-1.811
6	1.0800	-2.3425	7.030	40.454	11.200	7.500	-4.170	32.954
7	1.0503	-1.1766	-0.000	-5.963	0.000	0.000	-0.000	-5.963
8	1.1000	-1.1738	0.032	31.006	0.000	0.000	0.032	31.006
9	1.0337	-2.7573	-0.000	0.000	29.500	16.600	-29.500	-16.600
10	1.0326	-2.9662	-0.000	0.000	9.000	5.800	-9.000	-5.800
11	1.0475	-2.7727	-2.080	-4.273	3.500	1.800	-5.580	-6.073
12	1.0535	-3.1932	-1.657	-3.322	6.100	1.600	-7.757	-4.922
13	1.0471	-3.2329	-3.344	-6.339	13.500	5.800	-16.844	-12.139
14	1.0213	-3.9896	-0.000	0.000	14.900	5.000	-14.900	-5.000
	TOTAL		**272.603**	**104.762**	**259.000**	**73.500**	**13.603**	**31.262**

Table 6.0 :Line Flows and Losses with Distributed Slack Bus(DSB) for Combined PF

From-To	P(MW)	Q(Mvars)	From-To	P(MW)	Q(Mvars)	Loss (MW)	Loss(Mvars)
1~2	150.170	-33.304	2~1	-146.011	46.002	4.159	12.698
2~3	73.691	3.152	3~2	-71.025	7.853	2.666	11.006
2~4	72.822	0.832	4~2	-70.540	8.783	2.282	9.615
1~5	55.951	2.328	5~1	-54.282	2.736	1.669	5.063
2~5	41.689	4.351	5~2	-40.772	-1.554	0.916	2.797
3~4	-21.374	12.377	4~3	21.767	-11.374	0.393	1.003
4~5	-59.781	12.541	5~4	60.265	-11.014	0.484	1.527
5~6	27.194	-17.195	6~5	-27.194	19.253	0.000	2.058
4~7	15.512	-3.045	7~4	-15.512	4.354	-0.000	1.309
7~8	46.047	-24.905	8~7	-46.047	31.125	0.000	6.221
4~9	10.349	12.729	9~4	-10.130	-12.270	0.219	0.459
7~9	9.751	6.551	9~7	-9.606	-6.248	0.145	0.303
9~10	21.776	16.317	10~9	-21.356	-15.490	0.420	0.827
6~11	-0.032	-29.606	11~6	0.032	31.006	0.000	1.400
6~12	27.226	16.257	12~6	-27.226	-15.254	-0.000	1.003
6~13	4.501	-0.278	13~6	-4.495	0.294	0.006	0.016
9~14	8.737	0.724	14~9	-8.646	-0.529	0.091	0.194
10~11	-4.505	-6.094	11~10	4.550	6.197	0.044	0.103
12~13	1.849	1.327	13~12	-1.839	-1.317	0.010	0.009
13~14	6.351	4.668	14~13	-6.254	-4.471	0.097	0.197
TOTAL LOSS						**13.603**	**57.809**

From tables 4.0-6.0,it can be easily observed that ,the combined participation factors(CPF) leads to reduced losses as compared to the real power participation factors (RPF) hence the increased importance of reactive power in power loss reduction.

b) Multi Objective Reinforced Learning [MORL]

The **RL parameters** that were used in the algorithm are given in table 7.0:

Table 7.0:MORL Parameters

ε	0.5
α	0.1
γ	0.5

Power scheduling was done considering the three sets of real power and reactive power demands shown in table 8.0. The optimal generation of the five generating units and the optimal cost are also tabulated as shown in Table 8.0.CRRED problem formulation and solution led to reduced fuel cost as compared to the pure real power.

Table 8.0: Real and Reactive Power Scheduling for a 14-Bus System

	P_D = 800MW **Q_D = 370MVAR**	**P_D = 900MW** **Q_D = 470MVAR**	**P_D = 1000MW** **Q_D = 570MVAR**
P_{g1} (MW)	193.8187	193.3338	192.9860
P_{g2} (MW)	173.2834	202.5915	202.2780
P_{g3} (MW)	40.9645	54.9518	77.0050
P_{g4} (MW)	235.0919	243.9489	256.8600
P_{g5} (MW)	126.4889	164.1163	215.8620
P_{loss} (MW)	*30.3526*	*41.0577*	*55.0090*
Q_{g1} (MVAR)	195.7260	195.4648	195.0305
Q_{g2} (MVAR)	-2.5670	25.6773	74.5531
Q_{g3} (MVAR)	21.2810	25.4025	22.9167
Q_{g4} (MVAR)	150.9200	199.4408	219.0609
Q_{g5} (MVAR)	4.2270	21.6678	49.8217
Q_{loss} (MVAR)	*0.4130*	*2.3468*	*8.6171*
$F(P_{gi})$ (\$)	**6,456.1**	**7,336.3**	**8,249.6**
$F(Q_{gi})$ (\$)	1,276.7	1,617.8	1,962.0
F_T (\$)	**5,420.2**	**6,192.6**	**6,992.1**

The cost of generation increased with increase in real power and reactive power demands. For low demands, the power flow will be within limits or deviates just slightly from the limits. As the power demand increases, the system resources continue being stretched and the power flow rises above the limits causing the cost to increase.

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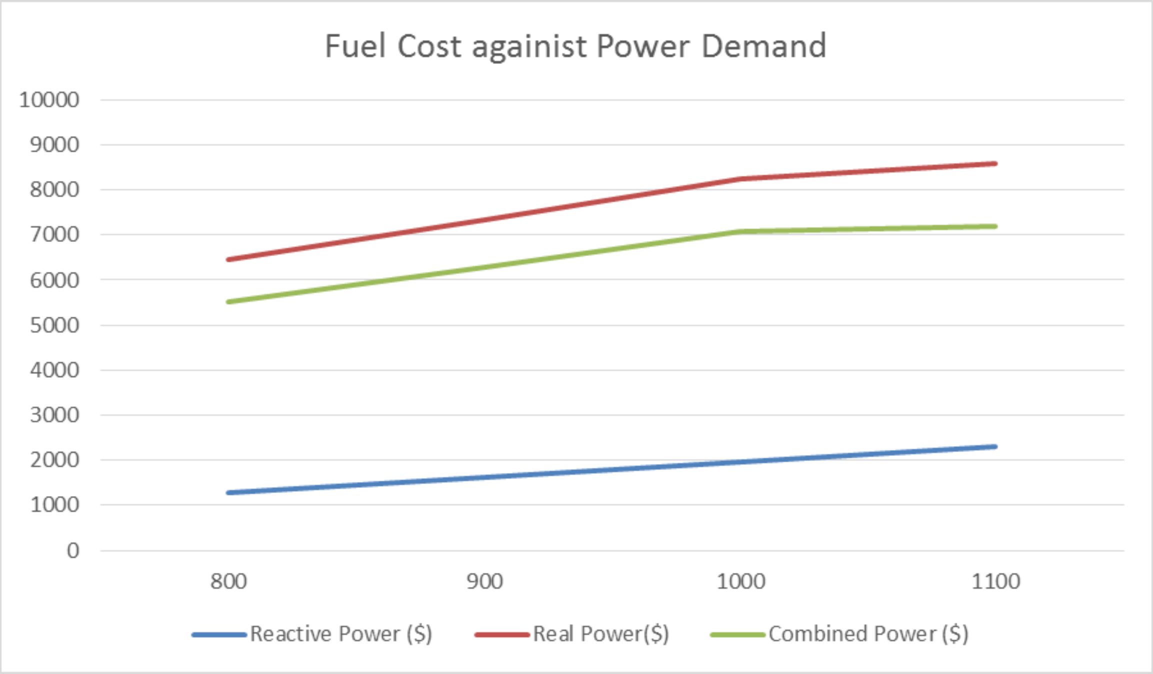

Figure 2.0: Fuel cost against Power Demand

From ***Figure 2.0,*** it is clear that the real power cost was higher than the reactive power cost. However, the combined real and reactive power cost was lower than the real power cost. This implies that the cost of generation reduces when combined real and reactive power cost is computed as compared to just considering real power generation that most economic dispatch problems involves. In ***Figure 2.0*** , a real power demand of 800MW corresponds to reactive power demand of 370MVAR, 900MW corresponds to 470MVAR, and 1000MW corresponds to 570MVAR (x axis).

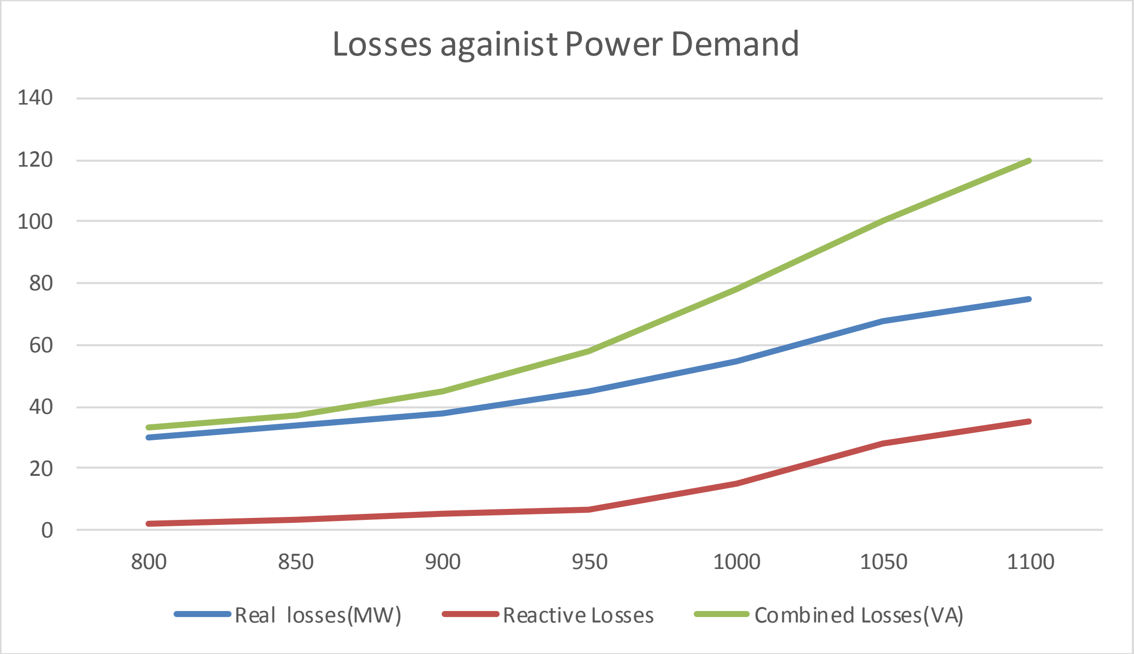

Figure 3.0: Power Losses against Power Demand

From ***Figure 3.0,*** the power losses increased with higher levels of power demanded. It is also clear that the real power losses were higher than the reactive power losses.The combined losses are a vector sum of the Real and reactive losses hence they are higher than both the two components considered separately.

c) MORL with DSB

As shown in table 9.0, use of MORL with Combined PF DSB led to lower system losses as compared to the real power DSB. This is because the inclusion of reactive power in DSB leads to improve voltage profile which translates to better reactive power management. The SSB –RL has the highest system losses. The generation cost are as tabulated in Table 10.0 for CRRED problem. From this table it is clear that which the generation cost are lowest in the DSB-MORL with combined PF compared to MORL with real power DSB and SSB. Further the inclusion of reactive power in ED formulation led to reduced cost as compared to a scenario in which only real power of the thermal units is considered. The algorithm with combined PF DSB provided a feasible solution with fewer iterations as compared to the other two scenarios.

Table 9.0: Comparison of Generated Power

		RL with SSB(MW)	RL with DSB using Real PF (MW)	RL with DSB using Reactive PF(MW)	RL with DSB With Combined PF(MW)
Generation:	Plant 1	232.593	232.408	223.861	**231.206**
	Plant 2	40.000	40.001	46.150	**40.0000**
Total System Losses		13.593	13.409	13.603	**13.301**

Table 10.0: Comparison of Generation Costs in MORL-DSB

	RL with SSB	RL with DSB with Real Power PF	RL with DSB Reactive Power PF	RL with DSB Combined PF
Generation Cost for Thermal Generators ($/Hr)	4814.131	4801.906	4808.3548	4800.2678
Generation Cost for CRRED ($/Hr)	**4781.009**	**4768.870**	**3966.6206**	**3378.6789**
Number of iterations	7	6	6	5

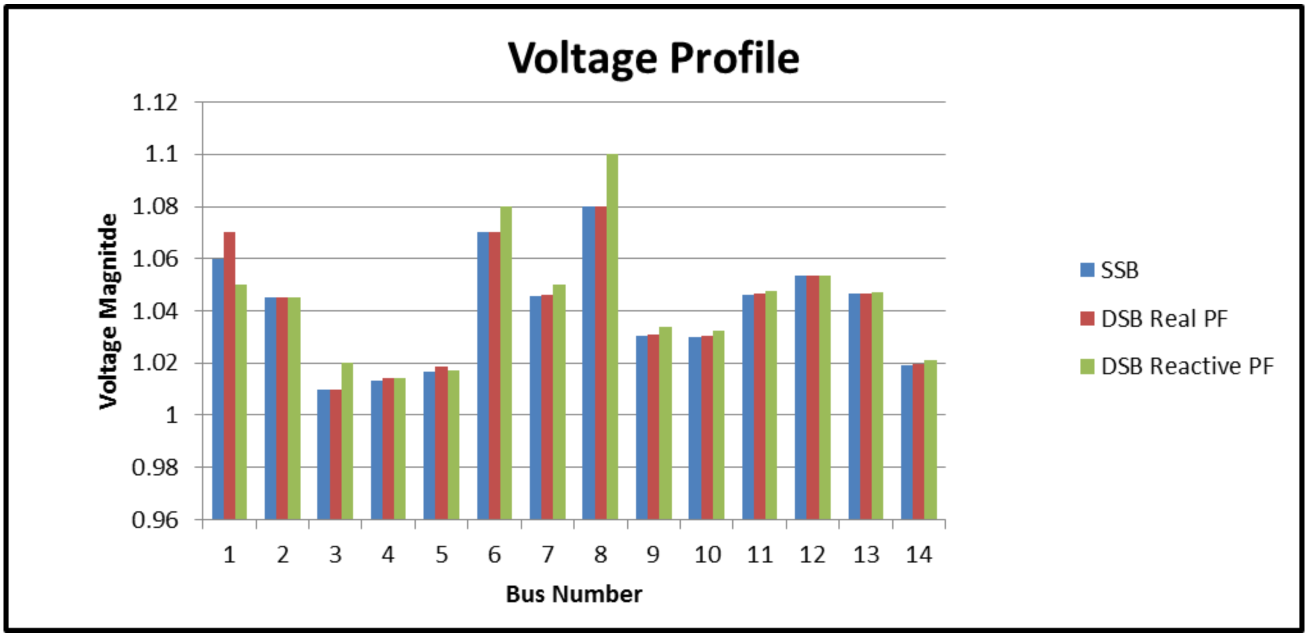

Figure 4.0 :Voltage Profile Comparison

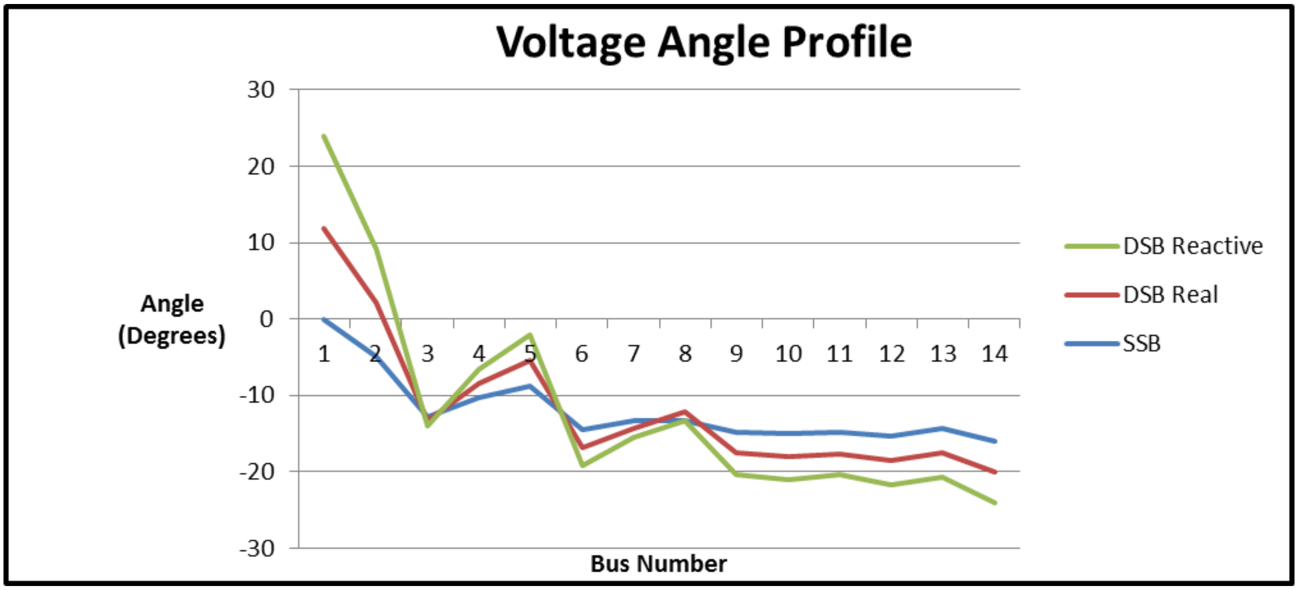

Figure 5. 0: Voltage Angle Comparison

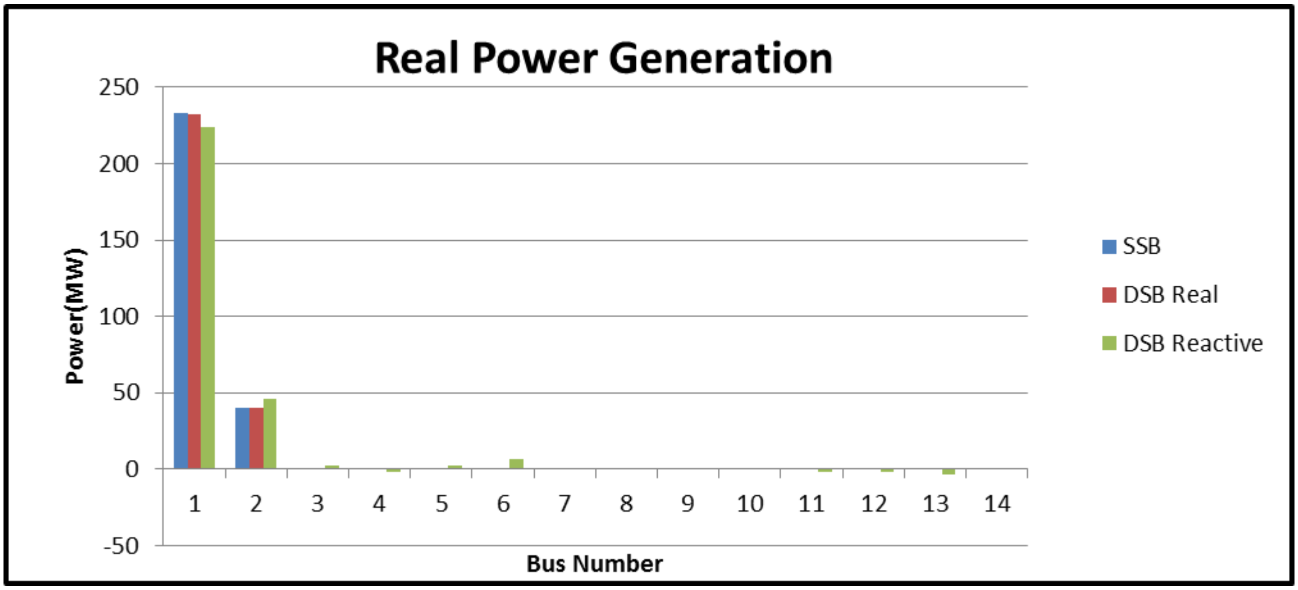

Figure 6.0: Comparison of Real Power Generation

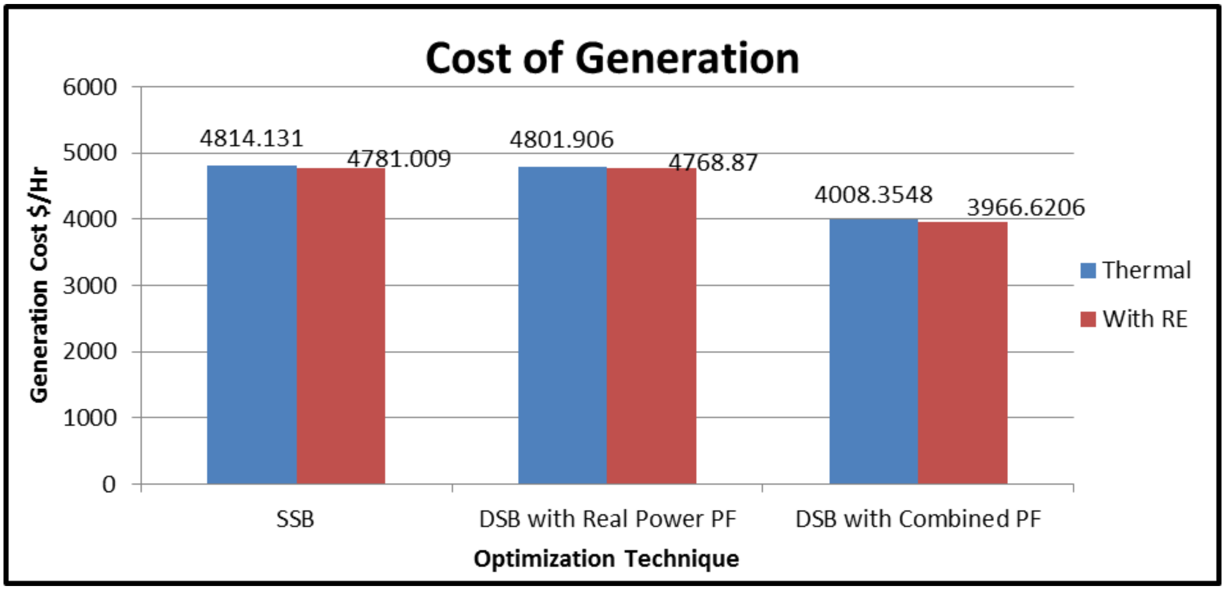

Figure 7.0: Comparison of Generation Costs

From figure 3.0, it is observed that the voltage magnitudes between buses are relatively similar. Voltage angles vary significantly in the two models as shown in figure 5.0. In the DSB-MORL, bus 1 was taken as the reference bus with a phase angle of 0.The DSB distributes system mismatches to all PV buses in the system through participation factors resulting in a change in phase angles. Power losses reduce by 0.184 MW in the DSB using real power participation factors compared to the SSB. However, the DSB using reactive power participation factors does not improve on the losses, this is because reactive power represents the power absorbed by the system. The generator real power outputs with a DSB are slightly less than the real power outputs with a single slack bus. This results in a lower generation cost in the DSB model as demonstrated in figure 6.0. The incorporation of renewable energy (CRRED) reduces the cost of generation in both the SSB and DSB as demonstrated in figure 7.0.

d) Comparison with other methods

To show the effectiveness of the proposed formulation and methodology, results are compared with related work carried out by researchers; Singh et al.2014 [14] and Hasanpour et al., 2009[15].Table 11.0 shows the comparison of results obtained under the IEEE 14 Bus System. Singh et al.2014 [14] used PSO which models the generators in terms of particles with respective velocities. The method ensures a complete search of the problem space, however it cannot be applied to a large practical network, Hasanpour et al., 2009[15] applied the Tracing Algorithm(TA) which is fair accurate ,realistic and easily formulated as compared to the deterministic methods. However the search space could not be exhausted leading to premature converge. The costs in [14] ($5460.5205) and

[15]($5690.6120) were found to be higher compared even to the DSB-MORL at minimum load($ 5420.2000**)** for the CRRED ,that is the MORL 15.24% 16.05 % better using the max and min approach respectively.The MORL with DSB Resulted into a far much reduced cost of $3378.6789 (29.6%) as compared to all other methods as losses involved have been optimized by DSB and further by MORL. The method provided an exhaustive search of the problem space with reduced number of iterations, reduced fuel cost and a better voltage profile.

Table 11.0: Comparison of proposed method with methods

Type of Cost ($)	**MORL(Max Demand)**	**MORL(Min Demand)**	**MORL With DSB Combined PF**	**Hasanpour, S et al.,2009[15]**	**Singh et al.,2014[14]**
Real power fuel cost, $F(P_{gi})$	8,249.6000	6456.1000	4800.2678	5998.8790	5678.5875
Combined fuel cost, F_T	6,992.1000	5420.2000	3378.6789	5690.6120	5460.5205
% cost Reduction	15.24	16.05	29.60	5.15	3.84

VI. CONCLUSION

DSB-MORL algorithm was successfully applied for the solution of CRRED. Power allocation was done among five generating units at optimum generating costs while taking into consideration the equality, inequality and the stochastic constraints. From the results and analysis done, CRRED of power was found to be cheaper by almost 0.95%(~$ 40/Hr)than when real dispatch of power only is considered. When network losses were optimized using the DSB and then RL applied for the CRRED, the cost was found to be even lower as compared to the pure RL. Reduced losses meant reduced cost due to the introduction of the renewable energy based reactive power. Dynamic reactive power results in improved reactive power management and improved voltage profile, hence reduced optimal cost. The DSB-MORL with Combined PF provided a feasible solution with fewer iterations as compared to the real power PF, reactive power PF and SSB. However, a better optimal cost can be achieved if more accurate cubic cost functions are used in modelling the CRRED. Lastly, increased practical application of the proposed DSB-MORL can be realized by showing the test results on IEEE 57 bus and IEEE 118 bus systems which are larger and more realistic.

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REFERENCES

[1] Lee, K.Y.; Park, Y.M.; Ortiz, J. L., "A United Approach to Optimal Real and Reactive Power Dispatch," Power Apparatus and Systems, IEEE Transactions on , Vol.PAS-104, No.5, pp.1147,1153, May 1985.

[2] Serrano, B. R.; Vargas, A., "Active-reactive power economic dispatch of very short term in competitive electric markets," Power Technology Proceedings, 2001 IEEE Porto, Vol.1, No.10 pp.6-8, 2001.

[3] Worawat Nakawiro et al “A Novel Optimization Algorithm for Optimal Reactive Power Dispatch: A Comparative Study” IEEE Transactions on Power Systems, Vol.1 pp. 1155-1161, 2011.

[4] R. Mallipeddi et al “Efficient constraint handling for optimal reactive power dispatch problems” Swarm and Evolutionary Computation Vol. 5, Pages 28-36, August 2012.

[5] Lopez, J.C.; Munoz, J.I.; Contreras, J.; Mantovani, J. R S, "Optimal reactive power dispatch using stochastic chance-constrained programming," Transmission and Distribution: Latin America Conference and Exposition (T&D-LA), 2012 Sixth IEEE/PES , Vol.3, pp.1-7, 3-5 Sept. 2012

[6] Q.H. Wu, Y.J. Cao, J.Y. Wen ”Optimal reactive power dispatch using an adaptive genetic algorithm” International Journal of Electrical power and energy systems Vol.20, Issue 8, Pages 563–569, November 1998.

[7] Yusuf Sonmez “Estimation of Fuel cost curve parameters for thermal power plants using the ABC Algorithm“ ,Turkish Journal Of Electrical Engineering and Computer Science ,Vol .21 pp. 1827-1841,2013

[8] K.M.S.Tong andM.Kleinberg, “A distributed slack bus model and its impact on distribution system application techniques,” in Proc. IEEE Int.Symp.CircuitsSyst.(ISCAS),vol.5, pp.4743–4746,May2005.

[9] S.TongandK.Miu, “A network-based distributed slack bus model for DGs in unbalanced power how studies, IEEETrans.PowerSyst” vol.20, no. 2, pp. 835–842, May 2005

[10] K. M. S. Tong, “Participation factor studies for distributed slack bus Models in three-phase distribution power flow analysis,”inProc.IEEE PESTransm.Distrib.Conf.Exhib.,2005/2006, pp.92–96,May 2006.

[11] S. Tong and K. Miu, “Slack bus modeling and cost analysis of distributed generator installations,” J. Energy Eng., vol. 133, no. 3, pp.111–120, 2007.

[12] Peter Musau Moses and Nicodemus Abungu Odero ”Distributed Slack Bus Model for a Wind Based Distributed Generation using Combined Participation Factors” International Journal of Emerging Technology and Advanced Engineering(IJETAE),Volume 2, Issue 10, ,PP 459-469, October 2012.

[13] E. A. Jasmin et al "Reinforcement Learning Approaches to Economic Dispatch Problem," Electrical Power and Energy Systems, Vol 33 ,pp 836-845, 2011

[14] Singh, H. P., Brar, Y. S., & Kothari, D. P., “Combined active and reactive power dispatch using Particle Swarm Optimization” Proceedings of Informing Science & IT Education Conference (InSITE) 295-304, 2014.

[15] Hasanpour, S., Ghazi, R., & Javidi, M. H. “A new approach for cost allocation and reactive power pricing in a deregulated environment”. Electrical Engg.,91 (1), 27-34,2009

[16] Deksnys, R., & Staniulis, R., “Pricing of reactive power services”. Oil Shale Estonian Acad. Publ.,24, 363–376,2007.

[17] Baughman, M. L., & Siddiqi, S. N. “Real time pricing of reactive power: Theory and case study results”. IEEE Trans. Power Sys.,6, 23-29,1993.

[18] Kahn, E., & Baldick, R. “ Reactive power is a cheap constraint”. The Energy Journal, 15, 191-201,1994.

[19] Muchayi. M., &. El-Hawary, M. E. “A summary of algorithms in reactive power pricing”. Electric Power and System Research, 21, 119-124,1999.

[20] Hogan, W.(1993). “Markets in real electric networks require reactive prices”. The Energy Journal, 14(3), 171-200,1993.

[21] Niknam, T., Arabian, H., & Mirjafari, M. “Reactive power pricing in deregulated environments using novel search methods”. IEEE Proceedings of Third International Conference on Machine Learning and Cybemetics, Shanghai, pp. 4234–4240,2004

[22] Bialek, J.W.,&Kattuman, P.A. “Proportional sharing assumption in tracing methodology”. IEE Proceedings Generation Transmission and Distribution, 151(4), 526-532,2004.

[23] Chung, C.Y., Chung, T. S., Yu, C.W., & Lin, X.J. “Cost-based reactive power pricing with voltage security consideration in restructured power systems”. Electr Power Syst Res.,70, 85–92,2004.

[24] Moses Peter Musau, Nicodemus Odero Abungu, Cyrus Wabuge Wekesa. “Multi Objective Dynamic Economic Dispatch with Cubic Cost Functions”. International Journal of Energy and Power Engineering. Vol. 4, No. 3, pp. 153-167,2015

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