A

Synopsis

On

Reactive Power Pricing in Restructured Power Systems

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Abstract

An adequate reactive power provision is one of the major concerns in a recent competitive electricity market, which is taken care by the Independent System Operator (ISO) in order to maintain the reliable, economical and secure operation of the power system. The voltage and reactive power are strongly coupled and hence the reactive power is essential to maintain the system voltage. Therefore optimal reactive power dispatch and pricing services have always been of great interest to researchers as well as system operators, especially after the restructuring of the power industry.

The research work is focused on optimal reactive power dispatch scheduling, optimal reactive power pricing with the objectives of active power transmission loss minimization, bus voltage deviation minimization and L index minimization as well as development of competitive reactive power market mechanism based on uniform auction mechanism.

The Grey Wolf Optimization (GWO) method is applied to solve the optimal reactive power dispatch problem. A more improved optimization algorithm called Hybrid Grey Wolf Optimization (HGWO) is also proposed to fast convergence. The results obtained by GWO and HGWO are compared with other methods of optimization mentioned in literature. The proposed approach is applied to IEEE 30 and IEEE 118 bus system, the optimal control variables and generator reactive power schedule is obtained for performance analysis.

The competitive reactive power market is developed with an objective function of total payment minimization. The generators and synchronous condensers are required to submit the reactive power offer (bids) and the ISO undertake a market-auction based on uniform pricing mechanism and compare it with pay as bid mechanism. The concept is demonstrated on IEEE 30 and 118 bus test systems.

Introduction and literature review

Electric power systems all over the world are moving toward deregulated electricity markets. In such power system operation, Reactive power and voltage control is one of the essential ancillary service. These ancillary service ensure proper voltage profile through injecting or absorbing reactive power. The reactive power play an important role for the following factors:

- Satisfy the requirement of reactive power load.
- Control bus voltage magnitude in a system wide.
- Decrease the transmission network active power loss.
- Relieve the transmission congestion.
- Provide sufficient reserve to ensure the security of system in emergency.

In vertically integrated power systems, reactive power pricing was done in a simple manner i.e. by imposing power factor penalties to HT consumers only. Reactive power support was regarded as the obligation of generators or grid owners. The system operators used a reactive power optimization program in which real power loss is taken as one of the objective function. In this situation, the reactive power suppliers and consumers could not make their own decision on how to use reactive power efficiently.

In the restructured environment, Reactive power support is provided by a variety of devices like generators, synchronous condensers belong to different entities. The different entities have their own costs and benefits for reactive power generation. There should be a mechanism to evaluate the reactive power resources and pricing it appropriately in different operating conditions.

In late 1990's, after the introduction of deregulation and subsequent restructuring of power system, the researchers started to view the reactive power management problem in both the perspectives: Technical and Economical. Initially, Chattopadhyay *et al.* [1] have presented an integrated framework to analyze the issues of reactive power planning along with its pricing. A simple bus-wise cost-benefit analysis (CBA) scheme is proposed which involves solving a modified optimal power flow problem (OPF) iteratively. A two-part reactive power spot-pricing scheme is formulated, by which the investment and operational costs can be recovered by the utility. Hao and Papalexpoulos [2] have discussed the technical and economic issues in determining reactive power pricing structures for an open-access environment. Some critical issues like reactive power reserves, capacitive and inductive reactive power, dynamic and static reactive power, reactive power capacity and production costs, joint cost allocation for reactive power are discussed. Weber *et al.* [3] have introduced a simulation based reactive power pricing mechanism in spot market environment by making a simple modification in the standard OPF in order to simulate the spot markets for real and reactive power. To achieve this, price-dependent load models are introduced for both real and reactive power. Ma *et al.* [4] have presented a flexible and efficient decoupled OPF-based approach for real-time calculation of price signals for active and reactive power that enables network security to become an element in the pricing process. The effects of voltage and thermal limits, as measures of system security, on the pricing structure are investigated. The voltage magnitude and power transmission limits are incorporated as non-equality constrains to incorporate the power system security issues. Zhu and Momoh [5] have proposed a method to study reactive power pricing and VAr source selection using the analytic hierarchical process, and presented a price structure to provide reactive power service and control based on the OPF approach. Momoh and Zhu [6] have also developed an integrated approach for reactive power pricing and control by dividing it into fixed and variable parts. The fixed part is the operational cost of reactive power service. The variable part of reactive power price is determined based on capability and contributions to the improvement of system performance such as security, reliability and economics. Muchayi and

Hawary [7] have presented a summary of some of the algorithms that have been proposed for pricing reactive power. The pricing rates are based on marginal costing of reactive power.

In 2002**,** Zhong and Bhattacharya [8] have proposed a competitive market for reactive power services and developed a system-wide market settlement approach based on uniform price auction. The payment mechanism based on uniform price is developed for the reactive power services from the generators and synchronous condensers. Moreover, a compromise programming method is suggested to optimize three objectives such as real power loss, deviation from contracted transactions and payment to reactive devices according to bid price. A possible structure of reactive bid is developed according to reactive capability of a generator and modelled within an OPF framework. Gross *et al.* [9] have examined the variable costs of reactive power production/absorption by a generator, identifying the most dominant cost component. The opportunity cost is identified as dominant component of the reactive power cost structure, which occurs when the generator reaches its capability curve and is required to reduce its real power generation in order to meet the reactive power requirements.

Hao [10], in 2003, has presented market-based solution for managing reactive power services using three distinct features: Obligating generation facilities to provide reactive services in proportion to their active power output; Optimizing and integrating the reactive procurement with market operation for least-cost solution; and taking into account the interactions of active and reactive powers for accurate calculation of the lost opportunity costs of generators. Chattopadhyay *et al.* [11] have proposed a spot pricing mechanism for reactive power that takes into account the contributions made by generators for providing reactive power to meet the current demand as well as for holding reactive power 'reserve' to maintain the system voltage stability to face the potential contingency.

Zhong *et al.* [12], in 2004, has proposed a localized competitive market for reactive power at the level of individual Voltage Control Areas (VCAs) based on the concept of electrical distance within a power system. The proposed reactive power market is settled on uniform price auction, using an improved optimal power-flow model. Rider and Paucar [13] have presented a methodology for calculating active and reactive power marginal prices by adopting a synchronous generators steady-state model with nonlinear reactive power limits in an improved OPF, and solved by a sequential linear programming technique enhanced by an improved predictor–corrector interior-point method. Chung *et al.* [14] have suggested a cost-based reactive power pricing, which can integrate the reactive power cost minimization and the voltage security problem into OPF by using Sequential Quadratic Programming (SQP). Xie *et al.* [15] have proposed decomposition of spot price using interior point nonlinear optimization methods. Wang and Xu [16] have presented a method of determining the minimum amount of reactive power required from generator.

In 2005, Federal Energy Regulatory Commission (FERC) have identified the reactive power and voltage support related problems and raised various concerns regarding the procurement practices and pricing policies for reactive power. FERC also gave some broad recommendations to address these problems and concerns for reliable and secure operation of power system.

El-Samahy *et al.* [17], in 2006, have presented a unified framework for reactive power management, in which, active and reactive power markets are decoupled, and proposed the division of reactive power management problem in two levels: Reactive power procurement and Reactive power dispatch.

Xu *et al.* [18], in 2007, have proposed an evaluation methodology based on voltage sensitivity and risk analysis from the perspective of voltage regulation. Sood *et al.* [19] have presented a generalized optimal model that dispatches reactive power in the pool along with privately negotiated bilateral and multilateral contracts by maximizing social benefit to determine the Locational Marginal Pricing (LMP). Pirayesh *et al.* [20] have presented a practical reactive power valuation method using a security constrained optimization model.

In 2008, El-Samahy *et al.* [21] have proposed a reactive power procurement model and argued that the reactive power services should be procured on seasonal (long term) basis. The reactive power procurement problem is formulated as a two-step optimization process: The first step consists of the determination of the marginal benefits of reactive power with respect to system security, which are then used in the second step to maximize a reactive power societal advantage function considering bids from service providers. Frías *et al.* [22] have proposed another comprehensive market approach for the procurement of the reactive power service. This approach identifies and weights the four different costs related with reactive power (i.e. VAR) procurement such as purchase of VAR capacity, generation re-dispatch to supply reactive power, energy losses and penalties for poor voltage quality and non-supplied energy, mainly in case of system contingencies. Feng *et al.* [23] have developed the must-run indices to analyze the market power problem for reactive power from both network and market aspects. Moreover, the issues of reactive power must-run capacity are investigated in power system operations and electricity markets. In Ref. [23]-[24], some methods are suggested for the measurement and assessment of *market power* possessed by potential reactive power suppliers by virtue of their strategic location in the power system.

Khazali *et al.* [25], in 2011, have developed a fuzzy adaptive PSO (FAPSO) based approach for clearing the reactive power market. The objective functions such as total payment function, voltage stability and voltage deviation are optimized by transforming them to membership functions and then a pseudo goal function is derived to express a unique objective function. De and Goswami [26] have proposed a circuit theory-based method to identify the different reactive power sources and allocates the amount of reactive power provided to different sources by using an improved Y-bus technique. Vyjayanthi and Thukaram [27] have presented a detailed analysis of all the reactive power sources and sinks scattered throughout the transmission system under normal and contingency conditions. Reddy *et al.* [28] have developed the multi-objective reactive power market clearing approach to optimize various objective functions such as total payment function, total real power loss, load served and voltage stability enhancement index.

Shaloudegi *et al.* [29], in 2012, have proposed a new locational marginal pricing (LMP) method based on remunerating distribution generation (DG) units for their participation in reduced amount of energy losses in distribution systems brought about by participation of all DG units in supplying demand. Recently, Sarkar and Khaparde [30], in 2013, have also suggested an OPF framework to determine two dimensional LMPs under the scarcity of reactive power. In contrast to classical OPF models, this OPF model also recognizes the dependence of the level of reactive power consumption on the level of active power consumption.

In [31], the pricing structure of reactive power is improved and it is aimed to modify the expected payment function (EPF) by making some changes in the reactive power transaction. Furthermore, in Ref. [32], an approximate decomposition of spot price as a new algorithm is derived to represent its effectiveness relative to the sensitivity analysis of nonlinear programming. In [33], firstly, ISO proposes candidate buses which have higher reactive locational marginal price (RLMP) in the case of reactive power production expansion planning. Then, annual profit-bid curve is drawn for each candidate bus and the reactive power associated with the maximum annual profit determines the optimal amount of produced reactive power at the location. Expected cost criteria and minimax regret are implemented to optimally determine the candidate locations. In [34] in addition of active and reactive power generation cost for synchronous generators, the capital cost of capacitors is also included in the OPF problem and its objective function. The OPF in this paper is solved by applying the ant colony search algorithm and sequential quadratic programming (SQP). Also, to obviate the problems associated with opportunity cost method, triangle method has been employed to have an accurate reactive power cost allocation. A novel reactive power market index is derived in [35] to have an effective measurement on the reactive market power for GENCOs by considering the deviation incentives of synchronous generators from the system optimal operation and their price altering ability in a competitive based market. Also, the bidding strategy problem that each GENCO is dealt with, it is solved using game theory. The impact of flexible AC transmission system (FACTS) controllers is taken into account in [36] along with their cost function. Then, a comparison between the cost of FACTS devices and other costs like fuel costs and reactive power cost is applied and their influence on the nodal price calculation is demonstrated. Ref. [37] has studied reactive power pricing in two objectives. Minimizing the reactive power payment and system energy loss for the market and also maximizing the voltage stability as the first objective and the second one refers to the probability of power line congestion through the reactive power market clearing that should be decreased. In addition, considering the allocated cost of active and reactive losses for each generator, a new approach is proposed for reactive power pricing based on tracing algorithm [38]. For the generation sector of the system, a deterministic model is applied in [39] in which it calculates the spot prices of active and reactive power in addition of their decomposition. So, general rules, including their behavior can be extracted and the influence of the constraints applied in the problem is assessed. In Ref. [40], it deals with the rules of spot prices and getting their decomposition. Their impact on constructing contractual relationships in a restructured environment is assessed that facilitates the agreements between producers and consumers in the case of energy purchasing. This is achieved by a model of the generation system in a deterministic manner. Ref. [41] has addressed the reactive power procurement cost by synchronous generator considering its two modes of operation which can be either below the nominal power factor within the generation limitation or above the nominal power factor operated as a condenser. For the operation below the nominal power factor, the capability curve of synchronous generator determines the reactive power cost and about operation as a condenser, capital cost and fuel cost are taken into account. In [42], a practical sheme in the context of reactive power pricing is proposed in which the increase in apparent power a raised from reactive power injection results in fair payment for the consumer and economic benefit to DG owners.

It can be seen from the above review of reactive power ancillary service pricing and management that most of the reported works focus either on developing suitable pricing methods that can effectively reflect the cost of reactive power production, or on proposing appropriate models for optimal reactive power procurement and/or dispatch. These models usually aim to achieve the minimization/maximization of a certain objective function (e.g. reactive power production cost minimization or social welfare maximization) using OPF models. An important requirement that has not been addressed in most of the existing or proposed models is the inclusion of system security in the reactive power procurement/dispatch process. The ISO typically seeks a reactive power solution that does not violate transmission security constraints, which are usually represented by voltage, thermal, and stability limits [35]. There is a need, then, for developing appropriate mechanisms for reactive power ancillary service management which aim at achieving optimal and secure reactive power provision and ensure a reliable and efficient network operation, while taking into account various market related issues.

Objectives

- To study current reactive power pricing policies of Indian power system and propose more efficient, voltage stability index based technique.
- To develop optimal reactive power dispatch algorithm for transmission active power loss minimisation using grey wolf optimization method.
- To proposed hybrid grey wolf optimization technique for fast convergence and batter values of objective functions.
- To perform comparative analysis of optimal reactive power pricing with three different objective functions, loss minimization, voltage deviation minimization and L-index minimization.
- To develop a competitive reactive power market model based on uniform price auction mechanism and compare it with pay as bid mechanism.

Scope of the work

- Pricing technique is analysed from the ISO and the grid operation perspective
- Steady state analysis is done in whole research work
- Reactive power pricing is analysed for reactive power support provided by synchronous generators and synchronous condensers in the power system (grid).
- Independent system operator is the sole authority for procuring this ancillary service

Mathematical modelling (definition) of the problem

The objective is to minimize the total real power loss in the transmission network

$$F = \sum_{k \in N_L} P_{k,loss} = \sum_{k \in N_L} g_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)]$$

$$k = (i, j); i \in N_B, j \in N_i$$

Where $P_{k,loss}$ is the real power loss in kth transmission line between i^{th} and j^{th} buses; N_L is Total number of transmission lines; gk is the conductance of the k^{th} *transmission* line; V_i, V_j are bus voltages in p.u. and δ_i, δ_j are phase angles in radians at the end buses i.e ith and j^{th} of the k^{th} transmission line, respectively.

System constraints in ORPD

The above objective functions F is minimized subject to all the system equality and inequality constraints as given below:

Equality constraints

$$P_{G,i} - P_{D,i} - V_i \sum_{j \in N_i} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0; \forall i \in N_B$$

$$Q_{G,i} - Q_{D,i} - V_i \sum_{j \in N_i} V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) = 0; \forall i \in N_B$$

Inequality constraints

$$T_k^{\min} \le T_k \le T_k^{\max}; k \in N_T$$

$$V_i^{\min} \le V_i \le V_i^{\max}; \forall \in N_B$$

$$Q_{G,i}^{\min} \le Q_{G,i} \le Q_{G,i}^{\max}; i \in N_{PV}$$

$$Q_{C,i}^{\min} \le Q_{C,i} \le Q_{C,i}^{\max}; i \in N_C$$

$$S_l \le S_l^{\max}; l \in N_L$$

$$P_{G,Slack}^{\min} \le P_{G,Slack} \le P_{G,Slack}^{\max}$$

Generalized augmented objective function

The infeasible solutions are handled by applying a constant penalty to these infeasible solutions. The penalty functions corresponding to all the dependent variables such as voltage violations at all load buses $\left(\mu_{VL,i}\right)$, reactive power violations at all generator buses $\left(\mu_{QG,j}\right)$, real power violations at slack bus $\left(\mu_{PG,slack}\right)$ and power flow violations at all transmission lines $\left(\mu_{S,l}\right)$ are included in objective function as follows:

$$F_n^{aug} = F_n + \sum_{i \in N_{PQ}} \mu_{VL,i} \left(V_i - V_i^{\lim}\right)^2 + \sum_{j \in N_{PV}} \mu_{QG,j} \left(Q_{G,j} - Q_{G,j}^{\lim}\right)^2$$

$$+ \sum_{k \in N_{Gslack}} \mu_{PG,slack} \left(P_{G,k} - P_{G,k}^{\lim}\right)^2 + \sum_{l \in N_L} \mu_{S,l} \left(S_l - S_l^{\lim}\right)^2 ; \forall n = 1 : N_{obj}$$

Where F_n is n^{th} objective function value. The limits of dependent variables are defined as:

$$V_i^{\lim} = \begin{cases} V_i^{\max} ; if V_i \rangle V_i^{\max} \\ V_i^{\min} ; if V_i \rangle V_i^{\min} \end{cases} ; \forall i = 1 : N_{PQ}$$

$$Q_{G,j}^{\lim} = \begin{cases} Q_{G,j}^{\max} ; if Q_{G,j} \rangle Q_{G,j}^{\max} \\ Q_{G,j}^{\min} ; if Q_{G,j} \rangle Q_{G,j}^{\min} \end{cases} ; \forall j = 1 : N_{PV}$$

$$P_{G,k}^{\lim} = \begin{cases} P_{G,k}^{\max} ; if P_{G,k} \rangle P_{G,k}^{\max} \\ P_{G,k}^{\min} ; if P_{G,k} \rangle P_{G,k}^{\min} \end{cases} ; \forall k = 1 : N_{G,slack}$$

$$S_l^{\lim} = \begin{cases} S_l^{\max} ; if S_l \rangle S_l^{\max} \\ S_l^{\min} ; if S_l \rangle S_l^{\min} \end{cases} ; \forall l = 1 : N_L$$

For any reactive power optimization problem such as ORPD, the system variables include all control (decision) variables and all dependent variables. The system control variables are voltage magnitudes of all generators, transformer tap-settings and shunt capacitors/inductors. The system dependent variables are reactive power output of all generators, load bus voltage magnitudes and line flows.

Methodology

The above defined problem is solved using Grey wolf optimization method. Grey wolf optimization method is a meta-heurist technique inspired by the hunting behaviour and leadership hierarchy of Grey wolves [43](Mirjalili et al 2014). Grey wolves prefer to live in a pack of size 5 to 12 and have a very dominant social hierarchy.

The leaders are called alphas. They are called decision makers as rest of the wolves follow his/her orders. Beta are the subordinate wolves that come on second level of the hierarchy, they help alpha in decision-making or other pack activities.

Mathematical model

The above social behaviour of Grey wolves is mathematically modelled and then optimization algorithm is developed.

1. *Social hierarchy:* The fittest solution is considered as the alpha (α), the second and third best solutions are beta (β) and delta (δ) respectively.

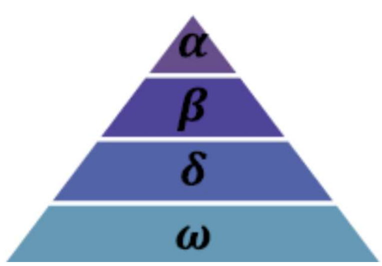

Figure 1 social hierarchy

The rest of the possible solutions are assumed to be omega (ω). Further hunting or optimization is guided by positions of α, β and δ and ω wolves follow these three wolves.

2. *Encircling prey:* Grey wolves encircles a prey during the hunt. Following equations are proposed to mathematically model encircling behaviour of grey wolves:

$$\vec{D} = \left|\vec{C}.\vec{X}_p(t) - \vec{X}(t)\right|$$
$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A}.\vec{D}$$

Where,

t - Current iteration

X_p - Position vector of the prey

X - Position vector of a grey wolf.

Vectors A and C are coefficient vectors calculated as follows

$$\vec{A} = 2a.\vec{r}_1 - a$$
$$\vec{C} = 2.\vec{r}_2$$

Where, r1, r2 are random vectors in [0, 1].

a is linearly decreased from 2 to 0 over the course of iterations.

3. Hunting: Grey wolves recognizes the location of prey and encircle them. Alpha then guides other wolves for hunt. The beta and delta might also help in hunting. But in any optimization problems we don't know the exact solution or the location of prey and thus we take help of alpha (best known solution) beta and delta to estimate the position of prey and guide other wolves towards the same. Following equations are used for updating the position of search agents based on location of α, β and δ.

$$\vec{D}_\alpha = \left|\vec{C}_1.\vec{X}_\alpha - \vec{X}\right|, \quad \vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.(\vec{D}_\alpha)$$
$$\vec{D}_\beta = \left|\vec{C}_1.\vec{X}_\beta - \vec{X}\right|, \quad \vec{X}_2 = \vec{X}_\beta - \vec{A}_2.(\vec{D}_\beta)$$
$$\vec{D}_\delta = \left|\vec{C}_1.\vec{X}_\delta - \vec{X}\right|, \quad \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.(\vec{D}_\delta)$$
$$\vec{X}_p(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3}$$

4. Attacking prey (exploitation): In order to mathematically model attacking behaviour we need to decrease the value of A, therefore the value of 'a' is decreased from [2 to 0], as the value of A will always be between [-a, a] if |A| < 1 then eq. 9 will force wolves to move towards the prey.

5. Search for prey (exploration): Grey wolves updates their position according to position of the alpha, beta, and delta. They diverge from each other or explore the search space to search for prey and converge or exploit to attack prey.

- If |A|< 1 == Attacking prey – Exploitation
- If |A|> 1 == Searching for prey – Exploration

Another parameter that favours exploration is vector C, its values is between [0, 2] and it can be considered as a hurdle for wolf to reach towards prey, if C>1 it emphasise or if C<1 it deemphasise the effect of distance D.

Hybridization of GWO

The simple grey wolf optimizer is also very flexible and convenient. It has given good results while tested on benchmark functions and other optimization problems in various fields. However, there is always room for improvement with these optimization tools. The operators like mutation and crossover are very popular population based operators in artificial intelligence. These operators are included in the original grey wolf optimizer to improve its performance.

Crossover

The crossover operator of the genetic algorithm (GA) is introduced into the original GWO. By incorporating crossover operator in the HGWO, the global search ability is improved since every member of the pack gets chance to share information with each other. It helps in maintaining necessary exploration and exploitation. Thus, it alleviates the problem of diversity and avoids premature convergence. The probability of crossover P_C can be 0 to 1. According to this probability 100XP_C % of strings of total population is selected for crossover. While 100X (1-P_C)% of the population remains as it is.

Crossover is the first operator applied on population of Grey wolves in hybrid grey wolf optimizer. The crossover probability is defined first for selection of pair of population. From the population of grey wolves, according to probability crossover is executed. The cross site is selected randomly from size of population matrix and the values after cross site is interchanged. The process is repeated for each population pair.

Mutation

Mutation operator is used to further improve string/array after crossover. Mutation operator can be used to compliment. The mutation probability *Pm is* decided first. In this algorithm P_m is set to 1%.Mutation is the second operator applied here on grey wolf matrix. A mutation matrix of zeros and ones is generated according to mutation probability and is multiplied with grey wolf matrix element to element thereby changing some of the values

Results and comparisons

Section I

The optimization problem is solved using GWO and HGWO methods for IEEE 30 bus and 118 bus system and it is compared with other methods available in literature.

Table 1 Comparison optimal values of control parameters and objective function of HGWO with Other optimization techniques for IEEE-30 bus system

Control variables	**HGWO**	**GWO**	**BBO**[44]	**PSO**[45]	**GPAC**[45]	**LPAC**[45]	**CA**[45]
V_1(p.u)	1.0266	1.069297	1.1	1.01775	1.02942	1.02342	1.02282
V_2(p.u)	1.0059	1.060347	1.0943	1.02458	1.00645	0.99893	1.09093
V_5(p.u)	0.9833	1.035578	1.0804	1.02466	1.01692	0.99469	1.03008
V_8(p.u)	0.9871	1.027609	1.0939	1.01421	1.03952	1.01364	0.95
V_{11}(p.u)	1.0283	1.00703	1.1	1.01717	1.03952	1.01647	1.04289
V_{13}(p.u)	1.004	1.014764	1.1	0.99613	1.0487	1.01101	1.03921
TC_{6-9}	0.9918	1.092684	1.1	1.09699	1.0425	1.04247	1.07894
TC_{6-10}	1.0391	0.966694	0.9058	0.92509	0.99417	0.99432	0.94276
TC_{4-12}	0.9999	0.964725	0.9521	1.00048	1.00218	1.00061	1.00064
TC_{27-28}	0.9	0.955906	0.9638	1.00714	1.00751	1.00694	1.00693
Q_{10}(MVAR)	9.1098	17.07352	28.91	15.365	17.267	17.737	15.32
Q_{24}(MVAR)	14.65	6.992714	10.07	6.22	6.539	6.172	6.249
Losses (MW)	4.8126	4.9717	4.9650	5.09219	5.09226	5.09212	5.09209
computational time(s)	2.922	3.800	3.5680	3.72	3.434	1.262	1.365

Table 2 Comparisons of objective values and computational time for 118 bus systems

Comparisons of objective values and computational time for 118 bus systems								
	HGWO	**GWO**	**BBO**[44]	**PSO**[45]	**GPAC**[45]	**LPAC**[45]	**CA**[45]	**IP-OPF**
Losses(MW)	127.06	127.14	128.97	131.91	131.91	131.90	131.86	132.11
computational time(s)	24.273	22.638	27.418	26.040	28.090	13.570	22.430	11.870

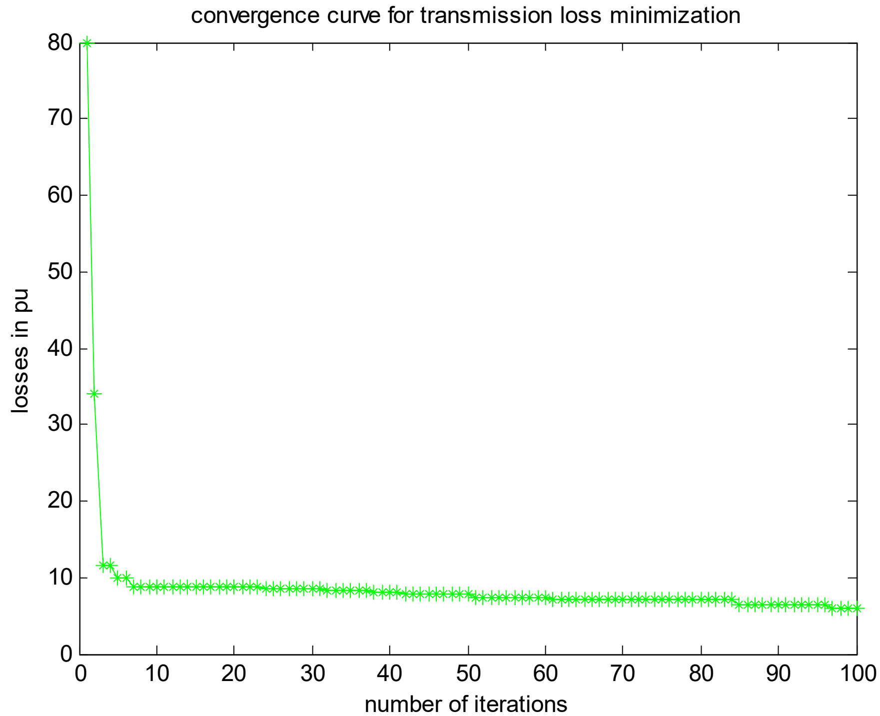

Figure 2 convergence curve of objective function using GWO method

Table 3Reactive power dispatch value of each generator obtained using HGWO and GWO in IEEE 30 bus system

Bus no	Reactive power dispatch of each generator using HGWO (MVAR)	Reactive power dispatch of each generator using GWO (MVAR)
1	6.215537	6.335581
2	23.33853	32.21293
5	8.444262	27.76506
8	33.21169	32.80172
11	6.714723	11.16305
13	8.602718	0.222903
Total	**86.52746**	**110.5013**

Table 4 Statistical values of objective function obtained after 10 independent runs.

	BEST	**AVG**	**STD DEV**
HGWO	4.8126	5.1017	0.1248
GWO	4.9717	5.4985	0.4022

The best optimal values of control parameters and objective function value (total real power transmission line loss) obtained by simple GWO, HGWO and other different methods are summarised in Table 1 & table 2 for IEEE 30 and IEEE 118 bus systems respectively. These results show that the optimal dispatch solutions determined by the HGWO lead to least value of total real power transmission loss as compared to other methods, which confirms that the proposed HGWO is well capable to determine the global or near-global optimum dispatch solution

Optimal reactive dispatch values of generators are calculated and compared in table 3which shows batter and fast values in terms of objective function. The convergence curve is shown in figure 2. Some statistical values like average value and standard deviation are obtained from 10 independent run, each run with 100 iterations is obtained and compared in table 4, and superior statistical results are obtained by HGWO compared to GWO.

Section II Reactive power market implementation

The following assumptions are made while designing the reactive power market:

• The Reactive Power Market Settlement (RPMS) is taken place after the active power Market Settlement

• Only the ISO has *monopsony* power in the reactive power market which means that only the ISO is a sole buyer of reactive power ancillary services. Therefore, the ISO calls for reactive power offers (bids) from all the reactive power providers.

• Only synchronous generators and synchronous condensers are considered as reactive power market participants and eligible to receive the payment for providing the reactive power supports.

Structure of reactive power offer bids

$$EPF = a_i + \int_{Q_{\min}}^{0} m_{1i} dQ_i + \int_{Q_{base}}^{Q_A} m_{2i} dQ_i + \int_{Q_A}^{Q_n} (m_{3i} Q_i) dQ_i \quad [46]$$

The coefficients in above eq. represent various components of reactive power cost incurred by the provider that need to be submitted in the reactive power ancillary service market. These are explained as

$a_{0,i}$ =cost of availability price offer

$m_{1,i}$ =cost of loss component price offer for operating in under excited mode (absorb reactive power) $Q_{G,i}^{\min} \le Q_{G,i} \le 0$

$m_{2,i}$ = cost of loss component price offer for operating in over excited mode. $Q_{Gbase,i} \le Q_{G,i} \le Q_{GA,i}$

$m_{3,i}$ =cost of lost opportunity price. $Q_{GA,i} \le Q_{G,i} \le Q_{GB,i}$

Objective function formulation of reactive power market model

The objective in the proposed market model is to minimize the *Total Payment Function (TPF)* for reactive power support provided by the generators and the synchronous condensers in order to settle the reactive power market. The total payment will depend on the market price of the four components of reactive power being offered to the service provider.

$$Min\ TPF = \sum_{i=1}^{NB} \sum_{u=1}^{NU_i} \begin{bmatrix} \rho_{q0} W_{0(i,u)} - \rho_{q1} W_{1(i,u)} + \rho_{q2} W_{2(i,u)} (Q_{2(i,u)} - Q_{base(i,u)}) + \\ \rho_{q2} W_{3(i,u)} (Q_{3(i,u)} - Q_{base(i,u)}) + 0.5 \rho_{q3} W_{3(i,u)} (Q_{3(i,u)}^2 - Q_{A(i,u)}^2) \end{bmatrix} [47]$$

Where gen is an index for generator at a bus. The reactive power output from i[th] provider is classified into three components $Q_{G1,i}, Q_{G2,i}, Q_{G3,i}$ that represents the regions $(Q_{G,i}^{\min}, 0)$, $(Q_{Gbase,i}^{\min}, Q_{GA,i})$ and $(Q_{GA,i}, Q_{GB,i})$ respectively.

Accordingly, only one of the binary variables W_1, W_2 and W_3 can be selected. In the above equation ρ_0 is the uniform availability price; ρ_1 and ρ_2 are uniform cost of loss prices for reactive power absorption and production respectively; ρ_3 is the uniform opportunity price. If a provider is selected, W_0 will be '1' irrespective of its reactive power output and it will receive the availability price.

Uniform market clearing

The market-based auction may be the most appropriate payment mechanism for realizing a competitive reactive power market. A market-based auction usually adopted either pay-as-bid approach or uniform price approach. A pay-as-bid approach is based on first price auction, where selected participants (service providers) are paid as per their respective bid. A uniform price approach is based on second price auction, where all selected participants are paid a uniform price, which is the highest accepted offer. Applying the uniform price to reactive power markets would be a natural extension to the already existing real power auction mechanisms.

Following points are assumed while developing reactive power market.

- The Reactive Power Market Settlement (RPMS) is taken place after the active power Market Settlement
- The Independent system operator (ISO) is a sole buyer of reactive power ancillary services. Therefore, the ISO calls for reactive power offers (bids) from all the reactive power providers.
- Only synchronous generators and synchronous condensers are considered as reactive power market participants and eligible to receive the payment for providing the reactive power supports.

Following three types of inputs are accepted by the proposed model:

- Four components of reactive power offers bid (a_0, m_1, m_2, m_3) submitted from each participating provider.
- Information related to the capability curve for each generator/synchronous condenser. As mentioned earlier, the opportunity price offer for synchronous condensers is "zero."
- Real power output schedule for all generators obtained from the day active power market settlement.

The solution of the proposed model yields the following outputs:

- The required reactive power output schedule for each generator/synchronous condenser.
- Uniform market clearing prices $(\rho_0, \rho_1, \rho_2, \rho_3)$ for the reactive power market which is listed in table 5
- The total payment made by the ISO to the reactive power service providers which is listed in table 6

Table 5 reactive market clearing components on IEEE 30 bus systems

	Uniform market clearing price component			
	ρ_0	ρ_1	ρ_2	ρ_3
IEEE 30	0.94	0	0.48	0.34
IEEE 118	0.92	0.91	0.9	0.36

Table 6 Comparison of reactive power cost with two auction mechanisms for IEEE 30 and 118 bus system

	Total payment with uniform auction in $	Total payment with pay as bid in $
IEEE 30 bus	56.39585387	46.64252082
IEEE 118 bus	1245.108129	1010.719203

The market is based on offers from generators for reactive power generation. The ISO, who is the sole buyer, settles the market using two methods, PAB and UPM with an optimization approach. Uniform market clearing price component values are obtained for IEEE 30 and IEEE 118 bus system as shown in table 5. Total system cost is calculated based on obtained components and listed in table 6 for both uniform price auction and pay as bid auction.
Test results show that the payment for reactive power is lower in PAB mechanism because only the costlier generator receives the high payment whereas in UPM besides the costlier unit, the other unit are also paid higher payment.

Conclusions

The research work proposes the development of algorithm for optimal reactive power dispatch and reactive power market settlement for reactive power ancillary services in the restructured power systems. Different single-objective optimization formulations are investigated for optimal cost allocation of reactive power and the settlement of reactive power market by incorporating various technical and economic aspects.
The optimal reactive power dispatch schedule is obtained with a new meta heuristic method called grey wolf optimization method (GWO). An improved hybrid GWO technique is also proposed which gives the advantage in terms of improvement in the optimization performance of GWO i.e. good convergence with better quality of the optimal solution in ORPD problem. It is found that the GWO based genetic operator helps in guiding the direction of stochastic search to reach the near global optimal solution effectively by producing the diverse population. The algorithm is tested for IEEE 30 bus power system, and IEEE 118 bus power system. The simulation results prove that the technique is able to undertake global search with a fast convergence rate. 3 to 6 % improvement is recorded in objective values as compared to other techniques.

Reactive Power Market model is developed based on uniform price auction mechanism which competitively determines four components uniform market clearing prices for whole power system. It is also compared with pay as bid mechanism The basic structure of a competitive reactive power market incorporates synchronous generator capability curve, cost of reactive power production from a generator and structure of reactive power offer bids. Subsequently, the reactive power market settlement mechanism is designed and the mathematical formulation of optimization problem is developed for the model. The total payment function is defined by considering the whole power system as one reactive zone. The system operating constraints include real and reactive load flow equality constraints, reactive power relational constraints, constraints determining the single zone market prices, reactive power provision limits, reactive power capability limits of generators, bus voltage limits, security and transformer taps setting constraints. According to the results, pay as bid mechanism leads to 17-19% decrease in total payment function.

Expected benefits of research work

- Due to a fair reactive power pricing mechanism investment in the area of reactive power generation will be encouraged, which will further improve the security power transmission system.
- The competitive reactive power market will provide the driving force to reactive energy sources to innovate and operate in the most efficient and economic manner in order to remain in the business and recover their cost.

Publications

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