International Journal of Electrical and Computer Engineering (IJECE)
Vol. 8, No. 5, October 2018, pp. 3427~3435
ISSN: 2088-8708, DOI: 10.11591/ijece.v8i5.pp3427-3435

Multi-Objective based Optimal Energy and Reactive Power Dispatch in Deregulated Electricity Markets

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Article Info

Article history:

Received Apr 9, 2018
Revised Jun 8, 2018
Accepted Jun 21, 2018

Keyword:

Evolutionary algorithms
Load modeling
Market clearing
Multi-objective optimization
Social welfare

ABSTRACT

This paper presents a day-ahead (DA) multi-objective based joint energy and reactive power dispatch in the deregulated electricity markets. The traditional social welfare in the centralized electricity markets comprises of customers benefit function and the cost function of active power generation. In this paper, the traditional social welfare is modified to incorporate the cost of both active and reactive power generation. Here, the voltage dependent load modeling is used. This paper brings out the unsuitability of traditional single objective functions, e.g., social welfare maximization (SWM), loss minimization (LM) due to the reduction of amount of load served. Therefore, a multi-objective based optimization is required. This paper proposes four objectives, i.e., SWM, load served maximization (LSM), LM and voltage stability enhancement index (VSEI); and these objectives can be combined as per the operating condition. The simulation studies are performed on IEEE 30 bus test system by considering the both traditional constant load modeling and the proposed voltage dependent load modeling.

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NOMENCLATURE

a_0	Availability price offer (in \$).
N_G	Number of generators participating in the market clearing.
N_D	Number of load demands participating in the market clearing.
np, nq	Voltage exponents.
P_{Gi}^k	Active power output from ith generating unit at hour k.
RR_i	Ramp rate limits of ith generating unit.
$C_{Gi}(P_{Gi})$	Cost function for generating the active power P_{Gi}.
$B_{Di}(P_{Di})$	Demand function at bus i.
a_i, b_i, c_i	Generator cost coefficients of ith generator bus.
d_i, e_i, f_i	Demand function coefficients of ith load bus.
$Q_{1,i}$	Operating region between ($Q_{min} < Q \leq 0$).
$Q_{2,i}$	Operating region between ($Q_{base} < Q \leq Q_A$).
$Q_{3,i}$	Operating region between ($Q_A < Q \leq Q_B$).
ρ_e^i	Bid price of ith generator.
ρ_e^{MCP}	Market Clearing Price (MCP) of energy only market.

1. INTRODUCTION

Independent System Operator (ISO) collects the half-hourly/hourly supply bids from the generation companies (GENCOs) and demand bids from distribution companies (DISCOs) for solving the day-ahead

(DA) market clearing (generation and load demand schedule) problem. In the deregulated power industry, establishing an effective and equitable reactive power market with the consideration of the voltage security problem is very important to provide a reliable power system. Ancillary services are necessary to support the transmission of electric power from producers to customers. These services are needed to ensure that the ISOs are able to meet their responsibilities and to enhance the system maintenance, reliability and quality.

Reference [1] proposes a new structure for joint energy and reactive power market to resolve the difficulties pertaining interactions between the active and reactive power markets. A stochastic multi-objective optimization (MOO) algorithm for simultaneous active and reactive power dispatch in electricity markets with wind power volatility is proposed in [2]. Reference [3] proposes a dispatching reactive power model based on optimal power flow (OPF) by which both the cost of procuring reactive power as auxiliary service and the losses of active power are minimized. Reference [4] deals with the obtaining, decomposition and deduction of behavior rules of spot prices, and their influence on established contractual relationships in a deregulated market environment which allows the power purchase agreements between consumers and producers. A new reactive power market structure is presented in [5] to improve the reactive power market and create fair competition between producers. An efficient stochastic framework to develop a coupled active and reactive market in smart distribution systems is proposed in [6]. Reference [7] presents an algorithm for procuring reactive power from reactive resources based on a reactive power pricing structure. Reference [8] proposes two new active/reactive dispatch models to be used by System Operators in order to assign reactive power and to validate the economic schedules prepared by Market Operators together with the injections related with bilateral contracts. A deterministic model of complete generation-grid system to obtain the active and reactive power spot prices and their decomposition, to deduce general rules concerning their behaviour, and to analyze the effect of the applied constraints is proposed in [9]. A new probabilistic algorithm for optimal reactive power provision in hybrid electricity markets is proposed in Reference [10].

The real and reactive power dispatch models used by the ISOs to assign the reactive power and to validate the economic schedules prepared by the market operators with bilateral contracts is described in Reference [11]. A multi-objective based day-ahead reactive power market clearing model is proposed in Reference [12]. A joined real and reactive power market clearing in the restructured electrical systems is presented in Reference [13]. In [14], uses multi-objective directed bee colony optimization algorithm to optimize the combined emission and generation cost. An optimal reactive power scheduling problem in restructured power system using the evolutionary based Cuckoo Search Algorithm is proposed in [15]. A meta-heuristic based approach to solve the Optimal Reactive Power Dispatch problem using Crow Search algorithm is proposed in [16].

From the literature review, it can be observed that most of the works in the literature doesn't considers the energy and reactive markets, simultaneously. Therefore, the motivation of this paper is to clear the market by optimizing both the energy and reactive powers, simultaneously, and considering the voltage dependent load modeling. In this paper, it is considered that the traditional single objectives such as Social Welfare Maximization (SWM) and Loss Minimization (LM) objectives are not feasible with voltage dependent load modeling due to the reduction in the amount of load served (LS). A MOO is required for solving the problems of this kind.

2. SEPARATE ACTIVE AND REACTIVE POWER MARKET CLEARING

Typically, the market clearing problem is solved by the system operator to know the accepted offers and bids and the resulting Market Clearing Price (MCP).

2.1. Centralized separate energy market

The concept of social welfare maximization (SWM) can be applied for the centralized electricity market with demand elasticity. The social welfare (SW) is the total surplus of generators and customers. The system operator solves the SWM [17] objective function, and it is formulated as,

$$SWM = maximize \left[\sum_{i=1}^{N_D} B_{Di}(P_{Di}) - \sum_{i=1}^{N_G} C_{Gi}(P_{Gi})\right] \quad (1)$$

Where

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

$$B_{Di}(P_{Di}) = d_i - e_i P_{Di} - f_i P_{Di}^2 \quad (3)$$

2.2. Reactive power market clearing

The synchronous generator's capability curve [18] consists of 3 operating regions. These regions reflect the armature, field current heatings and the under-excitation limits.

2.2.1. Reactive power bid structure

Similar to the real power, synchronous generators bids for the reactive power [18]. These bids consist of a capacity component which is paid in advance for their readiness to absorb/ produce the reactive power.

Expected Payment Function (EPF): The reactive power payment of generators consists of different cost components depending upon their operating regions. EPF is a mathematical formulation of generator reactive power cost components of generator's expectation of payment towards utilization, capacity and compensation components. Figure 1 depicts the EPF of a generating unit, as a function of amount of reactive power output. The terms of EPF i.e., opportunity cost, cost of loss are presented in Reference [18].

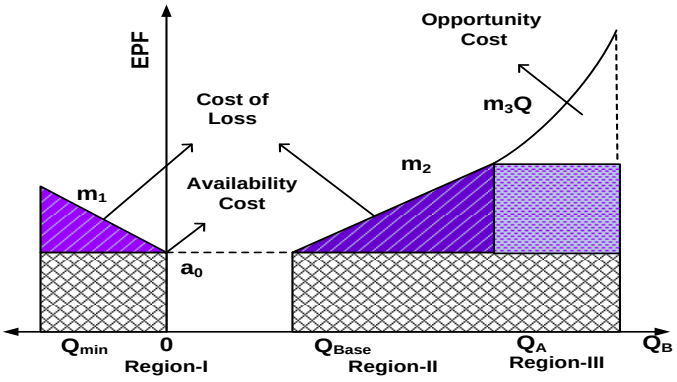

Figure 1. Structure of reactive power offers from the generating units

Figure 1 depicts the operating regions of generator on the reactive power coordinates and these regions are clearly presented in Reference [19]. The expected payment function (EPF) of a generator is expressed as,

$$EPF_i = a_{0,i} + \int_{Q_{min}}^{0} m_{1,i} dQ_i + \int_{Q_{base}}^{Q_A} m_{2,i} dQ_i + \int_{Q_A}^{Q_B} m_{3,i} dQ_i \quad (4)$$

Where a_0, m_1, m_2 and m_3 in the above equation represent different components of reactive power cost offered by the generator. m_1 is cost of loss price offer for operation in the under-excited mode ($Q_{min} \leq Q \leq 0$) (\$/Mvar-h), m_2 is cost of loss price offer for the operating in region ($Q_{base} \leq Q \leq Q_A$) in (\$/Mvar-h), and m_3 is opportunity price offer, for operating in region ($Q_A \leq Q \leq Q_B$) ((\$MVar-h)/MVar-h). The Total Payment Function (TPF) is expressed as [20], The last term in equation 5 represents the LOC payment.

$$TPF = \sum_{i=1}^{N_G} \left[\begin{matrix} \rho_0 W_{0,I} - \rho_1 W_{1,i} Q_{1,i} + \rho_2 W_{2,i} \left(Q_{2,i} - Q_{base,i}\right) + \rho_2 W_{3,i} \left(Q_{3,i} - Q_{base,i}\right) \\ + \frac{1}{2} \left(\rho_3 W_3 \left(Q_{3,i}^2 - Q_{base,i}^2\right) \right) \end{matrix} \right] \quad (5)$$

3. DESIGN OF COUPLED ACTIVE AND REACTIVE POWER MARKET CLEARING

In this section, different objective functions for the coupled ARPMC are proposed.

3.1. Loss opportunity cost (LOC) formulation

The LOC of a generator plays a vital role in the reactive power scheduling and pricing [19]. To use the LOC in Equation (7), the results of separate energy dispatch are required. Therefore, the separate energy dispatch must be performed before the coupled ARPMC problem. Here, the LOC of a generator, which is

forced to produce the reactive power, can be expressed as [20]:

$$LOP_G^i = \begin{cases} \rho_e^{MCP} - \rho_e^i & if\ \rho_e^{MCP} > \rho_e^i \\ 0 & if\ \rho_e^{MCP} \le \rho_e^i \end{cases} \quad (6)$$

$$LOC_G^i = max\left[0, LOP_G^i\left(P_{G0}^i - P_G^i\right)\right] \quad (7)$$

The TPF for reactive power compensation in coupled ARPMC consists only operation and availability payments [18], and this can be expressed as,

$$TPF = \sum_{i=1}^{N_G}\left[\rho_0 W_{0,I} - \rho_1 W_{1,i} Q_{1,i} + \rho_2 W_{2,i}\left(Q_{2,i} - Q_{base,i}\right)\right] \quad (8)$$

3.2. Load modeling

Generally, the active and reactive power loads are modeled as the constant power loads. But, they are voltage dependent [21] in the practical real time operation. In this paper, for the sake of simplicity, exponential load demand model is used, and it can be expressed as,

$$P_{Li} = P_{Li}^0\left(\frac{V_i}{V_i^0}\right)^{np} \quad (9)$$

$$Q_{Li} = Q_{Li}^0\left(\frac{V_i}{V_i^0}\right)^{nq} \quad (10)$$

where *np* and *nq* are depend on composition and type of the load demand. The objective functions considered in the centralized DA coupled ARPMC problem are as follows.

3.3. Social welfare maximization (SWM) in coupled ARPMC

In this paper, an OPF based approach is used to find the market clearing price (MCP), and to get the active and reactive power schedules that satisfy the system operation requirements. In coupled ARPMC model, the objective is to maximize social welfare (SW). SWM objective function can be formulated as [17], SWM is an important objective under all system operating conditions.

$$\text{maximize, } SW = \sum_{i=1}^{N_D} B_{Di}(P_{Di}) - \sum_{i=1}^{N_G} C_{Gi}(P_{Gi}) + TPF + \sum_{i=1}^{N_G} LOC_i(Q_{Gi}) \quad (11)$$

3.4. Loss minimization (LM)

The goal of this objective is to find the optimal settings of control variables which result in optimum transmission losses. The LM objective is suitable only for the constant load modeling at light loading condition. If load demands are modeled as voltage dependent, the SWM and LM objectives lead to the load served (LS) reduction through the voltage reduction. This LM objective is expressed as [22],

$$LM = 0.5\sum_{i,j}\left[G_{ij}\left(V_i^2 + V_j^2 - 2V_iV_jcos\left(\delta_i - \delta_j\right)\right)\right] \quad (12)$$

3.5. Amount of load served maximization (LSM)

The practice, the load demands are the function of voltages, therefore the voltage dependent load modeling is utilized. The improvement of system voltages increases the amount of load served (LS). Under the voltage dependent load modeling, the LSM objective is appropriate at light loading conditions, and it is formulated as Equation (13). This LSM objective will never be used as an independent objective.

$$LSM = \sum_{i=1}^{n} P_{Li}^0\left(\frac{V_i}{V_i^0}\right)^{np} \quad (13)$$

3.6. Voltage stability enhancement index (VSEI)

To monitor the voltage stability in the system, L-index [23] of the load/demand buses is considered. L-index/VSEI uses the information from the power flow and is in the range of 0 (no load) to 1 (voltage collapse). L-index presents the stability of complete system, and it is expressed as,

$$L_j = \left|1 - \sum_{i=1}^{ng} F_{ji} \frac{E_i}{E_j}\right| \quad (14)$$

$$L - index = VSEI = \sum_{j=ng+1}^{n} L_j^2 \quad (15)$$

where j = ng + 1, ..., n. The values of F_{ji} are calculated from the Y-Bus matrix [18]. In the case of voltage dependent load modeling, the L-index/VSEI minimization objective improves the voltage profile of the system and hence the amount of load served (LS).

3.7. Equality and inequality constraints for the coupled ARPMC problem

3.7.1. Equality constraints

The nodal power balance constraints include the active and reactive power balance equations. They are expressed as,

$$P_{Gi} - P_{Di} = \sum_j \left[V_i V_j Y_{ij} cos\left(\theta_{ij} + \delta_j - \delta_i\right)\right] \quad (16)$$

$$Q_{Gi} - Q_{Di} = \sum_j \left[V_i V_j Y_{ij} sin\left(\theta_{ij} + \delta_j - \delta_i\right)\right] \quad (17)$$

3.7.2. Generator constraints

The generator outputs are limited by their minimum and maximum active power outputs as,

$$\max\left[P_i^{min}, P_{Gi}^{k-1} - RR_i^{down}\right] \le P_{Gi}^k \le \min\left[P_i^{max}, P_{Gi}^{k-1} + RR_i^{up}\right] \quad (18)$$

Using the reactive power offers from the generators in different operating regions, the constraints are formulated as,

$$Q_i = Q_{1,i} + Q_{2,i} \quad (19)$$

$$W_{1,i} Q_{min,i} \le Q_{1,i} \le W_{1,i} Q_{base,i} \quad (20)$$

$$W_{2,i} Q_{base,i} \le Q_{2,i} \le W_{2,i} Q_{max,i} \quad (21)$$

$$W_{1,i} + W_{2,i} \le W_{0,i} \quad (22)$$

3.7.3. Demand limits

$$P_{Di}^{min} \le P_{Di} \le P_{Di}^{max} \quad (23)$$

$$Q_{Di}^{min} \le Q_{Di} \le Q_{Di}^{max} \quad (24)$$

3.7.4. Constraints on MCPs

$$W_{0,i} a_{0,i} \le \rho_0 \quad (25)$$

$$W_{1,i} m_{1,i} \le \rho_1 \quad (26)$$

$$W_{2,i} m_{2,i} \le \rho_2 \quad (27)$$

3.7.5. Generator reactive power constraints

$$Q_i^G \le \sqrt{\left(\frac{V_t^i E_{af}^i}{X_s^i}\right)^2 - P_{Gi}^2} - \frac{\left(V_t^i\right)^2}{X_s^i} \quad (28)$$

$$Q_i^G \le \sqrt{\left(V_t^i I_a^i\right)^2 - P_{Gi}^2} \quad (29)$$

The minimum limit of reactive power generation (Q_i^{min}) is given by,

$$Q_i^{min} \leq Q_i^G \tag{30}$$

3.7.6. Security constraints

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{31}$$

$$|S_{pq}| \leq S_{pq}^{max} \tag{32}$$

$$T_i^{min} \leq T_i \leq T_i^{max} \tag{33}$$

where S_{pq} is power flow in a line/MVA flow, S_{pq}^{max} is maximum power flow/thermal limit of the transmission line connected between the buses p and q. In this paper, the single objective optimization problem is solved using the Genetic Algorithm (GA), and the Strength Pareto Evolutionary Algorithm 2+ (SPEA 2+) algorithm is used to solve the coupled ARPMC problem. The fuzzy min-max approach [22] is used to determine the best-compromise solution [24].

4. SIMULATION RESULTS AND DISCUSSION

Here, IEEE 30 bus system [25] is considered to test the effectiveness and feasibility of the proposed centralized day-ahead (DA) coupled ARPMC problem. Five generator active powers, 21 power demands, 6 generator bus voltage magnitudes, 4 transformer taps and 9 bus shunt admittances are considered as the control variables. Here, the exponential (i.e., voltage dependent) load modeling with np = 1 and nq = 2 are utilized [18]. In this paper, they assumed as $Q_{Base} = 0.1*Q_{max}$; Q_A is restricted by armature or field heating limit; $Q_B = 1.5*Q_A$.

4.1. Case study 1: Solving the coupled ARPMC problem using the constant load modeling with light loading condition

Table 1 presents the control variables and objective function values for the Case Study 1 considering the single and multiple objectives with constant load modeling. When the SWM objective is optimized independently then the obtained SW is 602.88 $/hr, which is the optimum value, but VSEI and losses are deviated from the optimum. When LM objective is optimized independently, then the obtained optimum loss is 2.8977 MW, but the obtained SW and VSEI are not optimum. In the same way, when one objective function is optimized independently, then the other objectives are deviated from the optimum value. Therefore, there exists a conflict between the optimum objective values when one objective is optimized independently.

Table 1. Optimum Objective Function Values and Control Variables for Case Study 1

Objective & Control variables values	Single Objective ARPPC			MO ARPPC
	SWM	LM	VSEI	SWM & LM
P_{G1} (MW)	162.49	62.87	106.53	77.23
P_{G2} (MW)	49.67	72.10	67.99	64.44
P_{G5} (MW)	24.35	44.78	28.08	41.25
P_{G8} (MW)	26.78	33.42	34.60	34.96
P_{G11} (MW)	12.81	25.69	10.40	29.99
P_{G13} (MW)	12.89	29.48	26.04	25.73
V_1 (pu)	1.0206	1.0488	1.0947	1.0934
V_2 (pu)	1.0565	1.0424	1.1000	1.0959
V_5 (pu)	1.0088	1.0294	1.0994	1.0759
V_8 (pu)	1.0424	1.0247	1.0994	1.0847
V_{11} (pu)	1.0959	1.0953	1.0994	1.0888
V_{13} (pu)	1.0347	1.0965	1.0994	1.0988
Generation (in MW)	288.99	268.34	273.64	273.60
Amount of Load Served (in MW)	278.38	265.45	267.58	269.85
Generation Cost (in $/hr)	1336.75	1452.42	1346.83	1415.14
Demand Cost (in $/hr)	1939.63	1868.65	1891.58	1905.85
Social Welfare (in $/hr)	602.88	416.24	544.75	490.71
Total System Losses (in MW)	10.6041	2.8977	6.0629	3.7451
VSEI	0.12296	0.10702	0.06133	0.08647

In this case study, SWM and LM objectives are selected as the appropriate objectives for the DA multi-objective coupled ARPMC problem. As it is the normal operating condition, the VSEI value is away from the voltage collapse point, so there is no need to optimize the VESI objective. Figure 2 depicts the Pareto optimal set of SWM and LM objectives for multi-objective based coupled ARPMC problem for case study 1. In this paper, SPEA 2+ algorithm is used to obtain the Pareto optimal front. The best-compromise solution can be obtained by using the fuzzy min-max method. The obtained best-compromise solution has the social welfare of 490.71 $/hr, and the loss of 3.7451 MW, and this is the better compromise solution as compared to the single objective coupled ARPMC problem.

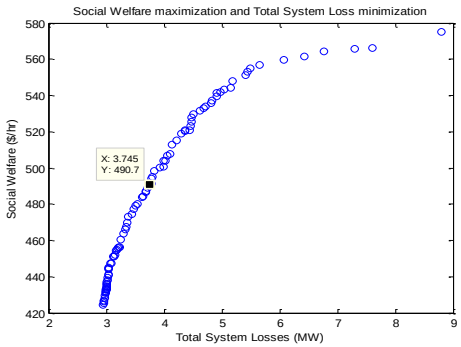

Figure 2. Pareto optimal front of SWM and LM objectives for case study 1

4.2. Case Study 2: Coupled ARPMC with voltage dependent load modeling at light loading condition

Table 2 depicts the control variables and objective function values obtained when the single and multiple objectives are optimized with voltage dependent load modeling. When the social welfare maximization objective is optimized individually, then the obtained optimum SW is 580.64 $/hr, and it is less than the social welfare obtained by constant load modeling, and load served (LS) is 259.46 MW, which is less than the load served by the constant load modeling. In this case, the SWM leads to reduction in voltages and therefore, the reduction in the amount of load served (LS). Due to this reason, the SWM should not be optimized individually. When the LSM objective is optimized individually, then the amount of load served (LS) is 314.90 MW, but the social welfare has decreased to 537.97 $/hr. As explained earlier, the LSM objective cannot be used as an independent objective.

Table 2. Optimum Objective Function Values and Control Variables for Case Study 2

	Single Objective ARPMC			MO ARPMC
Objective & Control Variables Values	SWM	LSM	VSEI	SWM & LSM
P_{G1} (MW)	144.89	120.08	158.36	132.50
P_{G2} (MW)	49.13	66.40	44.06	65.57
P_{G5} (MW)	23.94	47.50	45.15	36.95
P_{G8} (MW)	24.55	34.53	25.48	34.71
P_{G11} (MW)	15.07	28.07	10.06	10.32
P_{G13} (MW)	12.3	25.55	12.57	17.65
V_1 (pu)	0.9529	1.0718	1.0971	1.0768
V_2 (pu)	0.9959	1.0988	1.0912	1.0613
V_5 (pu)	0.95	1.1	1.0912	1.0796
V_8 (pu)	0.9541	1.1	1.1	1.0671
V11 (pu)	0.95	1.0988	1.1	1.0542
V13 (pu)	0.9512	1.0994	1.0941	1.0583
Generation (in MW)	269.87	322.13	295.68	297.70
Total System Losses (in MW)	10.4092	7.231	7.6954	8.0654
Generation Cost (in $/hr)	1278.40	1558.88	1412.36	1405.21
Demand Cost (in $/hr)	1859.05	2096.85	1970.38	1967.91
Social Welfare (in $/hr)	580.64	537.97	558.02	562.70
Amount of Load Served (in MW)	259.46	314.90	287.98	289.63
VSEI	0.29138	0.10192	0.07499	0.15043

When the VSEI objective is optimized individually, then the obtained optimum value is 0.07499, which is away from the voltage collapse point. Hence, there is no need to optimize VSEI at this operating

condition. Therefore, the SWM and LSM objectives are considered to be the appropriate multiple objectives to be optimized simultaneously. The compromise solution has social welfare of 562.70 $/hr and 289.63 MW of load served. Figure 3 depicts the Pareto optimal front of SWM and LSM objectives for the coupled ARPMC for Case Study 2.

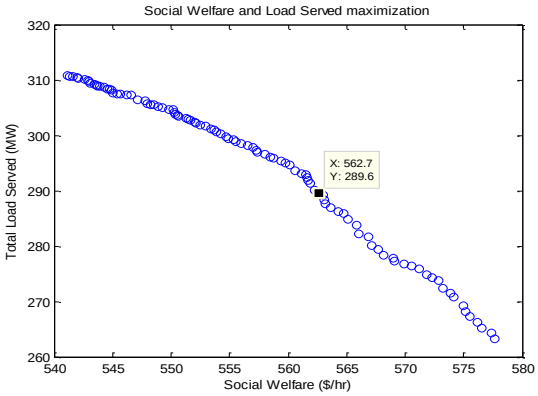

Figure 3. Pareto optimal set of SWM and LSM objectives for case study 2

In this paper, it has been shown that the LM and SWM objectives do not make valid single or joint objectives with this voltage dependent load model, due to reduction of load served. SWM and LSM are best suited objectives to be optimized simultaneously for light to moderate loading condition.

5. CONCLUSIONS

This paper has proposed a day-ahead (DA) multi-objective based centralized coupled active and reactive power scheduling and pricing mechanism using the practical voltage dependent load modeling. Different objective functions such as SWM, LSM, LM and VSEI are proposed. The SWM objective includes the offer cost for generators active power production, reactive compensations and the LOC payments for generators and benefit function of customers. In this paper, it is shown that SWM and LM objectives do not make valid single or multiple objectives with the voltage dependent load model, due to the reduction in the amount of load served (LS). Simulation studies on IEEE 30 bus test system shows the suitable and optimum choice of multiple objectives to be selected for a given operating condition. SWM and LSM objectives are appropriate for unstressed loading condition to moderate loading condition, with voltage dependent load modeling. The Pareto optimal front allows the system operator to make a better decision, by considering the better compromised solution.

ACKNOWLEDGMENTS

This research work is based on the support of “Woosong University Academic Research Funding-2018”.

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