Electrical Power and Energy Systems 55 (2014) 13–20

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Optimization of India's electricity generation portfolio using intelligent Pareto-search genetic algorithm

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ARTICLE INFO

Article history:
Received 26 December 2011
Received in revised form 28 January 2013
Accepted 24 August 2013

Keywords:
Optimal generation mix
Mean variance portfolio optimization
Pareto-search genetic algorithm
Climate change mitigation in India

ABSTRACT

Optimization of power generation mix is a significant strategy of climate change mitigation for countries like India. This involves multi-objective optimization of cost reduction, emissions reduction and risk mitigation taking into account relevant constraints. We use a variant of portfolio optimization technique to generate India's 12th five year plan electricity generation portfolio taking into account the carbon costs. For fitness evaluation of a generation portfolio, we use levelized generation costs and a Comprehensive Risk Barrier Index (CRBI), the latter capturing the cost risks modulated by project implementation barrier indices. For constrained optimization, we develop a fast hybrid algorithm, namely, Intelligent Pareto-search Genetic Algorithm (IPGA), which systematically evolves successively efficient frontiers and finally converges to the global Pareto-optimal front. This algorithm combines non-dominated sorting and separate elite population, while utilizing dual mode search for faster convergence and cluster reduction strategy for enhancing diversity. Halting mechanisms have been proposed for local and global Pareto convergence. We apply this generalized algorithm to simulate the impact of carbon costs, risks and barriers on India's optimal generation portfolio.

1. Introduction

New planning and risk management tools are important to respond to uncertainty in climate change and the adaptation/mitigation policies of governments [1]. Optimization of energy strategy portfolios is a critical component of such response. We have formulated a methodology of hierarchical multi-objective optimization of India's energy strategy portfolios in this context [2,3]. Optimization of generation portfolio is a key component of the first level optimization incorporated in this framework. Optimal generation planning is particularly important due to incorporation of Renewables Portfolio Standards, which is fast emerging as a significant constituent of power generation portfolio worldwide. Despite this trend, according to the projections of IPCC, the energy mix supplied to run the global economy in the 2025–30 timeframe will essentially remain unchanged, with more than 80% of energy supply based on fossil fuels [4]. As far as India is concerned, coal will remain the mainstay of power generation during the 12th Plan (2012–2017) providing at least 50% base load power, though renewables' share is growing steadily as mandated by the Electricity Act, 2003.

Though renewables contribute 13% of global energy consumption [5] today, most involve unsustainable uses of wood or hydropower with only 2% share of green new renewables and 6% nuclear. Distributed generation using renewables or otherwise, has a number of advantages. The primary drivers of advancing distributed generation [6] are limiting greenhouse gas (GHG) emissions, avoidance of new transmission circuits and large generating plants, risk reduction in electricity markets, improved power quality, reliability and enhanced energy security. More than doubling of the renewable energy generation in India is projected during the current decade [7] accounting for 25% of the total energy consumed by the year 2020–21.

Optimal generation planning with renewables in the portfolio is an important strategy of climate change mitigation [8]. There are various approaches to this optimization problem. Ref. [9] arrives at an optimal generation mix for Malaysia using two-phase K-best dynamic programming trade-off method, comparing coal, nuclear, solar thermal and biomass technologies based on three criteria, namely, economic cost, reliability and socio-environmental cost. Ref. [10] presents a compromise model for optimal generation mix calculations. A fuzzy linear programming optimization approach for generation planning in India for the year 2020 is indicated in [11] and analytic hierarchy process is employed for green energy sources selection in [12].

Mean variance portfolio theory has been applied to the Irish electricity sector in [13]. A multi-parametric quadratic programming technique is described for fast computation of portfolio problems in [14]. California Energy Commission [15] uses levelized cost

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http://dx.doi.org/10.1016/j.ijepes.2013.08.024

estimates including carbon costs along with risks to assess the climate change impact of generation technologies. However, in the context of a developing country like India, barriers to project implementation are as important as cost risks while planning capacity augmentation. We, therefore, propose a modified approach where we generate a composite index, namely, Comprehensive Risk Barrier Index (CRBI) and use it along with levelized costs to generate efficient frontiers. To implement constrained optimization, we devise a generalized genetic algorithm and optimize India's 12th five year plan electricity portfolio taking into account the impact of carbon costs.

2. Optimization approach for generation planning

Generally, countrywide policies have multiple objectives. Multi-criteria decision-making (MCDM) methods in an integrated assessment framework offer a better alternative to cost/benefit and similar methods [16]. Since bi-objective optimization is easy to visualize and does not require computation of surfaces, it is proposed for generation planning, the twin objectives of which have to be carefully selected. Essentially, the first will be financial/economic cost criterion and the second would relate to policy/project implementation focusing on the quantification of risks and barriers. Portfolio optimization techniques [14,17–19] can be employed using these twin criteria to generate a Pareto-optimal portfolio.

Portfolio optimization is a bi-objective problem of maximizing portfolio return and minimizing portfolio risk. Risk is estimated by evaluating the standard deviation of the portfolio return, as in the case of Sharpe ratio [20], though there are several ways of defining risk [21]. For generation planning, we use portfolio levelized cost and risk to formulate a minimization problem. For a portfolio, cost and standard deviations are computed by the matrix equations,

$$\text{Portfolio Cost}, f_1(\mathbf{X}) = \text{Expectation of cost vector} = \mathbf{X}^{\mathbf{T}}\mathbf{C} \tag{1}$$

$$\mathbf{C} = \text{Column vector of levelized costs}$$

$$\mathbf{X} = \text{Column vector of weights}$$

$$\text{Portfolio standard deviation(risk)}, f_2(\mathbf{X}) = (\mathbf{X}^{\mathbf{T}}\Sigma\mathbf{X})^{0.5} \tag{2}$$

$$\Sigma = \text{Covariance matrix}$$
$$= \begin{bmatrix} \sigma 1 & 0 & \dots & \dots & 0 \\ 0 & \sigma 2 & \dots & \dots & 0 \\ 0 & 0 & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & \dots & \sigma n \end{bmatrix} \times \begin{bmatrix} 1 & \rho 12 & \dots & \dots & \rho 1n \\ \rho 21 & 1 & \dots & \dots & \rho 2n \\ \rho 31 & \rho 32 & \dots & \dots & \rho 3n \\ \dots & \dots & \dots & \dots & \dots \\ \rho n1 & \rho n2 & \dots & \dots & 1 \end{bmatrix} \times \begin{bmatrix} \sigma 1 & 0 & \dots & \dots & 0 \\ 0 & \sigma 2 & \dots & \dots & 0 \\ 0 & 0 & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & \dots & \sigma n \end{bmatrix}$$
$$\sigma_i = \text{Standard deviation of the } i\text{th element(risk)}$$
$$\rho_{ij} = \text{Correlation coefficient between } i\text{th and } j\text{th elements.} \tag{3}$$

The mean variance portfolio optimization problem can then be stated as:

$$\begin{aligned} &\text{Minimize} \quad f_1(\mathbf{X}), f_2(\mathbf{X}) \\ &\text{subject to} \quad g_1(\mathbf{X}), g_2(\mathbf{X}) \dots, gk(\mathbf{X}) \le 0, \\ &\qquad \text{with } \mathbf{x} \in S, S \in \Re^n \text{ being the decision variable space.} \end{aligned} \tag{4}$$

3. Comprehensive risk barrier index (CRBI)

Apart from the risks associated with each cost component, there are barriers in implementing projects especially in the context of a developing country like India. We use a comprehensive risk barrier index (CRBI) to indicate the combined impact of risks and implementation barriers associated with each portfolio. While risk parameters are estimated using the standard deviations of the respective costs, multi-criteria ranking methods [22] can be used to evaluate the barrier indices. Analytic hierarchy process (AHP) [23,24] has been selected in this work which is an important multi-attribute weighting method making use of pair-wise comparison matrices estimated based on expert judgments. AHP has been implemented using Web HIPRE software [25] to obtain the Perron vector (principal eigenvector) of the reciprocal comparison judgment matrix. We use the consistency measure of this matrix as in Web-HIPRE [26]. Risk and barrier indices are then integrated into a composite index by a suitable combination function. The estimated portfolio cost and portfolio CRBI give the fitness indication of a particular generation portfolio as against its competitors, to be employed as inputs to the bi-objective minimization problem.

We consider the following barrier profiles in the Indian scenario:

(i) Land availability barrier.
(ii) Public policy support/barrier.
(iii) Environmental clearance barrier.
(iv) Infrastructure and resource availability barriers.
(v) Grid connection and market barriers.

In the AHP, the priority vector for each of the barriers is computed using the pair-wise comparison matrix. Individual barrier priority vectors are combined to compute the overall barrier index vector for all energy technologies. If the barrier importance column vector is **B**, and the matrix of barrier priority vectors is **A**, then the overall barrier index vector for various energy technologies, **P** is given by:

$$\mathbf{P} = \mathbf{AB} \tag{5}$$

$$\text{Portfolio barrier index}, \quad B = \mathbf{X}^{\mathbf{T}}\mathbf{P} \tag{6}$$

The risk and barrier indices can now be aggregated to form the comprehensive risk barrier index (CRBI) using a suitably weighted risk-barrier combination function. CRBI is an index which captures the combined impact of the risk and barrier random variables. A proportionality function of these independent variables is the simplest approach to capture this impact, though a variety of telescopic functions are possible to accentuate or reduce the impact of each at various regions of the domain. This is the choice to be exercised by the policy maker as to what kind of relative functional priorities need to be attached to the risk and barrier profiles. The simple product function could be replaced by other choices such as $\mathbf{b^2r}$, $\mathbf{br^2}$, $\mathbf{b^2r + br^2}$ etc. where **b** is the barrier random variable and **r** is the risk random variable. In this analysis, we utilize the product function of the risk and barrier indices to generate CRBI.

$$\text{Portfolio CRBI} = K * (\text{Portfolio barrier}) * (\text{Portfolio risk})$$

$$= K * (\mathbf{X}^{\mathbf{T}}\mathbf{P}) * (\mathbf{X}^{\mathbf{T}}\Sigma\mathbf{X})^{0.5} \tag{7}$$

where K is a positive constant.

4. Intelligent Pareto-search Genetic Algorithm (IPGA)

Though there are analytical approaches to solve optimization problems, heuristics such as Genetic Algorithm are especially useful for hard problems. Genetic algorithms are intrinsically parallel due to which they can generate a number of near-optimal solutions. They have been gainfully employed in many power sector problems such as economic dispatch [27,28], electric load forecast-