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Joint Market Clearing of Energy and Demand Response Offers Considering Voltage Dependent Load Models

This paper presents a new multi-objective day-ahead market clearing (DAMC) mechanism with demand-side reserves/demand response offers, considering realistic voltage dependent load modeling.
The paper proposes objectives such as Social Welfare Maximization (SWM) including demand-side reserves, and Load Served Error (LSE) minimization. In this paper, energy and demand-side reserves are cleared simultaneously through co-optimization process. The paper clearly brings out the unsuitability of conventional SWM for DAMC in the presence of voltage dependent loads, due to reduction of load served (LS). Under such circumstances multi-objective DAMC with demand response offers is essential. Multi-objective Strength Pareto Evolutionary Algorithm 2+ (SPEA 2+) has been used to solve the optimization problem. The effectiveness of the proposed scheme is confirmed with results obtained from IEEE 30 and IEEE 300 bus test systems.

Keywords: Demand elasticity, Demand response, Electricity markets, Load modeling, Multi-objective optimization, Social welfare.
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1. Introduction

Power system gets subjected to variations in operating conditions all the time. Contingent situations may arise due to sudden increase in electrical load demand, forced outage of a generator or transmission line, or any defect in one of the system equipments. Optimal generation rescheduling and demand response (DR)/load reduction during contingency situations is one of the most important issues in planning secure operation of power systems. In recent years, there has been a massive focus on fostering demand response programs (DRP)/demand-side reserves as ancillary service. Following this, some independent system operators (ISOs) or regional transmission organizations (RTOs) such as Pennsylvania-New Jersey-Maryland Interconnection (PJM), California Independent System Operator (CAISO), New York ISO (NYISO), ISO-New England (ISO-NE) and electric reliability council of Texas (ERCOT) have recently started considering the prospect of letting their demand responsive resources to participate in the ancillary services markets. DR schemes are important in cases where there is lack of adequate spinning reserve margin or inadequate tie line capacity to make up for the lost generation or sudden load changes [1].

A common characteristic of the large regional markets is that they have hourly energy markets that are simultaneously co-optimized with ancillary service markets, in which all generators and loads are allowed to participate. The Curtailment Service Providers (CSPs) in PJM energy market [2], and the Demand Response Providers (DRPs) in CAISO energy market [3] can submit demand response offers/load reduction bids individually, or in aggregated fashion. CAISO energy market has demand response programs especially designed to provide the end use customers ability to participate in energy load reduction. Demand response occurs when end use customers reduce their electrical usage in response to price signals generated in day-ahead/real time markets.

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CSPs of PJM market and DRPs of CAISO energy markets may provide load adjustment/demand response capabilities to their customers as a demand response resource, to participate into the wholesale electricity markets. Customers may have the capability to curtail their normal consumption in order to participate in the DAMC [4]. They submit either an aggregated or an individual demand/load reduction bid based on the grouping of their clients. A client bids individually only when it is large enough to do so, else a group of customers bid in aggregation. The DRPs or consumers can submit bids into the wholesale day-ahead and/or real time market and respond to dispatches at the directions given by CAISO. The day-ahead and real time markets have separate bidding, clearing and settlement processes.

In competitive electricity market, where all generators are paid the market clearing price under a uniform auction structure, even a small reduction in demand can result in an appreciable reduction in system's marginal costs of production. PJM provides subsidies to customers who reduce their consumption in response to price signals [5] and offers incentives for load/demand participation in the form of payments related to the locational marginal price (LMP) at the time of demand curtailment [6]. Various benefits of demand response in electricity markets are described in [7]. The current experiences with DR programs, analyzes China's situation and makes suggestions for DR implementation are reviewed in [8]. The reference [9] illustrates how the introduction of demand response into constrained electricity markets can significantly reduce volatility in wholesale electricity prices and potentially check the exercise of market power by generators. In [10], an algorithm for day-ahead market to allocate energy and determining the optimum amount of real power reserve capacity and the share of generating units and demand-side contribution in providing reserve capacity requirements is presented.

In [11], the effects demand response program on local marginal price spikes and operation cost reduction are evaluated by using emergency demand response program, economic load model and local marginal price evaluation techniques are discussed. The framework of [12] enables the study of the effect of optimal reserve scheduling and emission reduction as well as an analysis of the system effects of pollution reduction. With the increased advanced metering instrument and smart grid realization, the reserve supplying demand response is becoming an important player in the reserve market, and thus, these resources are also taken into account. In [13], day-ahead demand response program as one of the incentive based demand response programs is implemented as a source of spinning reserve. The technical and economic potential of energy-intensive industries to provide demand-side management in electricity and balancing markets through 2030 are investigated in [14]. An economic model for two demand response programs namely, Interruptible/Curtailable program and capacity market program has been developed, where the penalty imposed on consumers who do not commit to their obligation is modeled in [15].

An economic dispatch model for the price responsive loads based on the concept of flexible price elasticity of demand and a customer benefit function are presented in [16]. The market dispatch problem of the pool-based day-ahead electricity market has been formulated in [17], so as to maximize the social welfare of market participants subject to operational constraints given by real and reactive power balance equations and security constraints in the form of apparent power flow limits over the congested lines. In [18], the combined/composite problem of optimizing economic dispatch, fast spinning reserve and load shedding is presented. Customers may alter their consumption during contingencies thereby contributing to system security. Demands may act as up or down spinning reserves by curtailing or increasing their consumption as when required by the system. A methodology considering the joint dispatch of demand response and distributed generation in the context of a distribution network operated by a virtual power player is proposed in

[19]. Reference [20] proposes a novel agent-based approach that applies SA-Q learning for the demand-side system reserve provision in co-optimized day-ahead electricity and reserve market. Reference [21] reviews the advanced typical Real-time electricity markets coordinated with the relevant ancillary service markets, which maintain reliable and secure operation of power systems. A co-optimized day-ahead energy and spinning reserve market is proposed in [22] to minimize the expected net cost under all credible system states, i.e., expected total cost of operation minus total benefit of demand, and solved by mixed integer linear programming. Reference [23] investigates and quantifies the cost impact of various demand response modelings on unit commitment and dispatch in a day-ahead market regime. Reference [24] presents an overview of the European markets, where aggregated demand-side-flexibility from small users may be of most value to the system, markets and individual consumers. From the literature it is clear that an important requirement that has not been addressed in most of the existing models, is the inclusion of voltage dependent load modeling in the energy and demand-side reserves market clearing.

In light of the above, this paper proposes a new Day-Ahead Market Clearing (DAMC) mechanism with demand response/demand-side reserves solving a multi-objective optimization problem. Handling of demand response is more complex under voltage dependent load modeling when compared to constant load modeling, and this has not been investigated so far. This paper presents co-optimization of energy and demand-side reserves considering constant and voltage dependent loads. Co-optimization of energy and demand-side reserves has been implemented in PJM, NYISO, CAISO, Midwest ISO. This co-optimization results in optimal generation dispatch set-points and demand response reserve assignments. The proposed DAMC approach is particularly suitable for stressed system operating conditions, where the demand elasticity alone cannot yield a feasible optimal solution. The feasible solution is obtained by invoking load reduction bids/demand response offers. Moreover, realistic voltage dependent loads have been modeled. It is shown that single objective optimization with social welfare maximization including demand response offers (SWM) is not suitable with this kind of load modeling, due to reduction of load served. Hence, this paper then presents the multi-objective optimization to tackle such a complex problem. This is achieved by adding load served error (LSE) minimization objective to the original SWM objective.

The characteristic of most of the power system problems with multi-objective optimization is that the objectives are competing and conflicting with each other. This paper, in particular serves to bring out the importance and benefits achieved by simultaneously optimizing multiple objectives like social welfare maximization including demand response offers (SWM), and Load Served Error (LSE) minimization for DAMC. In the present work, Strength Pareto Evolutionary Algorithm 2+ (SPEA 2+) is selected as one suitable multi-objective algorithm.

The rest of the paper is organized as follows: Section 2 describes the DAMC problem formulation including demand-side reserves. Section 3 presents brief description about multi-objective DAMC. Section 4 provides results and discussion. Finally, Section 5 concludes by highlighting the contributions of the paper.

2. Day-Ahead Market Clearing (DAMC): Problem Formulation

Demand-side reserves are being increasingly used in day-ahead market clearing (DAMC), despite their much higher costs; in critical situations where, either conventional generation reserves are insufficient or cannot be deployed fast enough, due to generation rate constraints (GRC). This is because the former are fastest in response, and are also strategically, very well distributed throughout the system. Although, all these things are very well known, how to handle them in voltage dependent load modeling context, has not been investigated so far. The customer providing this service needs to be told, what actual load relief is required, at a specific voltage (obtained from optimization), so that the difference between nominal load relief, and the actual load relief is clear. This is quite complex, and unlike the simple, single load relief quantum instruction given, with constant load model.

Transmission line overload alleviation and maintenance of system voltages within limits under stressed condition has been formulated as a non-linear optimization problem taking into consideration the demand-side reserves/demand response offers. Before presenting the problem formulation of DAMC with demand response offers, load modeling has been described.

2. 1 . Load Modeling

The strong and robust nature of the power system networks in the early 1980's helped keep the voltage profile near to its nominal value, which made the modeling of loads as voltage dependent almost redundant. Post 1980, power systems were subjected to operation scenarios with low voltages, including the extreme ones threatening voltage stability. As mentioned in [25]-[27], voltage dependent load models became essential in such situations, without which the results were found to be impractical.

Generally, the loads are modeled as constant power loads. However, practical real and reactive loads are voltage dependent, which is even more true for the aggregated load representation as seen from the EHV buses. This could primarily be accounted for the fact that the effects of sub-transmission and distribution system are also reflected in this equivalent load representation. More realistic approach is brought into this present work by modeling loads as voltage dependent [27]. For steady state analysis, ZIP (polynomial) load model or exponential load model can be used. Here, the exponential load model has been used, where the active and reactive powers of the load bus are related to the bus voltage, through an exponential function,

$$P_{Dk} = P_{Dk}^{0}\left(\frac{V_k}{V_k^0}\right)^{np} \quad (1)$$

$$Q_{Dk} = Q_{Dk}^{0}\left(\frac{V_k}{V_k^0}\right)^{nq} \quad (2)$$

where k=1,2,...,N_D. N_D is number of loads/demands in the system. P_{Dk} is the active power load, Q_{Dk} is the reactive power load, V_k is the bus voltage magnitude, $P_{Dk}{}^0$, $Q_{Dk}{}^0$ and $V_k{}^0$ are the nominal values of the active, reactive power loads and the voltage magnitude at the k^{th} bus respectively. np and nq are voltage exponents which depend on the type and composition of the load.

Next, we discuss possible primary as well as supplementary objectives. Supplementary objectives are the ones which cannot be used in isolation. They need to be coupled with the primary objective function in order to formulate a multi-objective formulation.

2.2. Social Welfare Maximization including demand-side reserves/demand response offers (SWM)

In the presence of demand elasticity, the market is settled with social welfare maximization as objective. Presently, most of the electric power markets have introduced demand-side bidding in the market clearing process. The concept of maximizing social welfare can be applied for the centralized market with demand elasticity. This traditional social welfare includes the total surplus of generators and customers. In this case, the system operator optimally dispatches the generators in such a way that the social welfare is maximized while satisfying the operation and security related constraints. The CSPs or

DRPs can bid into the market in terms of fixed bids, linear bids or quadratic bids. In case of CAISO, the demand response offers (load reduction bids) exactly similar to generation bids are solicited. Hence, the modified social welfare is the traditional social welfare including demand response offers. This can be formulated as follows,

Maximize,

$$modified\ SW = \sum_{k=1}^{N_D} B_{Dk}(P_{Dk}) - \sum_{i=1}^{N_G} C_{Gi}(P_{Gi}) - \sum_{k=1}^{N_D} \left[a_k^{'} + b_k^{'}(P_{red,k}) + c_k^{'}(P_{shd,k})^2\right] \quad (3)$$

where

$$B_{Dk}(P_{Dk}) = d_k - e_k P_{Dk} - f_k P_{Dk}^2 \quad (4)$$

$$C_{Gi}(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (5)$$

i=1,2,...,N_G. N_G is number of generators, P_{Gi} is the power output from ith generator, P_{Dk} and $P_{red,k}$ are demand bids and amount of load reduction/demand response at bus k, $B_{Dk}(P_{Dk})$ is demand cost function at bus k, $C_{Gi}(P_{Gi})$ is cost function for generating real power P_{Gi}; d_k, e_k and f_k are demand coefficients of kth load bus; a_i, b_i and c_i are generation cost coefficients of ith generator; a'_k, b'_k and c'_k are the demand response cost coefficients of kth load bus, respectively.

2.3 Load Served Error (LSE) Minimization

When the loads are modeled as voltage dependent, it can be seen that an attempt to maximize social welfare results in load served (LS) reduction, through voltage reduction. Hence, to bring the load served (LS) to be equal to the nominal load (LS^0), a new objective called Load Served Error (LSE) minimization has been proposed. It is important to note that, this objective function is applicable only for voltage dependent loads, and is formulated as follows:

$$minimize \quad LSE = (LS - LS^0)^2 \quad (6)$$

'Load served' is the net amount of load supplied/served by the system, which is the difference between sum of cleared demand bids and the sum of cleared load reduction bids/demand response offers. Amount of load served (LS) with voltage dependent load modeling is evaluated as follows:

$$LS = \sum_{k=1}^{N_D} P_{Dk}^0 \left[\left(\frac{V_k}{V_k^0}\right)^{np}\right] - \sum_{k=1}^{N_D} P_{red,k}^0 \left[\left(\frac{V_k}{V_k^0}\right)^{np}\right] \quad (7)$$

where V_k, V_k^0 are available from optimization. P0red,k is the load reduction at nominal voltage. LS^0 is nominal load served, when SWM is optimized independently with voltage dependent load modeling. LS^0 is also unknown/variable and it is calculated by using the voltages obtained after optimizing the social welfare. LS^0 is evaluated as follows:

$$LS^0 = \sum_{k=1}^{N_D} P_{Dk} \left[\left(\frac{V_k}{V_k^0}\right)^{\frac{1}{np}}\right] - \sum_{k=1}^{N_D} P_{red,k} \left[\left(\frac{V_k}{V_k^0}\right)^{\frac{1}{np}}\right] \quad (8)$$

Improvement of system voltage increases the amount of load served. The LSE minimization objective can never be used as an independent objective, but can be used as a supplementary objective to ensure that load served reduction is prevented to the extent possible.

The above objectives can be fulfilled by optimal selection of control variables. The control variables considered for this problem are generator active power outputs, load demands and load reduction bids/demand response offers, generator bus voltage magnitudes, transformer tap settings and bus shunt susceptances.

2.4 Equality and inequality constraints of DAMC with demand response offers/ demand-side reserves

The equality and inequality constraints for the proposed DAMC are as follows:

2.4.1 Equality Constraints (Nodal power balance Constraints)

The power balance constraints include real and reactive power balances (typical load flow equations).

$$P_{Gp} - (P_{Dp} - P_{red,p}) = V_p \sum_{q=1}^{n} V_q (G_{pq} cos\delta_{pq} + B_{pq} sin\delta_{pq}) \quad (9)$$

$$Q_{Gp} - (Q_{Dp} - Q_{red,p}) = V_p \sum_{q=1}^{n} V_q (G_{pq} cos\delta_{pq} - B_{pq} sin\delta_{pq}) \quad (10)$$

In Eqs. (9) and (10), p=1,2,...,n. Where n is the number of buses in the system. In demand side bidding, load active power is adjusted and its reactive power is usually varies at a constant power factor (i.e., Q/P of load should be kept constant).

2.4.2 Generation capacity limits

The generator active power outputs are restricted by their lower and upper real power generation limits as,

$$max[P_{Gi}^{min}, P_{Gi}^{0} - RR_{Gi}^{down}] \le P_{Gi} \le min[P_{Gi}^{max}, P_{Gi}^{0} + RR_{Gi}^{up}] \quad i = 1,2,\ldots,N_G \quad (11)$$

where P_{Gi}^{0} is power output of i^{th} generator at previous hour; P_{Gi}^{max} and P_{Gi}^{min} are maximum, minimum generation capacities, and RR_{Gi}^{up}, RR_{Gi}^{down} are ramp up and ramp down limits of i^{th} generator in MW/hr.

The generator reactive power is limited by lower and upper reactive power generation as

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \quad i = 1,2,\ldots,N_G \quad (12)$$

where Q_{Gi} is reactive power output of generator i, Q_{Gi}^{max} and Q_{Gi}^{min} are the maximum and minimum reactive power capacities of generator i.

Generator voltage magnitudes (VG) are limited by

$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} \quad i = 1,2,\ldots,N_G \quad (13)$$

2.4.3 Demand limits

$$P_{Dk}^{min} \le P_{Dk} \le P_{Dk}^{max} \quad i = 1,2,\ldots,N_G \quad (14)$$

where P_{Dk}^{max} and P_{Dk}^{min} are the parameters submitted as part of demand side bids (maximum and minimum demand bids at bus k). In case of an inelastic demand, the two limits become equal i.e., $P_{Dk}^{min} = P_{Dk}^{max} = P_{Dk}$.

2.4.4 Demand-side Reserve (Demand Response) Constraints

This constraint provides relation between $P_{red,k}$ and P_{Dk}.

$$0 \le P_{red,k} \le \left(P_{Dk} - P_{Dk}^{min}\right) \qquad k = 1,2,\ldots,N_D \tag{15}$$

that is

$$0 \le P_{red,k} \le P_{red,k}^{max} \qquad k = 1,2,\ldots,N_D \tag{16}$$

where $P_{red,k}^{max}$ is the maximum demand response offer provided by loads.

2.4.5 Transformer Constraints

$$T_t^{min} \le T_t \le T_t^{max} \qquad t = 1,2,\ldots,N_T \tag{17}$$

where T_t stands for transformer tap setting.

2.4.6 Switchable VAR sources

The switchable VAR sources are also restricted by limits as follows,

$$Q_{cs}^{min} \le Q_{cs} \le Q_{cs}^{max} \qquad t = 1,2,\ldots,N_c \tag{18}$$

2.4.7 Security Constraints

These include the limits on the load bus voltage magnitudes and line flow limits.

$$V_{Dk}^{min} \le V_{Dk} \le V_{Dk}^{max} \qquad k = 1,2,\ldots,N_D \tag{19}$$

$$\left|S_{pq}\right| \le S_{pq}^{max} \tag{20}$$

where S_{pq} is MVA flow and S_{pq}^{max} denotes thermal limit of the line connecting buses p and q.

In this paper, single objective optimization considering each of the above objectives at a time is solved using Genetic Algorithm (GA). The variables in GA have been represented in binary strings and the corresponding description about their representation, encoding of chromosome and genetic operators can be found in [28].

A penalty function [29] is added to the objective function, if the functional operating constraints violate any of the limits. A review of constraints handling techniques is presented in [28].

3 Multi-objective DAMC with Demand-side Reserves

Most of the power system problems involve multiple and conflicting objectives to be optimized simultaneously. One of the emergent areas in which meta-heuristic techniques have become increasingly popular is multi-objective optimization. The multi-objective optimization problem is minimization or maximization of multiple evaluation criteria having conflict with each other. The solution which is an optimum for one criterion may not be optimal for multi-objective optimization, because the multiple criteria have trade-off relationships with each other. In this paper, Strength Pareto Evolutionary Algorithm 2+ (SPEA 2+) has been used to solve the optimization problem, which provides a set of points on the pareto optimal front. The user can then select the point which suits his/her needs in the best possible manner. Alternatively, best compromise solution can be provided through a fuzzy min-max approach [30].

SPEA 2+ is a new multi-objective genetic algorithm that improves the search performance of SPEA 2. SPEA 2+ is SPEA 2 with the addition of mating selection, neighborhood crossover and application of two archives to maintain diverse solutions in the design variable space and the objective space [31]. The description of mating selection and neighborhood crossover is presented in [31]-[32]. The algorithm of SPEA 2+ is described in [33]-[34].

SPEA 2+ gives the Pareto optimal set of non-dominated/non-inferior solutions (Pareto optimal front). The extraction of best compromise solution from the Pareto optimal front is obtained after the optimization, known as post-optimal process, can be of fuzzy membership approach or pseudo-weight vector approach [35]. In this paper, fuzzy membership/fuzzy min-max approach [30] is used.

4 Results and Discussion

IEEE 30 and 300 bus systems are used to test the effectiveness of the proposed DAMC approach.

4.1 Simulation Results on IEEE 30 Bus System

IEEE 30 bus system [29] has been used to test the effectiveness of the proposed DAMC approach with demand-side reserves. The test system consists of 6 generators, 21 loads and 41 branches, of which 4 branches have tap setting transformers. Buses 10, 12, 15, 17, 20, 21, 23, 24 and 29 have been [29] selected as shunt compensation buses. It is assumed that, system operator receives generator offers, demand bids and load reduction bids/demand response offers from customers to perform the DAMC. It has been further assumed that all the generators and loads participate in the DAMC.

In genetic algorithm, the encoding is performed using different gene lengths for each set of control variables, depending on the desired accuracy. Five generator active power outputs, 21 power demands, 21 load reduction/demand response powers, 6 generator bus voltage magnitudes, 4 transformer tap settings and 9 bus shunt susceptances are considered as control variables. The gene length for unit of generation or demand or demand side reserves is 12 bits, generator voltage magnitude is 8 bits, and they are treated as continuous controls. The lower and upper limits for transformer tap settings are 0.9 p.u. and 1.1 p.u. respectively, and the step size is 0.0125p.u. Hence, they can take 17 discrete values and each one is encoded using 5 bits. The bus shunt susceptances can take 6 discrete values each one is encoded using 3 bits, the lower and upper limits are 0.0 p.u. and 0.05 p.u. respectively, and the step size is 0.01 p.u. Therefore, the chromosome length for proposed DAMC approach is (5×12)+(21×12)+(21×12) +(6×8)+(4×5)+(9×3) = 659. In this paper, exponential load modeling with np = 1 and nq = 2 has been used [27].

DAMC problem with demand response offers has first been solved using single objective optimization and later using multi-objective SPEA 2+ approach. The effect of realistic voltage dependent load modeling on the same has been evaluated. In each case, the algorithm has been stopped when maximum number of generations is reached or all the population members have assumed similar fitness values.

The GA and SPEA 2+ parameters that have been used are shown in Table 1. The population and archive sizes have been selected, after some trials. The developed SPEA 2+ uses population size of 100 chromosomes. A set of strong dominated solutions is selected from population of chromosomes to form the Pareto optimal set. If the Pareto optimal set size exceeds maximum size, a hierarchical clustering technique is used to limit its size.

Table 1: GA and SPEA 2+ Parameters

Paramaters	GA	SPEA 2+
Chromosome length	659	659
Population size (N)	60	100
Archieve size ($\overline{N}$)	—	100
Reproduction Operator	Roulette Wheel	Mating
Crossover operator	Uniform	Neighborhood
Mutation operator, Mutation rate	Bitwise, 0.001	Bitwise, 0.001
Maximum generations	200	100

Two different cases - one with constant load modeling and the other with voltage dependent load modeling have been simulated at stressed loading conditions with 140% loading (emergency situation). This emergency situation can be because of increased load, generator outage and transmission line outage etc. Here, 140% loading is assumed only to show how the demand response offers/demand-side reserves are utilized in the market clearing process. It is observed that, the demand elasticity bids alone cannot yield a feasible optimal solution. Load reduction bids/demand response offers have used to obtain the same. The results have been described as follows:

4.1.1 Case 1: DAMC with demand response offers considering constant load modeling

Table 2 presents the objective function values obtained when Social Welfare Maximization including load reduction cost/demand response offers (SWM) is optimized, considering constant load model. The variables are the generator active power outputs, load demands, and the demand response offers at corresponding buses.

When SWM objective is optimized, the optimum SW obtained is 367.2945 \$/hr, and the amount of load reduction (P_{red}) is 17.4815 MW. The net amount of load served is 370.4629 MW. The net amount of load supplied is the difference between the total demand supplied and the amount of load reduced.

Table 2: DAMC with demand response offers considering constant load modeling for IEEE 30 bus system.

Objective function value	SWM
Social Welfare (\$/hr)	**367.2945**
Load Reduction (MW)	17.4815
Generation Supplied (MW)	384.8818
Demand Supplied (MW)	387.9084
Line Losses (MW)	14.4548
Net Load Supplied (MW)	370.4269

4.1.2 Case 2: DAMC with demand response offers considering voltage dependent load modeling

Any voltage between the minimum and maximum limits is acceptable from operations point of view. However, with voltage dependent load modeling it can be seen that an attempt to maximize the social welfare will result in load served reduction through voltage reduction. Hence, social welfare maximization cannot be the sole objective for these type of loads. There are two alternative approaches to prevent this load reduction. The first is through the appropriate enforcement of hard constraints on voltages, and the second being through the proposed multi-objective optimization approach. The first approach requires that the minimum voltage limit should be nominal voltage of the load bus so that, satisfaction of the same will not allow load reduction. Apparently this logic is perfect. However, achieving the same through the proposed multi-objective optimization alternative provides us with significant advantages. Distributed nature of the reactive resources do not normally allow perfect voltage control at all the buses simultaneously. In such situations, the former optimization technique may simply result in an infeasible solution. The proposed approach however attempts to keep the loads near to their nominal values, thereby having better chances of providing a feasible solution. The proposed approach is flexible, attempting to strike a compromise between two conflicting requirements. Such a compromise by very nature, results in a feasible solution, unlike that in the previous approach.

Table 3 presents the objective function values, when individual and combined objectives were optimized, considering voltage dependent load models. When social welfare maximization is the sole objective, voltage profile is pushed down to maximize the social welfare, as a result the net amount of load served (LS) is decreased. The voltage profile obtained in this case is shown in Table 4. The obtained optimum values are: social welfare is 411.5994 \$/hr, amount of load reduced (P_{red}) is 14.6827 MW, and the net amount of load served (LS) is 357.8960 MW. Here, the nominal load (LS^0) is calculated using Eq. (8) with the voltage profile as given in Table 4, the nominal load (LS^0) is found to be 371.9697MW. In this case, the net amount of load served comes out to be 357.8960 MW, which is less than the nominal load of 371.9697 MW.

Table 3: DAMC with demand response offers/demand-side reserves considering voltage dependent load modeling using SPEA 2+ for IEEE 30 bus system.

Objective function value	SWM	SWM & LSE min.
Social Welfare (\$/hr)	**411.5994**	**382.1684**
Load Reduction (MW)	14.6827	15.7126
Generation Supplied (MW)	371.4425	382.6713
Demand Supplied (MW)	372.5787	386.2266
Line Losses (MW)	13.5464	12.1573
Net Load Supplied (MW)	357.8960	**370.5140**

Table 4: Voltage profile of the system when SWM is considered as an independent objective with voltage dependent load modeling

Bus No.	Voltage	Bus No.	Voltage	Bus No.	Voltage
1	1.0029	11	0.9459	21	0.9248
2	1.0029	12	0.9383	22	0.9262
3	0.9624	13	1.0061	23	0.9471
4	0.9941	14	0.9809	24	0.9207
5	0.9718	15	0.9707	25	0.9231
6	1.0429	16	0.9678	26	0.9024
7	0.9845	17	0.9410	27	0.9348
8	0.9799	18	0.9451	28	0.9826
9	0.9843	19	0.9336	29	0.9153
10	0.9646	20	0.9348	30	0.9016

Therefore, SWM objective should not be optimized independently. Hence, another new objective called Load Served Error (LSE) minimization has been proposed, which brings the amount of load served approximately equal to the nominal load. However, as discussed earlier LSE is only a supplementary objective, and should never be used alone. Hence, multi-objective DAMC is proposed.

In order to get a better compromise solution SWM, and LSE minimization objectives are optimized simultaneously using multi-objective SPEA 2+ approach. In this case, the voltages are pushed to nominal to get the load served to be nearly equal to nominal load (LS^0). Then the compromise solution has SW of 382.1684 \$/hr, P_{red} of 15.7126 MW and the net amount of load served (LS) of 370.5140 MW, which is nearly equal to the nominal load (LS0) of 371.9697 MW. The LSE obtained in this case is 1.4557 MW. Here, LSE minimization objective is combined with SWM objective to get the load served (LS) approximately equal to the nominal load served. Figure 1 shows the Pareto optimal front of SWM and LSE minimization with voltage dependent load modeling.

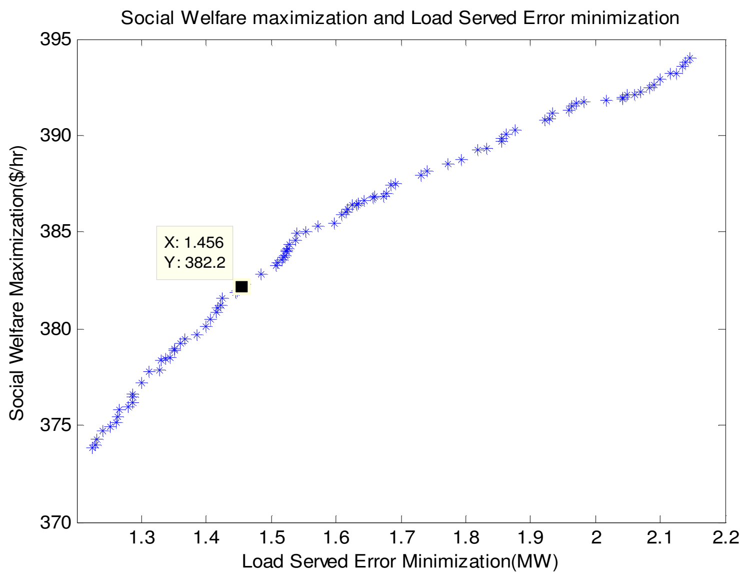

Figure 1: Pareto optimal front of SWM and LSE minimization with voltage dependent load modeling using SPEA 2+.

4.2 Simulation Results on IEEE 300 Bus System

IEEE 300 bus system [37] consists of 69 generators, and 411 branches of which 62 branches are tap setting transformer branches, and 12 buses have been selected as shunt compensation buses. The total load in the system is 23246.86MW. The two case studies including constant and voltage dependent load models are presented next:

4.2.1 Case 1: DAMC with demand response offers considering constant load modeling

Table 5 presents the objective function values obtained when SWM is optimized considering the constant load modeling. In this case, the optimum SW obtained is 316982.6133\$/hr, and the amount of load reduction (P_{red}) is 940.6605MW. The net amount of load served is 22220.8609MW.

Table 5: DAMC with demand response offers considering constant load modeling for IEEE 300 bus system.

Objective function value	SWM
Social Welfare ($/hr)	**316982.6133**
Load Reduction (MW)	940.6605
Generation Supplied (MW)	23053.0655
Demand Supplied (MW)	23161.5214
Line Losses (MW)	832.2046
Net Load Supplied (MW)	22220.8609

4.2.2 Case 2: DAMC with demand response offers considering voltage dependent load modeling

Table 6 presents the objective function values obtained when individual and combined objectives were optimized, considering voltage dependent load models. When the SWM is optimized independently, then the obtained optimum values are: SW is 390054.6291$/hr, amount of load reduced (P_{red}) is 913.3582MW, and the net amount of load served is 21652.5083MW, which is less than the nominal load of 22231.0319MW. Therefore, the SWM objective should not be optimized independently.

Table 6: DAMC with demand response offers/demand-side reserves considering voltage dependent load modeling using SPEA 2+ for IEEE 300 bus system.

Objective function value	SWM	SWM & LSE min.
Social Welfare ($/hr)	**390054.6291**	**362440.5136**
Load Reduction (MW)	913.3582	929.2377
Generation Supplied (MW)	22469.4640	23033.8191
Demand Supplied (MW)	22565.8665	23155.4130
Line Losses (MW)	816.9557	807.6438
Net Load Supplied (MW)	21652.5083	**22226.1753**

In order to obtain the better compromise solution, SWM and LSE minimization objectives are optimized simultaneously using multi-objective SPEA 2+ approach. Then, the compromise solution has SW of 362440.5136$/hr, P_{red} of 929.2377MWand the net amount of load served (LS) of 22226.1753MW, which is nearly equal to the nominal load of 22231.0319MW. The LSE obtained in this case is 4.8566MW. Here, LSE minimization objective is combined with SWM objective to get the load served approximately equal to the nominal load served.

In view of the above, the ISO is prompted to employ appropriate objective function for DAMC with demand response offers/ demand-side reserves.

5 Conclusions

The paper develops a multi-objective day-ahead market clearing mechanism with demand response offers, considering realistic voltage dependent load models. The objectives considered in this paper are Social Welfare Maximization including demand response offers/load reduction cost (SWM), and Load Served Error (LSE) minimization. Investigations on IEEE 30 and IEEE 300 bus systems have been provided to support the appropriateness of choice of multiple objectives to be used with voltage dependent loads. When the loads are modeled as voltage dependent, then it is shown that SWM is not valid single objective with this load model, due to reduction in load served. With voltage dependent load modeling, SWM and LSE minimization are best suited multiple objectives to be optimized simultaneously. The Pareto curve provided by SPEA 2+ allows the decision maker to make a better informed decision regarding the compromise between the conflicting objectives.

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