CONSUMER PRICE SENSITIVITY IMPACT ON TARIFF LEVEL IN ISOLATED RURAL POWER SYSTEMS

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ABSTRACT

Uncertainties in demand and supply are among the challenging aspects when planning isolated power systems as well as one of the reasons why plans are not as optimal as expected. Most consumers in these areas are price sensitive and their sensitivity may change over time. To be able to estimate the outcome of certain investments in such markets with uncertainties, it is important to have a realistic modelling of the market. The modelling of markets can be performed using probability methods. This paper presents a methodology using Monte Carlo simulation to analyse the impact of price sensitivity of consumers on the probability distribution of tariff as a basis for making decision during planning. The stochastic nature of the market due to uncertainties in sensitivity, demand and supply has been modelled explicitly by random variables of given distributions. The developed model has been demonstrated on a small test system. The results include probability distributions showing the impact on the tariff levels for various system configurations.

INTRODUCTION

Provision of reliable power supply at a reasonable cost is among the key requirements for economic growth and development in developing nations. Long distances between the existing grids and isolated rural communities in combination with comparatively low demand for electric power in villages make the extension of large-scale grids not economically viable. Stand alone power systems may be an alternative solution, as they remove the need for long and costly transmission lines. However, the demand for electricity in these communities depends on a number of factors including income of consumers, tariff levels, costs of competing fuels (such as paraffin), costs and availability of appliances, and reliability of the supply. Initial knowledge about the behaviour of the market is vital for planning and optimal design of power supply facilities (such as generation and distribution). Planners have to put into consideration that most consumers are price sensitive and their price sensitivity may change over time. Hence, the price sensitivity of the consumers may be considered as a random market parameter. Uncertainty in demand and supply is among the challenging aspects for planning power systems and the reasons why plans are not as optimal as expected [1],[2]. Uncertainties in the market are critical in predicting appropriate operation costs and tariff. Without interaction with the consumers a supplier could attempt to set tariffs which are either too high (thereby risking loss of sales) or too low (hence sacrificed profit). The impact of price sensitivity of the consumers on an electricity market has been addressed in various studies. Econometric methods for assessing effects of electricity price changes presents several challenges which include complex simultaneity problems between price and consumption, and high data requirements [5]. *Kanudia et al* used a constant price-sensitive demand function to relate the end use demand and price of energy without considering the uncertainties in the market [2]. The methods in previous research work do not show the impact of time response to tariff and stochastic nature of the market due to uncertainties in consumer price sensitivity.

This paper presents a method to use Monte Carlo simulation for analysis of possible tariff levels. The results can be used as a basis for decision making when planning isolated rural power systems. In the simulation, the price sensitivity of consumers is modelled by random variables. It has been assumed that the power system operator will choose the least tariff which makes the system economically sustainable. This assumption is justified if the operator of an isolated rural power system is not profit maximising, but operates with an objective to make public electricity accessible to the rural population. The paper is arranged as follows: modelling of the load and generation systems is described first, followed by an outline of the simulation procedure. The procedure is demonstrated on a small example system supplied either by diesel generator sets or a wind–diesel hybrid system. The paper is concluded by a discussion of applications and further development of the methodology.

MODELING

In this paper it has been assumed that an isolated rural power system can be modelled by price-sensitive demand and power sources (diesel generator sets and wind turbines).

A. Load

The load at a specific time, D is assumed to be the product of the peak demand, D_P, and relative load D^{rel}, as given in (1).

$$D(t) = D_P \times D^{rel} \qquad (1)$$

The peak demand depends on the tariff. Mathematically, consumers' response to changes in price can be represented by one of the three demand functions distinguished as linear, Cobb-Douglas and constant price-sensitive [2], [3], [6]. The mathematical simplicity of the linear function makes it theoretically attractive compared to the rest. Thus, the relation between peak demand and tariff is expressed as

$$D_P = f(\lambda) = \frac{\alpha - \lambda}{\beta} \qquad (2)$$

where α and β are the demand factor and sensitivity respectively. Both these parameter (herein refereed to as *market parameters*) are assumed to be random variables with known probability distributions, which constitute inputs to the simulation.

The relative load is continuously varying. For example, the relative load of an isolated rural power system is typically low during the night and during the day, but will be closer to the peak demand during the evenings. In this model, the relative load is simply represented by known probability distribution, which also constitutes an input to the simulation. Thus, the load at an instant is a random variable that depends on the probability distributions of both market parameters and relative load.

B. Thermal Generation

Thermal generation is characterised by rated capacity and availability of diesel generator sets (gensets), and their generation cost which is assumed to be a constant. The simplest model of a thermal power plant used is a discrete two states model: either available or not available [5]. Considering a thermal generation plant comprising of n gensets, the total generation is in 2^n states and the total generation cost depends on both demand and availability of the units.

C. Wind Power Generation

Wind power generation is characterised by the generation at a given wind speed, availability and operation costs. The generation is modelled as a probability distribution for the available generation capacity at a given wind speed which in many cases can be assumed to follow a Rayleigh distribution [4], [5]. The available generation is a random variable with the probability density obtained by combining the probability distribution of wind speed (see figure 1) and the inverse of the generation function $W(v)$ as given in figure 2. The generation function is given between the cut-in, v_{in} and cut-out, v_0 wind velocities.

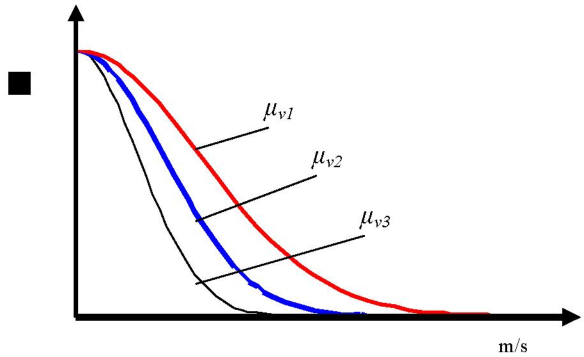

Figure 1 Probability distributions (Rayleigh distribution) of wind speed are represented by duration curves for different means ($\mu_{v1} > \mu_{v2} > \mu_{v3}$)

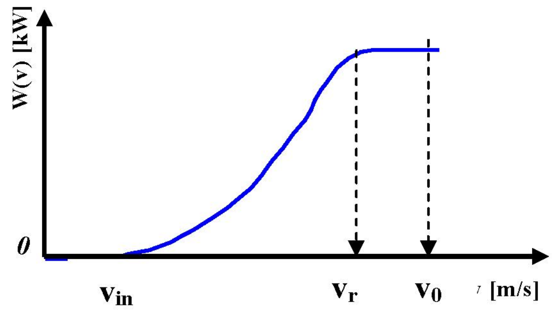

Figure 2 Power curve of the wind turbine

SIMULATION PROCEDURE

The simulation procedure is based on the principle of simple sampling in which the consumers' price sensitivity to and other properties of the power system are analysed. The simulation involves two nested Monte Carlo simulations. In the outer simulation, random values of the market parameters α and β (cf. Modelling) are generated. It has been assumed that the power system operator observes the price sensitivity of consumers and adjusts the tariff to ensure economical sustainability of the system, i.e., the expected revenue should be equal to the expected operation cost plus the fixed costs of the system. In order to come up with the necessary tariff, an iterative procedure is performed.

The first step in the iteration is to assume an initial tariff. The performance of the system is simulated based on this tariff (this constitutes the inner Monte Carlo simulation). If the expected revenue and costs do not balance, then the tariff is updated and the performance is simulated again until a sufficient tariff which makes the system economically sustainable has been attained for the particular set of market parameters. Then, the obtained tariff can be considered as a sample in the outer Monte Carlo simulation.

The system parameters used in the simulation are:

- G_j installed capacity of the j^{th} genset, j = 1, 2 … n (for n diesel generator sets)
- C_{Gj} generation cost of the j^{th} genset [US$/kWh]
- W_l the installed capacity of the l^{th} wind turbine, l = 1, 2 … m (for m wind turbines)
- C_{Wl} generation cost of l^{th} wind turbine [US$/kWh]
- FC_q fixed cost of the q^{th} generator [US$/h], q = 1, 2 … n+m

Let us differentiate between "*cases*" and "*scenarios*" as used in the simulation description. A case represents a sample in the outer Monte Carlo simulation. The inputs and outputs of the different cases are distinguished by the index k. The parameters of a case are:

- λ_k adjusted tariff in the k^{th} case [US$/kWh]
- β_k price sensitivity for the k^{th} case (randomised from a probability distribution) [US$h/kWh^2]
- α_k demand factor for the k^{th} case (randomised from a probability distribution) [US$/kWh]
- D_{Pk} peak demand in the k^{th} case, [kWh/h], cf. (2).

A scenario represents a sample in the inner Monte Carlo simulation, executed within block D of figure 3. The inputs and outputs of different scenarios are distinguished by index i. The scenario parameters are:

- $D^{rel}_{k,i}$ relative demand in the k^{th} case and i^{th} scenario (from a probability distribution).
- $G_{k,i,j}$ available generation capacity from the j^{th} genset in k^{th} case and i^{th} scenario [kWh/h], $G_{k,i,j} = 0$ or $G_{k,i,j} = G_j$.
- $W_{k,i,l}$ available generation capacity from the l^{th} wind turbine in k^{th} case and i^{th} scenario [kWh/h], where $0 \le W_{k,i} \le W_l$

For each generated scenario, the outputs are:

- $D_{k,i}$ demand in k^{th} case for i^{th} scenario [kWh/h], cf. (1)
- $D^*_{k,i}$ supplied load in k^{th} case for i^{th} scenario [kWh/h], where $0 \le D^*_{k,i} \le D_{k,i}$, depending on the available generation
- $TOC_{k,i}$ total operation costs (for the k^{th} case and i^{th} scenario) [US$/kWh]
- $TRC_{k,i}$ total revenue collection (for the k^{th} case and i^{th} scenario) [US$/kWh]
- $LOLO_{k,i}$ loss of load occurrence, k^{th} case and i^{th} scenario

It is assumed that the available units are dispatched starting with those units with low generation costs i.e., wind power. If the load, $D_{k,i}$ at any moment is greater than the total available generation capacity ($\sum G_{k,i,j} + \sum W_{k,i,l}$) then the supplied load, $D^*_{k,i} = (\sum G_{k,i,j} + \sum W_{k,i,l})$ and $LOLO_{k,i} = 1$. Otherwise $D^*_{k,i} = D_{k,i}$ and $LOLO_{k,i} = 0$. $TOC_{k,i}$ is calculated by multiplying the dispatched generation in each power plant by the corresponding operation cost, and $TCR_{k,i}$ is the product of tariff, and the supplied load, i.e., $TRC_{k,i} = \lambda_k . D^*_{k,i}$.

The number of samples in the inner Monte Carlo simulation is either set in advance or can be determined by a convergence criterion. For simplicity, we have assumed that the number of samples is predetermined. Hence, for N_S generated scenarios, the expected performance indices of the system is estimated by the averages of the three observed samples of $TOC_{k,i}$, $TRC_{k,i}$ and $LOLO_{k,i}$ as in (3a), (3b) and (3c).

$$ETOC_k = \frac{1}{N_S}\sum_{i=1}^{N_S} TOC_{k,i} + \sum_{q=1}^{(n+m)} FC_q \,, \qquad (3a)$$

$$ETRC_k = \frac{1}{N_S}\sum_{i=1}^{N_S} TRC_{k,i} \,, \qquad (3b)$$

$$LOLP_k = \frac{1}{N_S}\sum_{i=1}^{N_S} LOLO_{k,i} \,, \qquad (3c)$$

where,

- $ETOC_k$ expected total operation cost, k^{th} case, [US$/h]
- $ETRC_k$ expected total revenue, k^{th} case, [US$/h]
- $LOLP_k$ loss of load probability for the k^{th} case

After a sufficient tariff (a tariff that makes the system economically sustainable) is found, the outputs of the k^{th} case are the tariff, λ_k as well as the $ETOC_k$, $ETRC_k$ and $LOLP_k$.

The complete simulation procedure is outlined in the flow chart given in figure 3, and the algorithm is explained as follows:

- *A:* The inputs to the simulation for different market *options* are defined, which include: probability distributions of generation, load and market parameters, and constants.
- *B*: Randomisation of market parameters for each case: sensitivity, β_k and demand factor, α_k.
- C: Setting the initial tariff in the iterative process to find the economically sustainable tariff.
- D: The inner Monte Carlo simulation in which N_S scenarios are generated from the performance indices are calculated according to equations (3).
- E & F: For profitability of the system, the expected total operation costs should be less than the expected total revenue ($ETOC_k \le ETRC_k$), therefore in the simulation the break even point has been set at marginal price when $ETOC_k \approx ETRC_k$ (checked in block F) with an error margin

below 1%. The iteration is performed by updating the tariff (block E) until a sufficient tariff is attained.

G: The sufficient tariff is stored to prepare for the simulation of the next case.

H: The simulation ends after attaining predetermined number of cases.

I: The results are presented for N_C cases.

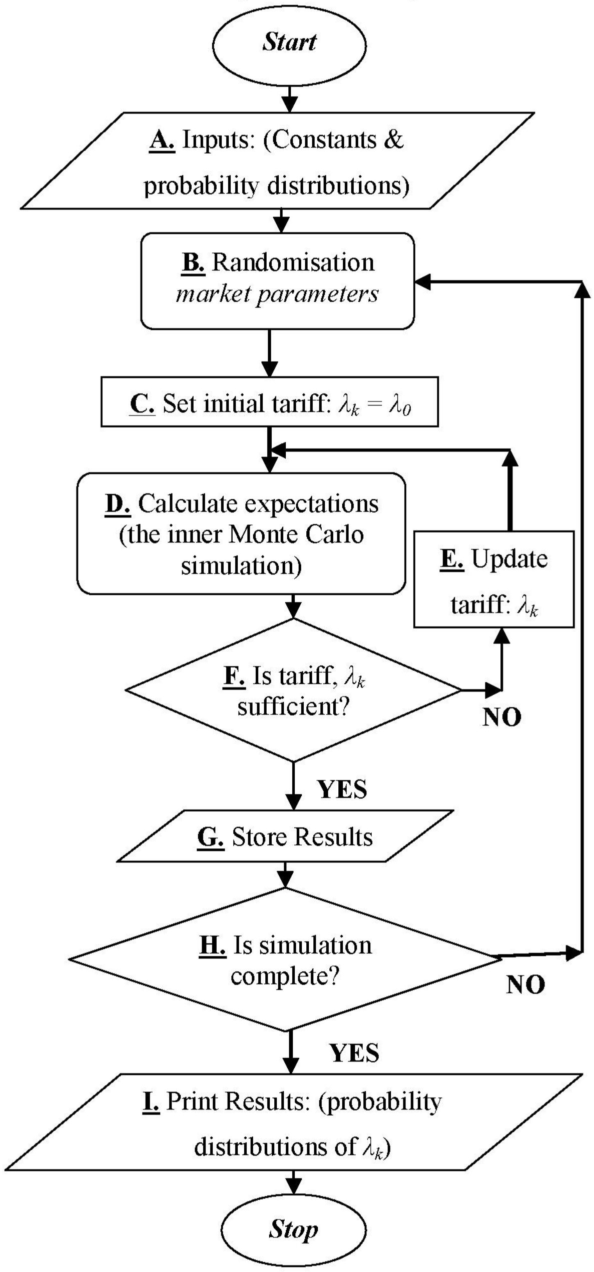

Figure 3Flow chart for the Simulation Procedure

EXAMPLE

The methodology developed in this paper has been tested on a fictitious rural power system. Four different market options have been investigated. In two options, the system is supplied only by diesel gensets (*D*) and for the other two options a wind-diesel hybrid system was considered (*H*). Each supply option was then simulated for either consumers with high price sensitivity (*HPS*) or low price sensitivity (*LPS*) in order to illustrate the impact of consumer price sensitivity on the performance of different supply options. The inputs for the simulated example are summarised in tables 1 and 2, and demand is represented by relative load duration curve in figure 4. In table 1, the installed capacity of the generating units in the example was chosen high enough to ensure that *LOLP* is kept as low as 0.1 in all cases.

Table 1 Summary of input data (power supply)

Variable	Gensets	WT
Number of units	1	1
Capacity [*kWh/h*]	300	0 – 60
Availability [*%*]	98	96
Distribution (Discrete)	2 states	Raleigh
Generation cost [$US\$cts/kWh_e$] as based on fuel	20	-
Investment cost, I_0 [x10^3 US$]	42	0 – 72
Expected life time (assumed to be the credit period) [years]	10	20
Assumed discount rate [%]	18	18
O&M Costs [% of annual, I_0]	10%	20%

Table 2 Summary of input data (market parameters)

Market options	Installed capacity [kW]		***β***, [US$Cts.hr/kWh^2]	***α***, [US$Cts /kWh]
	Genset	WT		
D-HPS	300	0	U(0.0812 ≤ β ≤ 0.1486)	N(38.5,5.8)
D-LPS	300	0	0.1	38.5
H-HPS	300	60	U(0.0812 ≤ β ≤ 0.1486)	N(38.5,5.8)
H-LPS	300	60	0.1	38.5

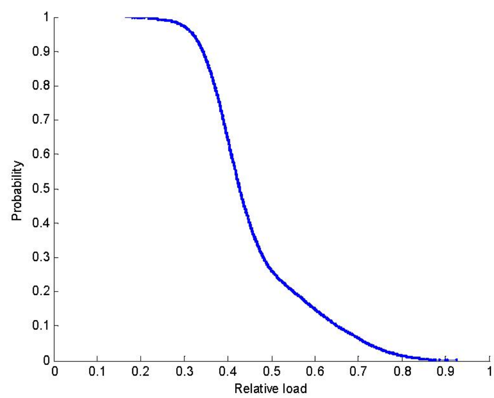

Figure 4 Probability distribution of relative load represented as a duration curve

Results from the simulation are probability distributions of tariffs for the two market options, and have been presented both graphically (using duration curves) and in tabular format as in figure 5 and table 3. The results can be used to analyse whether or not it is preferable to build only a diesel genset system or a hybrid system.

When studying consumers with low price sensitivity it is obvious that the hybrid system is preferable to a system supplied solely by diesel gensets. For instance, the maximum tariff for a hybrid system is less than the minimum tariff for a diesel genset system (graphs *H-LPS* and *D-LPS* in figure 5). The results for consumers with higher price sensitivity are less definitive, but still indicate that a hybrid system is likely to be preferable. Both supply options have similar probabilities for tariffs in the higher range, but the probability for lower tariffs is larger with hybrid system than the diesel system.

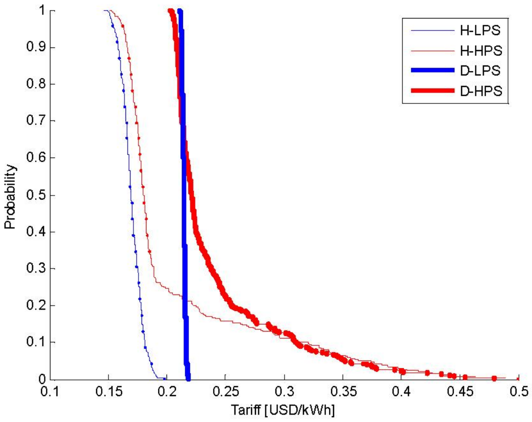

Figure 5 Tariff duration curves for the two market options showing probabilities, *P (λ > x)*

Table 3 Mean and standard deviation values of tariff

Market options	*WT* [kW]	μ_λ *[US$/kWh]*	σ_λ *[US$/kWh]*
D-HPS	0	0.24	0.05
H-HPS	60	0.21	0.06
D-LPS	0	0.21	0.00
H-LPS	60	0.17	0.01

The example shows that the price sensitivity of consumers will have an impact on the tariff which is necessary for economic sustainability of an isolated rural power system. The wide range of possible tariffs for the system with price-sensitive consumers leads to uncertainties in the economic performance of the system. Hence, in order to provide the decision-maker with a comprehensive data, it is advisable to include the consumer price sensitivity in the modelling.

CONCLUSIONS

Uncertainties in demand and supply of power systems should be the motivation for using stochastic planning methods. A procedure for investigating tariff levels in an electricity market has been discussed based on Monte Carlo simulation, wherein market parameters have been explicitly modelled as probability distributions. The methodology has been demonstrated on an example test system and it has been shown how the results can be used as a basis for decision-making. It has been realised that price-sensitivity of consumers has a significant impact on the economic performance of isolated rural power system. Thus, special consideration must be given when when planning these systems. In practice, the development of probability distributions of market parameters needs long term data from the field to mimic and approximate the market behaviour.

The methodology outlined in this paper could be useful to planners and researchers when predicating possible range of tariffs and investigating risks involved when setting tariffs in an electricity market with uncertainties in both demand and supply.

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