

Technical loss computation and economic dispatch model for T&D systems in a deregulated ESI

The global trend of reform in the electricity supply industry can be attributed to several factors, such as: the introduction of competition in the industry as a means of providing lower energy prices; consumer demand for price transparency and regulation of cross-subsidies among different users; need for higher energy efficiency in technical systems of utilities; significant growth in energy demand especially in developing countries; and pressure on governments to raise funds for social services, balance budgets and to carry out economic reform. Lower technical losses will provide for cheaper electricity and lower production costs, with a positive influence on economic growth. This article evaluates technical losses in transmission and distribution systems, presents results of technical loss estimation in South Africa's grid network, and discusses issues of loss minimisation and economic dispatch under a deregulated electricity supply industry.

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The structure of deregulated electricity industries across the world shows unbundling of generation, transmission and distribution with an independent system operator (ISO)¹ as the emerging standard. In South Africa's proposed structure, the ISO and transmission company will function as a business entity. In the past, the major consideration of electric utilities was construction costs of new transmission and distribution, including grid extensions to rural communities.

Environmental, regulatory and economic challenges, as well as changing public perception, are shaping a radically different world for electric utility operations in both developed and developing countries.¹

These pressures have narrowed down utility objectives to: reducing cost of energy to customers, providing better service to customers and ensuring a high environmental

standard, plus health and safety of personnel and equipment.

To deal with these technical and economic demands, electric utilities and allied industries have focused on a number of transmission and distribution (T&D) strategies and advanced technology developments. The emerging issues facing utilities include how to: run T&D systems at the lowest operating and maintenance costs; extend the life-span of plant and equipment; manage with reduced manpower; execute deregulation of the electricity industry effectively and efficiently, and meet these economic constraints while enhancing system reliability and efficiency.²

The strategies adopted by electric utilities and allied industries in power system operation are summarised as:²

- upgrading and uprating of transmission systems

- the switch to automated control and protection
- flexible AC transmission systems (FACTS)
- integrated utility communications
- energy efficiency in T&D systems
- advanced distribution.

Losses in T&D systems

Energy losses arise as power flows through the network to meet customer load demands. Some of the input energy is dissipated in the conductors and transformers along the delivery route. These losses are inherent in the processing and delivery of power but can be minimised to maximise returns. Losses represent a considerable operating cost, estimated to add 6-8% to the cost of electricity and some 25% to the cost of delivery. The accurate estimation of electrical losses enables the supply authority to determine with greater accuracy the operating costs for maintaining supply to consumers. This in turn enables a more accurate estimate of the system lifetime costs, over the expected life of the installation. Hitherto, utilities operating as government monopoly institutions in vertically integrated structures, have overlooked these losses since they do not constitute major operational or quality of supply problems. However, their impact is economic, hence they are assuming greater importance in a market-driven deregulated environment. Electricity supply industry (ESI) losses are both technical and non-technical:

- *Non-technical losses:* Non-technical losses (NTL) are more dominant in lower levels of distribution networks. They include unauthorised line tapping, equipment vandalism, metering errors, inadequacies/inaccuracies of meter reading, inaccurate customer billing and inaccurate estimation of non-metered supplies, such as public lighting.
- *Technical losses:* These losses are due to the current flowing in the electrical network and include line losses, copper resistance and iron losses of transformers. The technical losses in the network constitute economic loss providing no benefits. NTL are construed as a loss of revenue by the utility. The magnitude of each of these losses needs to

be accurately estimated and practical steps taken to minimise them. From the utility perspective, both these losses need to be reduced to their optimal level. This article addresses technical losses.

Types of technical losses

Losses occur in all conductors, and may be any of three types: copper, dielectric and induction/radiation losses. *Copper losses* are the I^2R losses that are inherent in all conductors because of the finite resistance of the conductors. In AC systems the copper losses are higher due to skin effect. The expanding and collapsing fields about each electron encircle other electrons. This phenomenon, known as self-induction, retards the movement of encircled electrons. Thus flux density at the centre of the conductor is great and current flow towards the surface of the conductor is greater. Therefore the skin effect increases the resistance and thus the power loss. The increase in resistance is proportional to the frequency of the AC signal.

Dielectric losses are losses that result from the heating effect on the dielectric material between conductors. The heat produced is dissipated in the surrounding medium. *Induction and radiation losses* are produced by the electromagnetic fields surrounding conductors. *Induction losses* occur when the electromagnetic field about a conductor links another line or metallic object and current is induced in the object. As a result, power is dissipated in the object and lost. *Radiation losses* occur because some magnetic lines of force about a conductor do not return to the conductor when the cycle alternates. These lines of force are projected into space as radiation and this results in power losses, that is, power is supplied by the source, but is not available to the load.

Transformer losses include copper losses due to the internal impedance of transformer coils and core loss. Power transformers are connected permanently to the power system, hence their no-load losses have to be considered. No-load losses are a function of the type of lamination, core material, insulation (paper, oil), voltage and frequency. The most

Losses represent a considerable operating cost, estimated to add 6-8% to the cost of electricity and some 25% to the cost of delivery

predominant no-load losses are the core losses, made up of hysteresis and eddy current losses, given by the equations: $P_H = K_h f B_m^n$ and, $P_E = K_e f^2 B_m^2$ where f is the frequency, B_m is the flux density of the core material; K_h , K_e and n vary with core material and lamination thickness.

Factors influencing system losses

Circulating current

With modern-day highly interconnected networks, failure to maintain a flat voltage profile across networks, will result in the flow of circulating currents. These power flows increase losses in the system. It is therefore important for a power system to maintain stringent voltage limits to minimise losses. Statutory limits are $\pm 6\%$ of nominal voltage. These, however, increase maintenance costs because of additional equipment required to regulate voltage.

Voltage regulation

Since line losses increase with the square of the load current, maintaining and/or increasing the normal operating voltage of the system can reduce both the maximum demand and energy losses.

Phase balancing

From the perspective of losses, this is of significance when dealing with heavily loaded lines. The objective is to balance the phase loads so that the maximum deviation from the average is below 10%.³

Power factor

At unity power factor the current is minimum and any reactive component will cause an increase in current with a resultant increase in real power losses. For large inductive loads, losses due to vars become significant and demand-side compensation becomes necessary. Furthermore, as a result of increased current in the system, the voltage drop due to line resistance and reactance is greater than it would be at unity power factor.

Model of loss minimisation in deregulated power systems

For specified system load, economic dispatch determines the power output of each plant that will minimise the overall fuel cost. Both the economic dispatch and minimum loss problems are complex to compute manually and are usually solved with the aid of computers.^{4,5} The first case is the economic distribution of load

between generating units within the same plant. The minimum cost of fuel is achieved when the incremental costs are minimal:⁶

$$\lambda = a_T P_{GT} + b_T \quad (1)$$

where

$$a_T = \left(\sum_{i=1}^K \frac{1}{a_i} \right)^{-1}$$

$$b_T = \left(\sum_{i=1}^K \frac{b_i}{a_i} \right)^{-1}$$

$$P_{GT} = \sum_{i=1}^K P_{Gi}$$

λ is the total increment fuel cost of the plant, P_{GT} and P_{Gi} represent the total plant output and the output of individual generating units respectively. a_i and b_i are the constants that describe how the incremental fuel costs varies with unit output.

Transmission losses are not considered in the above case, because the load was shared by generating units in the same plant. However, when distributing load between various power stations, transmission losses have to be factored in to determine most economical operation, as power plants are in different locations. Using a penalty factor allocated to each plant by the equation:⁶

$$L_i = \frac{1}{1 - \frac{\partial P_L}{\partial P_{Gi}}} \quad (2)$$

L_i is the penalty factor of the plant, P_{Gi} is the power generated by the plant, and P_L is the system loss⁷ defined as:

$$P_L = \sum_m \sum_n P_m B_{mn} P_n \quad (3)$$

where \sum_m and \sum_n indicate independent summations to include all generators. B_{mn} are the loss coefficients or B-coefficients.

The B matrix takes into account the system parameters like impedance and var generation. The system losses are usually calculated using load flow software.

Distribution system loss calculation

For the distribution level, we use Eskom (South Africa electricity company) as a case study. The total system loss is given by the

Table 1 Distribution losses January 2000

energy purchases			energy losses		
GWh	rands, millions	c/kWh	distribution technical losses, (GWh)	cost of losses 74 c/kWh (rands million)	peak demand loss
2860.99	210.85	7.4	143.04 (5% of purchases)	10.58	238MW (transmission losses included)

difference between the energy generated or delivered and the energy sold. The energy used in power station or substation auxiliaries is deducted from the losses to obtain the system losses:

$$\text{system loss \%} = \frac{\text{energy delivered} - \text{energy sold}}{\text{energy delivered}} \times 100 \quad (4)$$

The value obtained from eqn. 4 includes both technical losses and a component of non-technical losses. NTL cannot be computed easily, but can be estimated from preliminary results, i.e. the result of technical losses are first computed and subtracted from the total losses, with the balance as NTL. The technical losses can be calculated using appropriate load flow software. Hitherto, many utilities arbitrarily selected estimated values for losses, because of the accuracy of available data and the simulation time required. However, software tools that allow load profiles to be considered will reduce simulation time and ensure accurate calculation of technical losses for various conditions. For South Africa, the losses are:³ for transmission, 2.5%-4.5% of generation; distribution: 3%-5% of energy supplied at main transmission substation (MTS); others: 0.5%-1% of energy supplied at MTS.

Distribution losses calculation

In Eskom (South African power utility) operations, the distribution business is made up of two parts: subtransmission (132kV-33kV) and reticulation (22kV and 11kV). First, the

load is measured at each point of common coupling between transmission and distribution. The copper losses of the transformer are calculated assuming $R = 4\%$ of X , where R = copper resistance, X = leakage reactance. The procedure is as follows:

- Obtain loading data at MTS substations.
- Calculate load factor (LF), where

$$LF = \frac{\text{total energy delivered} - \text{energy sold}}{\text{peak load} \times \text{hours in period}} \times 100\% \quad (5)$$

- Apply the peak load to scale the base case in PSS/E (power system simulation load flow program).
- Run PSS/E to calculate the peak load loss (P_{pl}) in MW.
- Determine the correct α and β factors.
- These have been found (empirically) to be $\alpha = 0.3$ and $\beta = 0.7$.
- Calculate the approximate power loss (A_{pl}):

$$A_{pl} = P_{pl} (\alpha LF + \beta (LF)^2)$$

- Calculate the approximate energy loss in GWh.
- Distribution technical loss (DTL) = $A_{pl} \times$ hours in accounting period.
- Calculate iron losses of transformers using developed loss tables.
- Add all zones together for total technical loss.
- To obtain non-technical losses this figure is subtracted from the total system loss.

Table 2 Environmental impact of losses

environmental measure	typical impact	impact due to losses (10800GWh)
water use	1.25 kL/MWh	13500 MI
ash emission	0.37 kg/MWh	4 ktonne
coal use	480 kg/MWh	5.18 Mtonne
CO ₂ output	900 kg/MWh	9.72 Mtonne
SO _x output	74 kg/MWh	80 ktonne
NO _x output	3.7 kg/MWh	40 ktonne

In order to determine where the losses are more dominant these loss calculations could be filtered down to different levels within the power network.

Discussion and conclusion

At Eskom, transmission losses include line and transformer losses in the 765kV to 275kV power networks. The distribution losses include line and transformer losses in the 132kV to 33kV networks. Other losses include line and transformer losses in networks with voltages ≤ 22 kV and non-technical losses. By considering the above estimates the cost of distribution technical losses to Eskom Eastern region for the month of January 2000 can be estimated, as shown in Table 1.³

The cost of the distribution losses in the region for the month was estimated to be R10.58 million. This figure is based on the average energy purchase price of 7.4c/kWh. In 1998 Eskom's gross energy sent out was 180000GWh and the peak demand was 27.8GW. Assuming 6% technical losses in the South African power system, the energy losses can be estimated to be 10 800 GWh. At peak demand, 1668MW is used to meet network losses.

From these figures³ it is easy to estimate the impact of losses on natural resources (coal, water) and the environment (see Table 2) and, conversely, the economic gains and pollution reduction.

Lower technical losses will provide for cheaper electricity, lower production costs with positive influence on economic growth. Its impact will be maximum during peak load conditions, as it will reduce the peak demand, thereby reducing energy requirement of the system at the critical stage when the unit cost of generation is usually the highest. The peak demand losses (MW) also have significant financial implications, because peaking stations (for top lopping) are required to meet the increase in demand, which are usually more expensive to run than base-load stations. Therefore small reductions in network losses will amount to significant financial savings to utilities as well as to customers.

To evaluate the impact of system losses, the

magnitude of these losses needs to be determined. As shown, the total system losses can easily be determined. The losses are then divided into technical and non-technical losses. The next step is to assess the continuing cost of losses, usually in annual terms. The best method for costing losses is to use the long-run marginal cost of the supply to each level of the power system. This cost should reflect cost of production, in terms of generating capacity, fuel consumption and the cost of capacity in the transmission and distribution networks.

These losses should be recognised as real and substantial costs on the supply of electricity and should be managed like other costs, and reflected in pricing methodologies on the spot market in a deregulated structure. A deregulated energy market pricing structure will be expected to reflect this loss factor in spot prices (see Appendix).

There are two approaches to dealing with these losses. A no-action policy is to invoke

the supply-side option of providing generation and upstream network capacity and consuming fuel to supply them. Alternatively we can reduce losses by local network development (demand-side option). By using this option one not only reduces the generation and system capacity but also reduces the cost of delivery of energy, which is the biggest contributor to the final cost of energy. This option also improves system efficiency and reduces the cost of electricity to consumers.

As a rule, there is an optimal level of network losses, which will minimise total cost of supply and hence lower the cost of energy. Attaining this optimum should be the goal of electric utilities. Some techniques of loss reduction involve little or no additional capital investments, such as optimal positioning of normally open points to distribute load as evenly as possible and proper phase balancing. The impact of losses on the transmission and distribution systems has far-reaching effects. They increase both the cost of production of energy as well as the delivery cost of energy. Therefore more generation and system capacity is required to serve the system load, which increases capital costs. During system peaks, the losses are also increased and therefore

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increase the cost of electricity production drastically as the cost of production is extremely high during this period. The environmental impact includes increased depletion of non-renewable energy resources, and consequent releasing of more pollutants into the environment.

Losses generate substantial cost and are a significant issue in power system management. Loss evaluation is complex but critical in assessing the overall performance of a power network. Reducing electricity costs to the customer and minimising loss of high-quality energy are worthy objectives for the industry and this will be challenging in the proposed deregulated ESI and electricity pricing in energy markets.

Acknowledgment

This work has been supported by the University of Natal and Dasela Engineering Consultants, Durban, South Africa.

References

- 1 DAVIDSON, I. E., and ODUBIYI, A.: 'Power system operation in developing economies—the Nigeria experience (Part 1)', Energy supply and management feature, *South Africa Electricity & Control Journal*, July 2001, pp. 6-11
- 2 DAVIDSON, I. E., McKECHNIE, D., and MADONSELA, G.: 'Integration and automation in the electrical telecontrol industry—prospects and problems', *Elektron*, Electronic Journal of the SA Institute of Electrical Engineers, January 2001, pp. 12-13
- 3 KRISHNASWAMY, N.: 'A holistic approach to practical techniques to analysis and reduce technical losses on Eskom power networks using the principles of management of technologies', Technology Leadership Program, Management of Technology Dissertation, April 2000
- 4 PAUL, C. R.: 'System loss in a metropolitan utility network', *Power Engineering Journal*, September 1987, 1, (5), pp. 305-307
- 5 MILLER, R. H., and MALINKOWSKI, J. H.: 'Power system operation' (McGraw-Hill Book Company, New York, 1970, 3rd Edn.)
- 6 KIRCHMAYER, L. K.: 'Economic operation of power systems' (John Wiley & Sons, New York, 1958)
- 7 GRAINGER, J. J., and STEVENSON, W. D., JUN.: 'Power system analysis' (McGraw-Hill, New Jersey, 1994)

Appendix

In a power system total generation equals total demand plus line losses:

$$\sum_i P_G = \sum_k P_D + \sum_n P_L \quad (i)$$

From eqn. (i) it can be assumed that total generation revenue will equal total customer revenue plus operating cost of the T&D network:

$$\sum_i C_{GR} = \sum_k P_D C_{SP} + \sum_n P_L C_{XL} \quad (ii)$$

where C_{GR} is generation revenue, P_D is consumer demand, C_{SP} is spot price paid by consumer, P_L is line losses and C_{XL} is operational cost of transmission line.

$$(P_L C_{XL})_T = (C_{GR})_T - P_D (C_{SP})_T \quad (iii)$$

$$\gamma = \frac{dC_{GR}}{dP_i} - \eta_k \frac{d(P_D C_{SP})}{dP_i} \quad (iv)$$

where γ is marginal transmission cost, P_i is power at node i and η is the Lagrangian multiplier for maximum capacity of line k .

Line loss is a function of power flow and system constraints. From the above we can minimise the following equation:

$$P_L = \sum_m \sum_n P_m B_{mn} P_n$$

subject to the constraints:

$$\gamma_{\min} \leq \gamma \leq \gamma_{\max}$$

$$P_{D(\min)} \leq P_D \leq P_{D(\max)}$$

$$P_{Gi(\min)} \leq P_{Gi} \leq P_{Gi(\max)}$$

$$Q_{Gi(\min)} \leq Q_{Gi} \leq Q_{Gi(\max)}$$

where P_{Gi} is the active power at node i and Q_{Gi} is the reactive power at node i .

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