Distributed Power Generation: Rural India – A Case Study

Anshu Bharadwaj and Rahul Tongia, *Member, IEEE*[*]

Abstract—In this paper, we present an analysis of a rural distribution network to examine what the benefits of decentralized generation would be for meeting rural loads. We use load flow analysis to simulate the line conditions for actual rural feeders in India, and quantify the loss reduction and system improvement by having decentralized generation available. We also present a framework for valuing ancillary services from the generator, viz., reactive power. This provides a starting point for utilities in developing countries to better plan their systems to meet dispersed loads, while optimizing for renewables and other decentralized generation sources.

Index Terms— Dispersed storage and generation, load flow analysis, power distribution economics, power distribution planning, reactive power.

I. INTRODUCTION

Rural electricity supply in India has been lagging in terms of service (measured by hours of supply) as well as penetration. Only 31% of the rural households have access to electricity, and the supply suffers from frequent power cuts and high fluctuations in voltage and frequency, with so-called blackouts and brownouts [1]. The demand-supply gap is currently 7.8% of average load and 13% of peak demand at current prices, which are heavily subsidized, on average. In order to bridge this gap and meet anticipated growth, it is necessary to double the present capacity, i.e., install an additional generation capacity of 100,000 MW by 2012. This would require an investment of Rs. (Rupees[1]) 7,500 billion (approximately $150+ billion) including investments in transmission & distribution [1]. A major bottleneck in the development of the power sector is the poor financial state of the utilities, which can be attributed to the lack of adequate revenues and state subsidies for supply to the rural subscribers. Of the total power generated, only 55% of the kilowatt-hours are billed[2], and only 41% of this is collected. The average cost of supply[3] is Rs. 3.04/kWh and the average revenue is only Rs. 2.12/kWh [1]. This is due to a skewed tariff policy of subsidizing the power supplied to agricultural consumers (in some states the power is free to agricultural subscribers!) at the cost of commercial and industrial consumers[4]. This, coupled with the fact that the electricity supplied to irrigation pumps is not metered, provides for wasteful consumption and theft. Agricultural consumption, to the extent estimated, is over 30% of total consumption in the country. Transmission and distribution (T&D) losses are over 25%, which are due to both technical losses and theft (termed "commercial losses" in official publications).

The State Electricity Regulatory Commissions in several states have attempted to rectify these tariff imbalances by increasing the agricultural tariff, only to have the governments reverse these steps due to strong opposition from farmers[5]. The farmers also complain that the electricity supplied to the rural areas is intermittent and of poor quality leading to high implicit costs because of damage to their equipment and downtime [2]. A World Bank study on India's power sector describes a "vicious circle" in which the skewed tariff policy and poor financial health of utilities leads to low investments in upgrading power quality, which, in turn, creates opposition for tariff reforms among consumers; which only exacerbates the already poor financial condition of the utilities [3].

The present policies of building large centralized generation and extended distribution networks are clearly unlikely to solve the problems of rural electricity supply, at least in the near future. Decentralized power generation close to the rural load centers using renewable sources appears to have the potential to address at least some of the problems of rural electrification described in the earlier section[6].

---

[1] 1 US $ ~ Rs 50

[2] In most states, tariff for agricultural consumption is either free or levied at a (highly subsidized) flat annual rate (Rupees per kW rating of the irrigation pump). Effectively, this means average tariffs for agriculture about half of one cent per kWh.

[3] "Cost of supply" is defined as utility total expenditure divided by total kWh transacted. It is an *average* number, and does not factor in sectoral cost variation, such as the higher cost to serve remote rural loads.

[4] The industrial and commercial tariffs in many states are high enough that many such users are switching to captive power generation, typically using diesel generators.

[5] One of the main objectives of establishing the State Electricity Regulatory Commissions was to ensure that electricity tariff setting is based purely on economic and financial considerations and isolated from political pressures. The utility submits tariff recommendations for different categories of consumers to the Commission, which makes final decisions. Any deviation in tariffs is meant to be covered by explicit subsidy by the state government.

[6] India's wind-based generation capacity is approximately 1,100 MW, though it is location specific. Biomass-based power has a potential of 17,000 MW from agro-residues and an additional 5,000 MW from cogeneration using rice husk and sugarcane bagasse. Presently India has more than 2,000 small-scale (< 100 kW) biomass-gasifier reciprocating engine systems using agro-residues for a total generation capacity of 35 MW. The generation capacity from bagasse/rice husk is more than 300 MW.

II. DISTRIBUTED GENERATION

A. Rationale for Distributed Generation

Distributed generation (DG) is attracting a lot of attention worldwide. Several potential applications of DG are standby power, combined heat and power (CHP), peak shaving, grid support and stand-alone power [4]. Widespread use of DG provides an alternate system architecture for the generation and delivery of heat and electricity with cost savings [5]. The California Energy Commission's report analyzed the several technical issues pertaining to interconnecting distributed generators to the grid [6]. Distributed power generation and its interfacing with the grid is further facilitated with the use of latest power electronics devices such as Flexible AC Transmission Systems (FACTS) and HVDC Light [7-9]. Distributed power generation also offers the possibility of creating micro-grids (within the utility's overall framework) to cater the requirements of a group of consumers in a well-defined geographical region. Davis et al (1999) have considered using microturbines for creating isolated zones of power supply for residential, commercial and remote applications [10]. Similarly, National Rural Electric Cooperative Association (NRECA) assessed the economics of different technology options and also discussed formation of rural electric cooperatives using local generation [11].

In the context of rural India, or other developing countries with similar needs, decentralized power generation in rural areas can improve voltage profiles, lower distribution losses and supply reactive power locally. Improved quality of power supply also can assist in creating incentives for tariff reforms.

B. Planning for Decentralized Generation

Conventional wisdom has indicated that large generation stations offer significantly better economies of scale. However, such calculations must be recalibrated when faced with the state of the power grid in many emerging economies such as India, viz., large distributed (rural) load, high T&D losses (including theft), limited capacity availability, and dramatically poor supply conditions. In such cases, a thorough analysis should be made for the policies, technical specifications, and economic analysis behind use of DG.

C. Current Policy for Renewable-Based Decentralized Generation in India

The Ministry of Non-Conventional Energy Sources (MNES), Government of India, frames the overall guidelines for interconnection of renewable DG units [12], and most utilities interconnect as per the central government's (non-binding) norms. Some of these guidelines and the associated contentious issues are discussed below.

1. Buy-back of power: The Ministry recommends a buy-back tariff of Rs. 2.25/kWh[7] with an annual escalation of 5% effective from 1994-95. This works out to Rs. 3.01/kWh as of now. In most states, this rate is higher than the average cost of electricity purchased from other sources. Fig 1 shows that in the state of Karnataka, while the average cost of purchase of electricity was Rs. 1.40/kWh, the price paid to renewable cogeneration units was Rs. 3.01/kWh. As a result, the cash-strapped utilities are often not enthusiastic to interconnect with DG units, even despite their low total capacity. In many cases, the utilities take an unduly long time, sometimes several months, to pay for the electricity that these units have already generated and supplied to the grid. Needless to say, this is a disincentive to such renewable-based power plants.
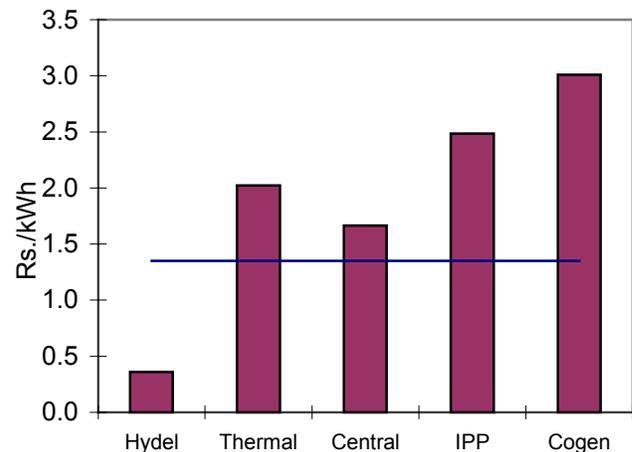

Fig 1: Cost of Electricity from different sources for the state of Karnataka (2001). Karnataka has abundant hydel power, the capital cost of which is paid up and hence cheap. The buy-back price for cogeneration is the most expensive and therefore the utilities are often reluctant to interconnect with these. The horizontal line is the average cost of electricity purchased.

2. Wheeling: The Ministry has allowed wheeling of power and recommended a 2% charge. However, some states do not allow wheeling, while others have imposed 20% wheeling charges, ostensibly equal to the transmission & distribution losses [8]. The utilities view these third-party generators as a threat as they take away industrial and commercial consumers who currently pay high tariffs and thus cross-subsidize agricultural consumers. Utilities therefore impose high wheeling charges to discourage such sales[9].

3. Interconnection: The utilities interconnect with the renewable DG generators at high voltages (> 66 kV or > 33 kV, depending on the state's lowest "transmission" voltage level). This gives the utility

---

[7] It is not clear how this buy-back rate was determined. The ministry has not published any calculation to this effect.

[8] There is no readily available document to explain the basis for the 20% wheeling charges.

[9] As an illustration, Karnataka Power Transmission Corporation Limited (KPTCL) charges Rs 4.55/kWh from commercial consumers. The cost of generation for biomass-based decentralized power generator is often lower (~Rs 3/kWh) and thus a commercial enterprise would be willing to purchase electricity from such a generator over the utility's distribution network. However, an imposition of a wheeling charge of 20% or more would discourage this transaction, given other hidden costs such as payment delays, required investments to interconnect, etc.

the flexibility to divert the power in the grid. However, the local area does not benefit significantly from decentralized generation and moreover, there is no discernible improvement in the power supply or in utility's revenues even though the utility purchases expensive power from the DG units. In many states, the generator pays for the wiring necessary to connect to the nearest sub-station.

The utilities' policy for DG units appears to be one-sided and overlooks the possible benefits of decentralized power generation in remote rural feeders. In this paper we examine the opportunities with decentralized power generation in rural areas and attempt a more rational basis for framing utilities' policies towards the DG units. In particular, we address the following issues:

1. Impact of DG on the voltage profiles and technical distribution losses.

2. Options for economic valuation of reactive power supplied by the DG.
3. Balanced approach to estimating wheeling charges.

III. SIMULATION AND ANALYSIS

A. Methodology

Our approach in this study is to conduct a three-phase AC load flow analysis of a rural distribution feeder in Tumkur district of Karnataka, India (Fig 2). This is representative of a typical rural distribution feeder and the results will therefore have a wider applicability. The crude hand sketch of the distribution feeder, taken from a field linesman, is often the best data available on rural power distribution networks in India. The lack of reliable power data is a handicap in planning for rural electricity supply.
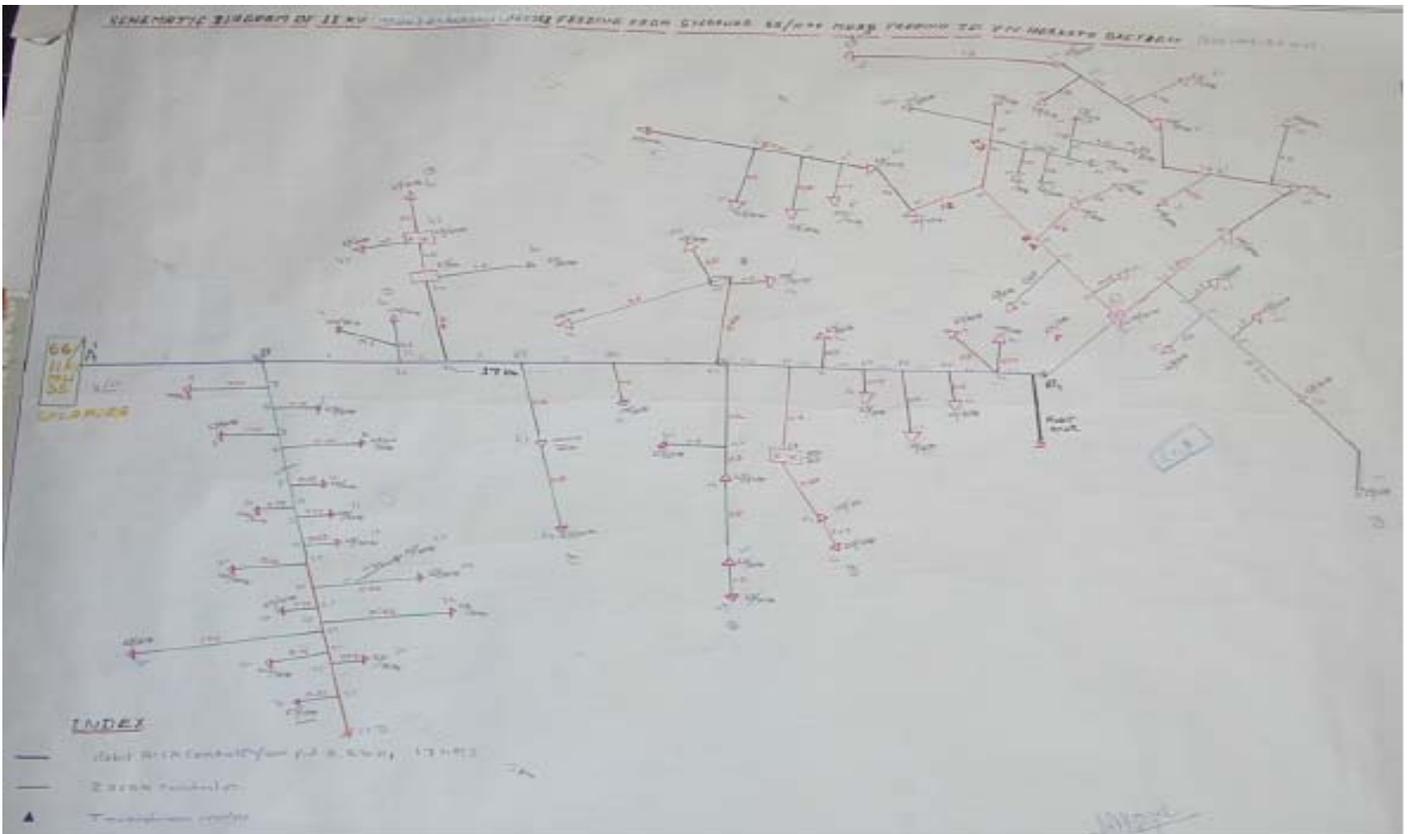

Fig 2: Sketch of the Rural Distribution feeder in Tumkur district, Karnataka (Peak demand 3 MW, 128 buses, Substation 66/11 kV). This crude sketch, taken from field linesmen, is often the best data available on power distribution networks, which are often unmapped, and largely unknown.

The feeder begins with a 66/11 kV sub-station. There are 128 buses out of which there are 74 load buses, each roughly supplying a village. Each load bus has a step-down transformer for either 440 V or 220 V and the transformer ratings are 25 KVA, 63 KVA, 75 KVA or 100 KVA. The distance between the sub-station and the farthest bus is about

25 km and the peak demand is 3 MW (TABLE 1). The feeder's load is predominantly irrigation pumps and motors that are inductive and often operate at power factor as low as 0.7[10].

---

[10] Utilities demand that consumers install power factor correction devices so as to maintain a minimum power factor of 0.9. However, it is rarely practiced.

TABLE 1

DETAILS OF THE RURAL DISTRIBUTION FEEDER

Substation Transformer	66/11 kV
Total number of buses	128
Number of Load buses	74
Peak Load	3 MW
Transformers in the feeder	25 KVA, 63 KVA, 75 KVA, 100 KVA

Appendix I gives the total sanctioned load at each bus. The buses are numbered in a sequential manner, but due to the branching of the network, higher numbered nodes are not necessarily further away from the substation.

The present annual consumption of the feeder is 7.8 Million Units (kWh). TABLE 2 gives the break-up of the kWh consumed. There are four main categories of consumers: domestic, commercial, industrial and agricultural (irrigation pumps). The kWh consumed by the first three categories are metered and they are charged on a per kWh basis, while agricultural consumers are not metered and they pay on a flat rate basis[11]. TABLE 2 shows that the metered consumers account for a very small fraction (~3%) of the total consumption. Agricultural consumption, technical distribution losses and theft account for the balance. This is typical of most rural distribution feeders in India. The tariff levied on domestic consumers is significantly lower than that levied on commercial and industrial consumers.

TABLE 2
CATEGORIES OF CONSUMERS, SANCTIONED CONNECTIONS,
ANNUAL kWh CONSUMPTION AND TARIFFS (TOTAL ANNUAL
CONSUMPTION IS 7.8 MILLION kWh)

Consumer	Sanctioned Connections	Annual kWh	Annual kWh /connection	Tariff
Domestic	1166	183,940	157	Rs 1.20/kWh
Commercial	12	1,300	108	Rs. 4.75/kWh
Industrial	25	13,320	533	Rs. 5.00/kWh
Irrigation Pumps	560	?	-	Rs 500/HP

Since irrigation pumps are not metered, there is no data available on their annual power consumption and it is estimated by back calculating as explained below. An energy balance analysis at a sub-station level is based on:

$$Total\,kWh_{Sub-Station} = kWh_{metered\,consumers}$$
$$+ kWh_{unmetered\,consumers}$$
$$+ Technical\,Distribution\,Losses + Theft \quad (1)$$

The only known quantities in (1) are the total kWh at the sub-station level and the kWh consumed by the metered consumers. It is therefore impossible to know precisely the three unknowns from a single equation. The recent tariff order of the Karnataka Electricity Regulatory Commission (KERC) explains a rough procedure adopted by the utilities to estimate these numbers. The utility makes an assumption of the annual kWh consumed by an irrigation pump by sampling a few predominantly agricultural feeders (clearly this is a crude exercise at best)[12]. This results in an estimate of the total losses: technical losses and theft. The utility then makes an assumption of the technical losses based on statistical data of a few feeders to obtain the commercial losses. Clearly, there is great subjectivity in such calculations and they could be easily challenged or manipulated. Often, the utilities lump theft with the irrigation pump consumption thus overstating the actual kWh consumed by the pumps.

B. AC Load Flow Study

Our approach is to conduct a three-phase AC load flow analysis for this feeder using the Gauss-Seidel algorithm (Appendix II). We first carried out a base case scenario (without DG) to obtain the voltage profiles and distribution losses and then considered the impact of a DG installed in the feeder. The assumptions made in the analysis are as follows (TABLE 3):

1. On-line load: This is defined as the fraction of sanctioned load that is connected at any instant. This is varied between 0.30 and 0.75, parametrically.
2. Power Factor: The load power factor is not known and we varied it parametrically between 0.7 and 0.95. This appears reasonable given the majority of the load are irrigation pump sets.
3. Theft is defined as the fraction of on-line consumption that is unauthorized. We have fixed this at 15% of the on-line load.
4. Transformer Losses: We have ignored the losses in each of the transformers because of non-availability of data.

---

[11] Irrigation pumps in Karnataka were metered till 1991. However, thereafter, irrigation pumps consumption was made free for a few years. Subsequently, the tariff was revised to a flat rate based on the kW (or Horsepower) rating of the pump.

[12] KERC assumes an average annual irrigation pump consumption of ~ 6,300 kWh. KPTCL, the utility, selects a few predominantly rural feeders and measures the annual kWh consumed. This is divided by the number of sanctioned irrigation pumps in the region to obtain the average kWh consumed per pump. However, this is a subjective estimate and extrapolation to the entire state can lead to significant error. In addition, there are a large number of unauthorized pumps, which are not captured by this calculation.

TABLE 3
ASSUMPTIONS FOR THE THREE-PHASE AC LOAD FLOW ANALYSIS

Variable	Value or Range
On-Line Load	30% - 75% of the sanctioned load
Theft	15% of on-line load
Power Factor	0.70 – 0.95 lagging

IV. FINDINGS

A. Voltage Profiles and Distribution Losses

Fig 3 shows the voltage profiles (per unit basis, or *pu*) under heavy load conditions (75%) with a theft of 15%, with the power factor varying between 0.7 and 0.9. The horizontal line is the acceptable voltage level i.e. within 6% of the specified voltage level. Under heavy load conditions and when the power factor is 0.7, the voltage at far-off buses drops to as low as 0.75 pu[13], which is severely damaging to the equipment. Even when the power factor is 0.9, the voltage at far-off buses is still below the acceptable norm.
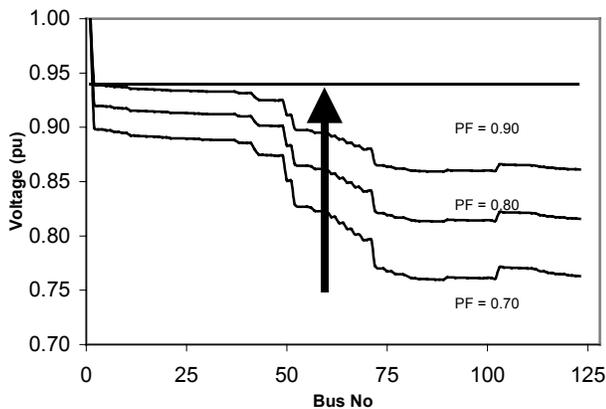

Fig 3: Voltages (pu basis) at different buses in the 128 bus feeder in Tumkur, Karnataka under heavy loads. On-Line load is 75% of the sanctioned load, theft is 15% of on-line load and power factor is varied parametrically between 0.7 – 0.9. The horizontal line is the acceptable voltage of 0.94 pu.

Fig 4 shows the calculated distribution losses as a function of the power factor under moderate loading condition of 60% with 15% theft. Depending on the power factor, the technical distribution losses are between 8% and 12%[14]. In most rural feeders, the power factor is 0.75 – 0.8 and therefore distribution losses are likely to be at least 10% under normal loading conditions [2]. The commercial losses (theft) were assumed to be 15% and hence the total losses (or unaccounted energy) in the feeder are 25%. When adding the technical transmission losses, estimated over 8%, we see that the total losses are unacceptably high (33%). One contribution of this study is therefore to quantify the technical distribution losses

---

[13] Voltage at each bus is on a per unit (pu) basis.
[14] The distribution losses in most OECD countries are on the order of 5% or less.

for rural Indian feeders from first principles, something not shown in publications before.
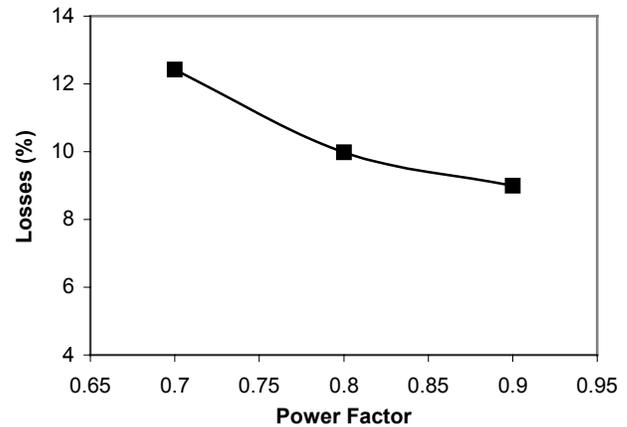

Fig 4. Technical Distribution Losses (I^2R) in the feeder under moderate loading of 60% as a function of the overall power factor. The losses are 8% to 12%. Thus the total losses after accounting for theft (15%) are 23% - 27% in just the distribution portion of the network.

The sub-station voltage itself is often below the stipulated 11 kV because of the upstream voltage fluctuations, and this has a cascading effect on the feeder voltages as well. Fig 5 shows the voltage at Bus # 89 as a function of the load when the sub-station voltage is 11 kV and l0 kV. When the sub-station voltage is 10 kV, the voltage at Bus # 89 drops down to 0.7 pu under heavy load.
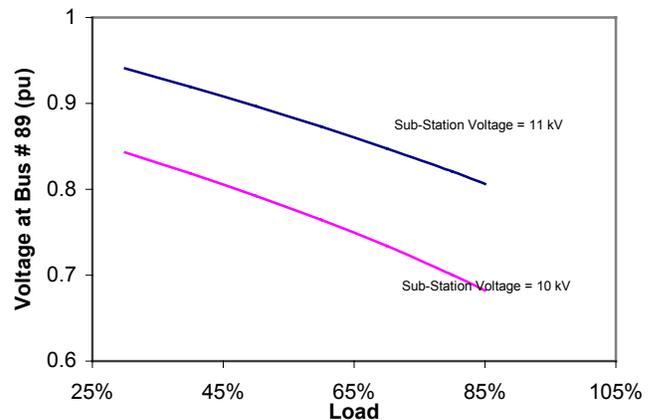

Fig 5. Voltage at Bus # 89 under different loads when the sub-station voltage is 11 kV and 10 kV.

To rectify the high losses, as well as poor voltage profile, the utilities would have to take one or more of the following steps:
  1) Increasing the voltage for distribution (reducing I^2R losses);
  2) Reducing the runs (lengths) for distribution;
  3) Enforcing power factor correction or utilizing capacitor banks for such;
  4) Using decentralized power for providing real and/or reactive power.

We now consider the impact of a decentralized generator located in the feeder.

Fig 6 shows the impact of a decentralized power generation source placed in the feeder at Bus # 73. The choice of the bus was made on the basis of it being centrally located in the feeder, and almost equidistant from all the branches[15]. The generator power was varied from 0 to 3 MW with a power factor of unity. As expected, the voltage profiles improve considerably throughout the feeder. For most of the buses, even with just a 1 MW plant, the voltages fall within acceptable norms. The same effect is also seen when a bank of capacitors is installed, which supplies only reactive power. Reactive power is therefore very important for voltage support in the context of rural feeders that have low power factors. This becomes relevant in the following sections as the generators could also act as sources of reactive power.
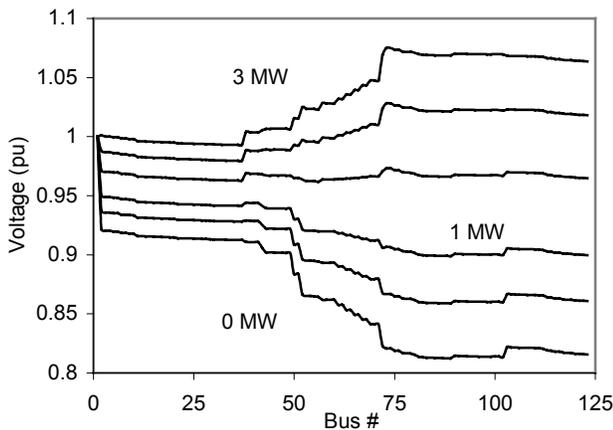

Fig 6. Impact of a decentralized generator placed centrally at Bus # 73 on the voltage profiles. The generator is varied from 0 MW to 3 MW. (On-Line load is 60%, theft 15%, power factor 0.8)

Fig 7 shows the technical distribution losses as a function of the generator MVA rating. There is a dramatic reduction in the losses from the base case of 10% without the decentralized generator. The losses keep on decreasing until a minimum is reached corresponding to a critical generator rating. At this point, the feeder is virtually drawing no current from the grid and therefore losses are very low. As the MVA rating is increased further, there is surplus power generation in the feeder and there is a net export of real power to the grid. As a result, there is a subsequent increase in the distribution losses.

Fig 7 also shows two instances where the generator power factors are 0.95 and 0.8. In the latter case, the generator is also supplying reactive power and this is modeled using a generator capability curve[16]. The losses are still lower in this case. In fact, when the generator rating is 2 MVA, the distribution losses are only 0.8%. There is thus a case for encouraging generators to run at lower power factors so as to supply the region with reactive power to the extent needed. The economic and policy issues associated with this option are examined in the following section.

---

[15] It is also possible to determine the optimal location of the generator so as to minimize the losses.

[16] There is a trade-off between the real and reactive power produced by a generator. This is explained in detail in a subsequent section.
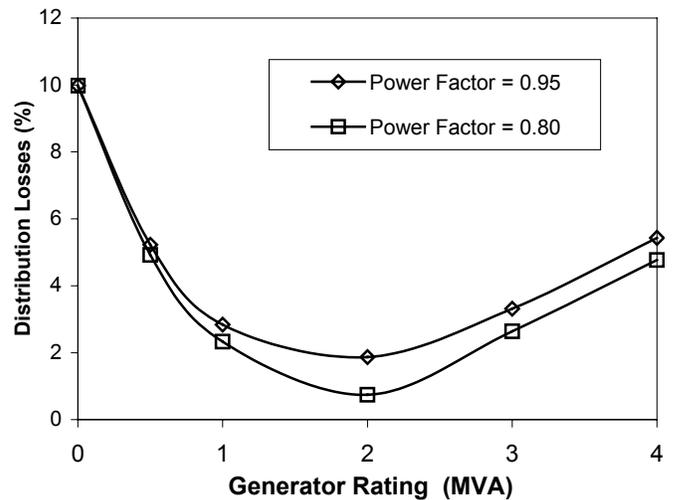

Fig 7. Technical distribution losses for different MVA ratings of the generator (0-4 MVA) and for two generator power factors of 0.80 and 0.95.

Fig 8 shows the power transactions with the grid when a 2 MVA generator is installed and the system is set to the following: load 60%, power factor 0.8 and theft 15%. The real power drawn from the grid then decreases as the generator power factor increases and at a power factor of 0.9 (lagging), the region does not draw any real power.
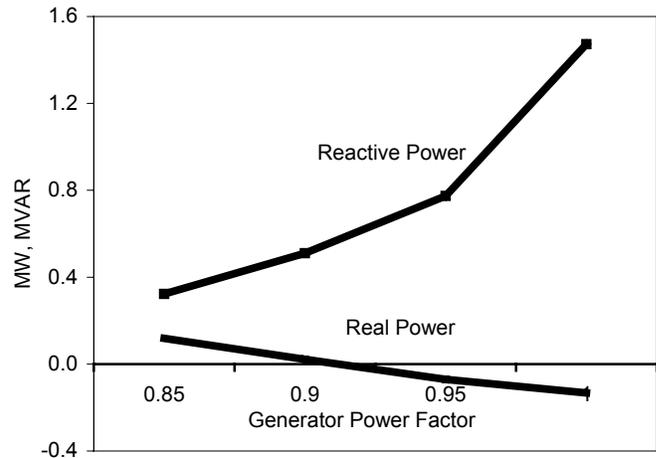

Fig 8. Transactions of real and reactive power with the grid when the power factor of a 3 MVA generator is varied between 0.85 lagging and 1.

Therefore, appropriate sizing and locating a decentralized generator improves the quality of power supplied to the feeder and also reduces the distribution losses. Using photovoltaic generation, other researchers have reported similar results that reduce distribution losses [13, 14].

The above discussion suggests that distributed generation close to the rural load centers benefits both the local consumers (improved power quality) as well as the utility (lower losses). It opens the possibility of creating rural micro-grids, or regions of stable and good quality power supply within the utility's network. Improved quality of power also creates incentives for tariff reforms in the agricultural sector and thus breaks the vicious circle. Rural electricity

cooperatives can be formed at a district level, wherever decentralized generation is possible. In this context, biomass-based distributed generators can play an important role because of the predominantly agrarian rural economy. The farmers get paid for the biomass they supply to the power plant and in return, they pay for the power consumed.

B. Valuation of Reactive Power

As discussed above, most rural buses have low power factors because of a large number of irrigation pumps and this leads to low voltages and high distribution losses in the feeder. State utilities attempt to improve the power factor by installing capacitors or Static Var Compensators (SVC) in the grid, though the progress is very slow due to poor financial health of the utilities [2]. In such a situation, decentralized generators can locally supply reactive power; improve the voltage profiles and avoid the capital costs of capacitors or SVC. Ideally, a generator should produce real power at its rated power factor so that the productive capacity is completely used and thus the profits are maximized. However, it is often desirable for generators to operate at lower power factors to supply reactive power if the load characteristics of the network so require for maintaining voltage profiles within acceptable limits. This implies reducing the real power generation as governed by the generator capability curve (Fig 9). This is still beneficial because the decrease in real power generation can be more than offset by the reduction in losses due to local var support.
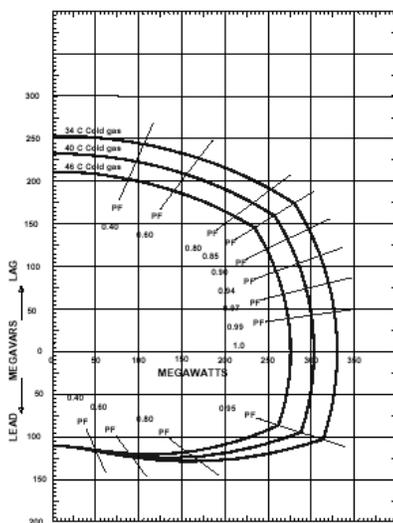

Fig 9. Typical Generator Capability Curve showing the limits of real and reactive power frontiers.

The present buy-back tariff policy of the utility compensates the generator only for the real power (kWh) supplied and therefore gives no incentive to the generator to supply reactive power (vars). We consider some of the options for pricing reactive power so as to create incentives for the generators to supply reactive power. Reactive power pricing is already a subject of extensive research in the context of deregulation and unbundling of electricity markets in several countries. Hitherto, reactive power management was the responsibility of the vertically integrated utility and reactive power price was bundled with the total plant capacity costs. With deregulation and open access environments, transmission and generation fall into different legal entities and hence unbundling of reactive power and appropriate pricing mechanisms are necessary. Reactive power support and voltage control by generators is one of the ancillary services as per US FERC Order # 888 [15]. The classical theory of real-time pricing of real and reactive power in electric power systems is based on solving a constrained optimization problem (optimal power flow) for minimizing the cost of supply (or distribution losses) subject to several constraints such as specified bus voltages, power transactions between buses and generation limits. The solution of the optimization problem determines the price of real and reactive power at each bus [16, 17]. Several researchers have taken this approach and solved for reactive power marginal price using standard bus systems [18-21]. These approaches have a limited applicability in the context of rural India because the supply is intermittent and lack of readily available data such as the real and reactive power load at each bus. Therefore, simpler techniques are needed for reactive power pricing. One approach is to consider the capital and operating costs of synchronous condensers (capacitors) as a base. Another possibility is to consider the triangular relation between active, reactive and apparent power for a particular power factor as per the generator capability curve [22]. If a generator is forced to operate at a lower power factor because of a feeder's voltage requirement, it should be compensated adequately so as to make it indifferent to producing real or reactive power [23]. This is the opportunity cost of reactive power such that it makes up for the lost revenues of producing active power. In our analysis, we use this approach as an illustration for reactive power pricing.

Calculation Example

Consider a 2 MVA generator. Normally most generators operate over-excited (lagging) with a power factor of 0.8 to 0.95. The capability of the generator in the overexcited region is limited by the capability of cooling the field winding and the overall MVA output (stator current) of the machine. From Fig. 9, when the power factor is 0.8-0.95, the generator capability is controlled by the overall MVA rating [24]. Thus, there is a triangular relation between real & reactive power and the total apparent power. The present buy-back policy of the Karnataka state utility is Rs. 3.01/kWh [25]. Therefore, for every choice of power factor, we can estimate the "losses" that the generator incurs by not operating at unity power factor. This then gives the unit price of reactive power. A variation of the price of reactive power is shown in Fig 10 for power factors corresponding to the stator current limit (0.8 to 0.95). This illustration is one of the several innovative pricing mechanisms possible that can encourage decentralized generators to operate at slightly lower power factors and significantly improve the system voltage profiles.
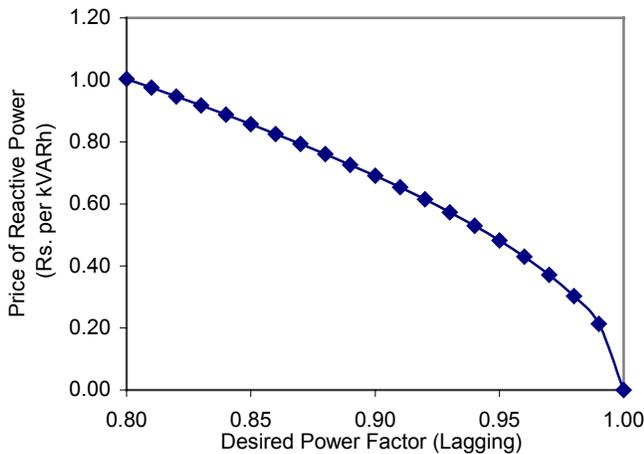
Fig 10. Suggested reactive power pricing (Rs./kVARh) for a 2 MVA generator operating as per the generator capability curve in Fig. 9.

C. Evaluating Wheeling Charges

We finally discuss qualitatively a balanced and scientific approach for assessing the wheeling charges by considering the costs and benefits to the utility. The present policy of 20% wheeling charges in some states is a serious deterrent to economic viability of renewable energy projects [26].

Economic definition of wheeling has been discussed in literature in good detail. Schweppe et al [27] mention that "wheeling is a mongrel concept resulting from the mating of two inherently different economic concepts; an ideal world of regulated utilities and an ideal deregulated competitive market. Wheeling would not exist in either extreme." Caramanis et al [28] have described the procedure for estimating wheeling charges under open access. This involves solving an optimal power flow problem for minimizing the cost of supply (or losses) subject to the constraints of voltage level at each bus and maintaining power transactions between buses. This approach is similar to the estimation of the reactive power marginal pricing as explained in previously. If a generator is located at bus i and it supplies power to a load at bus j, then the wheeling charge is defined as the difference of the marginal costs of power at the two buses i and j [28-30]. *A corollary of this definition is that if wheeling of electricity results in a reduction of the transmission and distribution losses, then the wheeling charges are negative, i.e. the utility pays the generator for wheeling the power* [28]. Li et al [30] explain that while the marginal cost of reactive power at a bus is negligible as compared to the marginal cost of real power (ratios mostly less than 1%), the *wheeling rate of reactive power* (defined as the difference in marginal costs of reactive power) is not a negligible factor. Therefore, independent pricing of reactive wheeling could be considered in many distribution networks.

The load flow studies of the rural distribution feeder showed that under most circumstances, the distribution losses decrease when a decentralized generator supplies power. This is because of the reactive power and voltage support provided by the decentralized generator, which helps to boost the sagging voltages. Therefore, even if it is wheeling the power to a third party (and hence possibly taking away the utility's paying customer), it is also assisting the utility by providing voltage support and reducing distribution losses. Therefore, the utility's present policy of assessing wheeling charges clearly appears to be one-sided without any scientific justification. A more balanced and rational basis is needed on a case-to-case basis to provide the incentives for renewable decentralized generators as well as keep the utility's interest in mind.

D. Conclusions

In this paper we examined opportunities for distributed power generation in rural India. Decentralized power generation close to the rural load centers has the potential of addressing the energy crisis facing rural India. We undertook a case study based approach and carried out AC load flow studies of a rural feeder in Tumkur district, Karnataka, to study the impact of a decentralized power generator located in the feeder. There is a significant improvement in the voltage profiles and reduction of technical distribution losses. This creates a possibility of setting up rural micro-grids or rural electricity cooperatives with biomass-based power generators. Improvement in quality of electricity supply also creates incentives for agricultural tariff reforms. Decentralized generators can locally supply reactive power and we discussed options for reactive power pricing. Finally, we assessed the present policies of utilities for wheeling charges and concluded that it is unscientific and ignores the benefits of decentralized generation to the utility in terms of voltage profiles and lower losses. This paper also presented for the first time proof that technical losses in Indian rural distribution systems are very high (around 10% today), and this is a serious issue for the long-term financial health of the utilities.

V. APPENDIX

Appendix 1: List of total load sanctioned at various buses

Bus #	Sanctioned Load (Horse Power[17])	Bus #	Sanctioned Load (Horse Power)
4	6	71	60
6	30	72	90
8	50	74	20
10	50	76	30
12	60	78	60
14	60	79	60
16	60	81	95
18	40	82	45
20	50	83	45
23	20	84	20
24	50	86	30
26	15	88	40
28	30	89	50
30	50	92	30
32	70	94	20
34	30	96	75
36	15	98	25
37	20	99	50
40	75	101	95
41	80	102	80
44	40	105	40
45	35	107	30
46	40	109	18
47	60	110	30
48	60	111	35
49	60	113	50
51	70	114	55
54	70	116	50
55	50	117	95
56	75	119	45
58	45	121	50
59	20	122	90
60	8	123	60
62	40	125	25
64	50	126	40
66	40	127	30
68	66	128	20
70	15		

---

[17] 1 Horse Power = 746 W

Appendix 2: Gauss Siedel Algorithm

The algorithm iteratively solves for the voltage at each bus by equating the total complex power at each bus with the product of the voltage and the complex conjugate of the current entering that bus, until convergence.

$$V_k Y_{kk} = [\frac{(P_k - jQ_k)}{V_k} - \sum_{i=1}^{N} Y_{ki} V_i] \qquad (2)$$

$$Y_{ij} = \frac{1}{R + j\omega L} \qquad (3)$$

where Y_{ij} is an element of the admittance matrix. This is the admittance (reverse of the impedance) of the distribution line connecting i^{th} and j^{th} buses (if connected).

R = Resistance of the connecting line (0.25 Ω/km)

L = Inductance of the line (1.62 x 10^{-3} Henry/km)

Ω = Angular frequency (rad/s)

P_k = Real power demand at k^{th} bus (kW)

Q_k = Reactive power demand at kth bus (kVAR)

N = Total number of buses (128)

VI. ACKNOWLEDGEMENTS

VII. REFERENCES

1. *Blueprint for Power Sector Development*. 2001, Ministry of Power, Government of India: New Delhi.
2. *Tariff Order 2000*, Karnataka Electricity Regulatory Commission: Bangalore, India.
3. *India's Power Supply to Agriculture, Volume I, Summary Report, Energy Sector*. 2001, World Bank: Washington DC.
4. *Distributed Generation: Securing America's Future with Reliable, Flexible Power*. 1999, US Department of Energy.
5. Strachan, N. *Distributed Generation and Path Dependancy*. in *5th Annual International Conference on Technology, Policy and Innovation*. 2001. The Hague, Netherlands.
6. *Interconnection in California (Connecting Distributed Generation to the Grid)*. 2000, California Energy Commission.
7. Grunbaum, R., Halvarsson, B., Wilczynski, W. 1999. Madrid, Spain. *FACTS and HVDC Light for power systems interconnections*. in *Power Delivery Conference*. 1999. Madrid, Spain.
8. Skytt, A.K., Holmberg, P., Juhlin, L.E. *HVDC Light for connection of wind farms*. in *Second International Workshop on Transmission Networks for Off-Shore Wind Farms*. 2001. Royal Institute of Technology, Stockholm, Sweden.
9. Asplund, G. *Application of HVDC Light to power systems enhancement*. in *IEEE Winter meeting*. 2000. Singapore.
10. Davis, M.W., Gifford, A.H., Krupa, T.J., *Microturbines - An Economic and reliability evaluation for commercial, residential and remote load applications*. IEEE Transactions on Power Systems, 1999. **14**: p. 1556-1562.
11. *White Paper on Distributed Generation*. 2000, National Rural Electric Cooperative Association.
12. *Annual Report*. 1999-2000, Ministry of Non-Conventional Energy Sources, Government of India: New Delhi.
13. Begovic, M., Pregelji, A., Rohatagi, A., Novosel, D. *Impact of Renewable Distributed Generation on Power Systems*. in *34th Hawaii International Conference on System Science*. 2001. Hawaii.
14. Hoff, T., Shugar, D.S. *The Value of Grid-Supported Photovoltaic to Substation Transformers*. in *13th IEEE T&D Conference*. 1994. Chicago, IL.
15. *Order No 888: Promoting Wholesale Competition Through Open Access Non-Discriminatory Transmission Services by Public Utilities*. 1996, Federal Energy Regulatory Commission.
16. Baughman M.L., S., S.N., Zarnikau, J.W., *Advanced Pricing in Electrical Systems Part I : Theory*. IEEE Transactions on Power Systems, 1997. **12**(1): p. 489-495.
17. Baughman M.L., S., S.N., Zarnikau, J.W., *Advanced Pricing in Electrical Systems Part II : Implications*. IEEE Transactions on Power Systems, 1997. **12**(1): p. 496-501.
18. Chattopadhyaya, D., Bhattacharya, K., Parikh, J., *Optimal reactive power planning and its spot-pricing: an integrated approach*. IEEE Transactions on Power systems, 1995. **10**(4): p. 2014-2020.
19. Dai, Y., Ni, Y.X., Shen, C.M., Wen, F.S., Han, Z.X., Wu, F.F., *A study of reactive power marginal price in electricity markets*. Electric Power Systems Research, 2001. **57**: p. 41-48.
20. Xu, W., Silva, C.P.D., Zhang, Y., Kundur, P., Warrack, A.A., *Valuation of dynamic reactive power support services for transmission access*. IEEE Transactions on Power systems, 2001. **16**(4): p. 719-727.
21. Keib, A.A.E., Ma, X., *Calculating short-run marginal costs of active and reactive power production*. IEEE Transactions on Power Systems, 1997. **12**(2): p. 559-565.
22. Hao, S., Papalexopoulos, A., *Reactive power pricing and management*. IEEE Transactions on Power Systems, 1997. **12**(1): p. 1997.
23. Silva, E.L., Hedgecock, J.J., Mello, J.C.O., Luz, J.C.F., *Practical Cost based approach for the voltage ancillary service*. IEEE Transactions on Power Systems, 2001. **16**(4): p. 805-812.
24. Murdoch, A., Boukarim, G.E., D'Antonio, M.J., Lawson, R.A. *Generator Over Excitation Capability and Excitation System Limiters*. in *Panel Session Summary for the IEEE/PES 2001 WPM, "Generator Overexcitation Capability"*. 2001. Columbus, OH: Excitation System Subcommittee and the Power System Stability Controls Subcommittee.
25. *Annual Report 1999-2000, Ministry of Non Conventional Energy Sources*, Ministry of Non-Conventional Energy Sources, Government of India: New Delhi, India.
26. *Tariff Order*. 2000, Karnataka Electricity Regulatory Commission: Bangalore, India.

27.   Schweppe, F.C. *Mandatory Wheeling: A Framework for Discussion*. in *IEEE/PES Summer Meeting*. 1988. Portland, Oregon.

28.   Caramanis, M.C., Bohn, R.E., Schweppe, F.C., *The costs of wheeling and optimal wheeling rates.* IEEE Transactions on Power Systems, 1986. **PWRS-1**(1).

29.   Caramanis, M.C., Roukos, N., Schweppe, F.C., *WRATES: A tool for evaluating the marginal cost of wheeling.* IEEE Transactions on Power Systems, 1989. **4**(2): p. 594-604.

30.   Li, Y.Z., David, A.K., *Wheeling rates of reactive power flow under marginal cost pricing.* IEEE Transactions on Power Systems, 1994. **9**(3): p. 1263-1269.

VIII. BIOGRAPHIES

Anshu Bharadwaj was born in New Delhi, India on May 27, 1967. He graduated from Indian Institute of Technology, Kanpur, in 1989 in Mechanical Engineering and got an MBA from the Indian Institute of Management, Calcutta, in 1991. He completed his PhD with the Departments of Mechanical Engineering and Engineering & Public Policy, Carnegie Mellon University, Pittsburgh, USA in 2002. Presently he is a Research Fellow at the Center for Energy and Environmental Studies, Department of Engineering & Public Policy, Carnegie Mellon University. His research interests are in advanced power generation technologies such as fuel cells and IGCC and their applicability to energy systems in developing countries. Notably, Dr. Bharadwaj is also an Indian Administrative Services (IAS) officer on leave from the Government of India.

Rahul Tongia (Student M '98, Member '03) was born in Jaipur, India, on February 10, 1974. He graduated from Brown University in 1995 as an Electrical Engineer. He completed his doctoral studies in 1998 at the Department of Engineering & Public Policy, Carnegie Mellon University, where he is currently a faculty member in the School of Computer Science and Dept. of Engineering and Public Policy. His professional interests include analyses of the technology, policy, and economics of infrastructure in developing countries.