Load modelling and load profiling to support network operation and design

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***Abstract*—The analysis of load profiles is essential to understand energy and power usage. The aspects considered when analyzing a load profile are the operating model of the entity, deriving a load model, modelling losses and identifying the load characteristics. The methods and techniques in calculating and determining these characteristics are outlined. Understanding these aspects is crucial for future system planning, operations and influences investment decisions such as the development of Smart Grids, where the pertinence of such data is essential. This paper considers 7 energy consumer load profiles and the analysis thereof to ultimately identify opportunities for load optimization.**

***Index Terms*—Loss factor, load factor, load profile, load modelling, energy saving, Smart Grid**

I. Introduction

There are several methods to determine load models and compute load and loss factors for an electrical network. These form part of the parameters used in the analysis of a network with the ultimate aim being to model a network. This allows for understanding and predicting the performance and behavior of the system which can assist in optimization control, growth projection, design and billing amongst other things. Load profiling and load modelling speak to different (but not separate) concepts as they are associated with different timelines, the former over say 24 hours and the latter a short/transient period as a function of voltage.

This paper presents a very brief outline of some of the popular methods to determine the factors describing these models. The most appropriate are selected and applied to 7 sets of load (meter) profile data. Where possible a high level characterization of the load model is commented on each data set. The results and the analysis thereof are presented. Based on this analysis, methods to reduce energy consumption costs and improve load profiles will be proposed for each of the users using a qualitative approach. The analysis is intended to provide an approach to profiling the loads with the goal being to enable an optimized solution to the delivery of through a Smart Grid. This could take the view of the aggregated load of feeder or as individual micro-grids. This type of information allows for more accurate network modelling and hence design as opposed to crude estimates which often lead to over-design.

The data analyzed is supplied by the University of Pretoria.

II. Methods for Determining Loss Factors

A. *Defining electrical losses*

There are several methods available to model loss factors within a distribution system. There are two types of losses in a network, technical and non-technical. Technical losses occur due to several physical characteristics of an electrical distribution system, including the following [1]:

- Corona Losses
- Leakage Current Losses
- Dielectric Losses
- Transformer and motor core losses
- Open-circuit Losses
- Resistance losses

Non-technical are losses that are not related to energy, but revenue losses from theft, metering issues, billing etc. This paper focusses on the technical losses of a system, which become complex to determine with a complicated network. Given these complexities many theoretical and empirical methods exist today and are discussed.

B. *Direct computation of i^2R losses*

This method essentially considers the resistance of feeders/conductors used in the power distribution circuit to calculate the losses [2]. Naturally this implies that the circuit conductors, lengths, current drawn and other parameters are known.

C. *Using B-Loss Coefficients*

This method is based on the derivation of a loss equation for a network of two sources and loads on either end with the transmission network impedance being represented by its bus impedance matrix. The solution can be expressed by equation 1 below which essentially represents the power loss as a function of the generated power. [3]

$$P_L = \sum_{i=1}^{K} \sum_{j=1}^{K} P_{gi} B_{ij} P_{gj} + \sum_{i=1}^{K} B_{i0} P_{gi} + B_{00} \quad (1)$$

Where: $P_L \equiv$ Power loss
$P_g \equiv$ Generated power
$B \equiv$ B-matrix or loss co-efficient
$P_L \equiv$ Power loss

$P_L \equiv$ Power loss

Several methods are used to determine these loss coefficients.

D. Differential power loss

This method essentially makes use of measurements at the generation and load ends to perform a comparative calculation to determine the losses incurred between those two points [2]. This is essentially an energy balance.

E. Loss factor based on load factor

This method estimates the actual power loss by means of a formula (approximation) as indicated in equation 2 below:

$$F_{LS} = 0.3 \times F_{LD} + 0.7 F_{LD}^2 \qquad (2) \qquad [4]$$

Where: $F_{LS} \equiv$ Power loss
$F_{LD} \equiv$ Load factor

III. LOAD FACTOR

It is apparent that load factors are not a measure used in isolation and have are key inputs into the calculation of losses on a network, for certain computational methods. The load factor describes to what extent the load can shift (increase) with respect to the average load. It is defined in equation 3 below.

$$F_{LD} = {}^{D_{avg}}\!/_{D_M} \qquad (3) \qquad [4]$$

Where: $F_{LD} \equiv$ Load factor
$D_{avg} \equiv$ Average load
$D_M \equiv$ Maximum demand

IV. LOAD MODELS

Load models essentially represent a mathematical relationship between reactive power, real power and voltage. This is typically used to define system behavior over a short duration if not transient behavior. Usually this takes the form of a polynomial function of voltage as in equations 4 and 5 below:

$$P = a_0 + a_1|V| + a_2|V|^2 + a^{-1}|V|^{-1} + \cdots \qquad (4)\ [4]$$
$$Q = b + b_1|V| + b_2|V|^2 + b^{-1}|V|^{-1} + \cdots \qquad (5)\ [4]$$

Where: $P \equiv$ Real Power
$Q \equiv$ Reactive Power
a_x, $b_x \equiv$ co-efficients

There are essentially two categories of load models, i.e. static and dynamic loads. These can further be classified into special cases as follows: [5]

Static models:

- Constant Power (only a_0 and b_0 non-zero of equations 4 and 5)
- Constant Current (only a_1 and b_1 non-zero of equations 4 and 5)
- Constant Impedance (only a_2 and b_2 non-zero of equations 4 and 5)
- Non-linear (exponential relationship)
- Frequency dependent

Dynamic models:

- Machine models (circuits with time dependencies), eg. an induction motor
- State space models
- Transfer function models

In reality, loads are composite combinations of the above approximations.

V. PURPOSE OF LOAD PROFILING

It is essential to understand the purpose and use of studying/researching load data to apply it in a pragmatic fashion. With new distributed generation technologies amidst economic and environmental pressures on utilities – metering, measurement, load management, power flow control and ICT; have to follow suit for operating costs, investments and revenue (billing) optimization.

The reason being, that distributed generation technologies such as photovoltaic, wind and energy storage technologies influence power consumption and energy usage from the electrical grid. This has spurred the development of the Smart Grid to cater for such. In some cases this may mean complete isolation or “islanding” presenting a complete removal from that demand. In other extremes, this may mean consumers becoming generators and sending power into the grid. This places a requirement on the (smart) metering to record power flow in the reverse direction, else it may reflect incorrect measurements and result in non-technical losses [6].

This change in the load (in some cases to a source) affects the loading of feeders and flow of power. Thus the network needs to consider how to re-route feeders, links, breakers such that efficient transmission of power is handled. This also influences protection schemes which together with metering information requires telecommunications infrastructure to support it. This all points to a “smart” grid.

Smart grids and the efficient design of such, requires detailed load profiling. Such data has become of such research interest it is provides a pool of data for statistical studies [7] and is already thoroughly investigated in developed countries to the point of segregating domestic loads [8]. Similarly demand side management benefits from this bi-directional communication and allows the user to manage his power usage. Ultimately this influences the maximum demand of a network and can impact investment decisions.

VI. ANALYSIS OF SAMPLE LOAD PROFILES

Data obtained from load data from 7 different consumers (of different types) are analyzed below. Naturally the analysis is based on an aggregate load model. It is assumed that the system is in a steady state over measurement intervals and the voltage is relatively constant. For each data set a mathematical model (continuous function) is generated and the best-fit selected by inspection. Comments regarding the load model are provided where it correlates with a load model type as per Section IV.

A. 5 Star Game Lodge

The load at a game lodge would be expected to be primarily lighting, air-conditioning, geysers and kitchen type of appliances. The number of rooms is expected to be small and exclusive, thus the load is not expected to be large as can be seen in Figure 1.

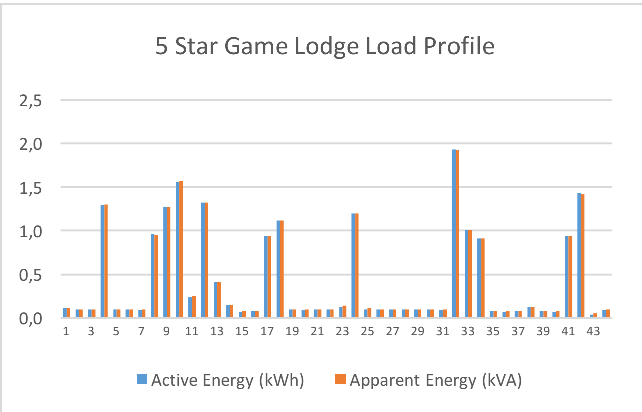

Figure 1: 5 Star game lodge load measured over 44 hour period

It can be seen that the load amplitude is not very consistent, however it correlates with peaks before breakfast, lunch and supper, with a small base-load when tours should be taking place. The load power factor is nearly unity, which would be expected from the types of loads. The load characteristics are summarized in the table below.

Table 1: Load characteristics for the 5 star game lodge

Load Characteristics	Value
Maximum demand	1.92
Load factor	0.23
Power factor (average)	0.97

By inspection this would most closely resemble a constant impedance load switched on and off intermittently with a negligible reactive energy component (predominantly resistive), as supported by the average power factor in Table 1.

To produce a mathematical relationship for such an individual such a load would best be done using fuzzy logic with a constant impedance model, as a polynomial expression would be of a very high order (10 and greater). For this reason it has not been generated, but is easily achievable.

B. Courier Company

A courier company operation is expected to operate on a 24/7 basis so it should work through the evening, however there would be interaction with customers to collect and receive goods. Thus the day would have a higher load than the evening due to the superposition of these activities. This pattern is seen in Figure 2.

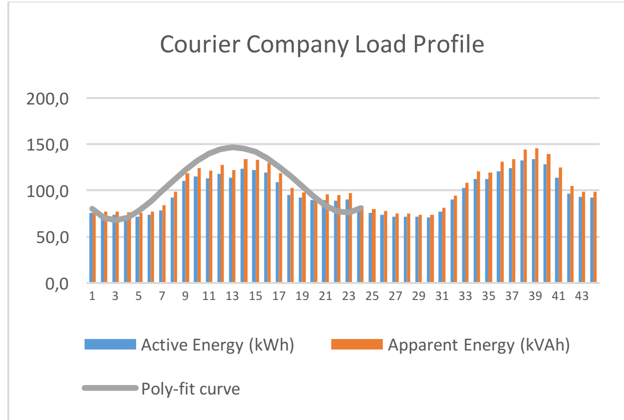

Figure 2: Courier company load measured over 44 hour period

It can be seen that the load factor is reasonably high, as is the power factor, which would probably be lighting, computers and printers. The computers, printers and electronics usually have a slightly lagging power factor, hence the increased apparent power during working hours [9].

This load type is that of a constant load with a superimposed constant power or constant impedance step to it. However using Matlab to produce a polynomial fit produces 4th order polynomial represented by equation 6.

$$Polyfit_{courier} = 0.005t^4 - 0.364t^3 + 3.405t^2 - 11.601t + 79.251 \quad (6)$$

Aggregate information can be obtained from looking at the load characteristics summarized in Table 2.

Table 2: Load characteristics for the courier company

Load Characteristics	Value
Maximum demand	145.73
Load factor	0.71
Power factor (average)	0.94

C. Car Dealership

A car dealership will be engaged in sales which is associated with equipment constituting a mixture of lighting and electronics. The other operational component may be servicing, with some hydraulic machinery etc, however both the sales and the servicing aspects are during usual working hours in the day. Out of working hours, the lighting and security load would be expected to remain. This trend can be seen in Figure 3.

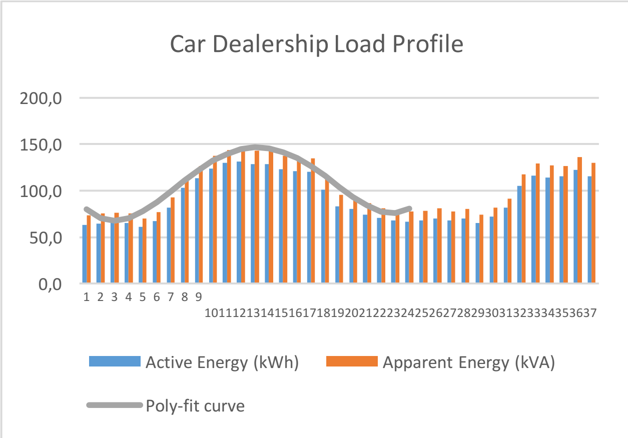

Figure 3: Car dealership load measured over 38 hour period

This load profile has a very distinct, almost normal/Gaussian distribution over a 24 hour window. This load profile would be best described as a constant power model by rough estimation based on inspection. However using Matlab to produce a polynomial fit produces a 4th order polynomial expression of the load profile represented by equation 7.

$$Polyfit_{car} = 0.008t^4 - 0.364t^3 + 5.021t^2 - 15.546t + 80.819 \quad (7)$$

Table 3: Load characteristics for the car dealership

Load Characteristics	Value
Maximum demand	145.84
Load factor	0.72
Power factor (average)	0.88

Table 3 above shows the other aggregate information over the entire period.

D. Residential Customer

A residential load is expected to peak in the morning before working hours and then later in the evening when returning from work. The load is typically a mixture of appliances, electronics but heavily weighted on heating and cooking. Thus the load is primarily resistive as can be seen in Figure 4.

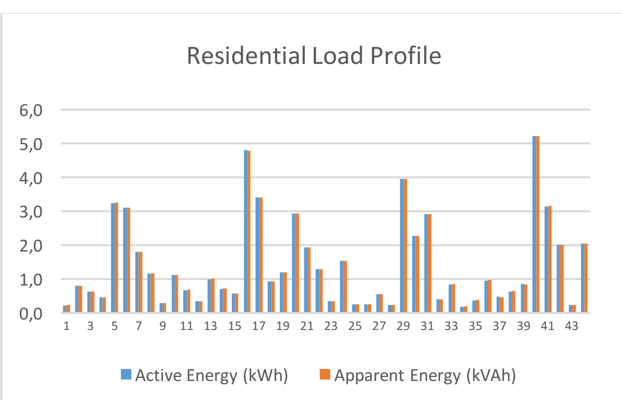

Figure 4: Residential customer load measured over 44 hours

It can be seen that the load is cyclical with peaks before breakfast and after working hours. Table 4 below indicates the characteristics of the load.

Table 4: Load characteristics for the residential customer

Load Characteristics	Value
Maximum demand	5.22
Load factor	0.27
Power factor (average)	1.00

This load profile would be best described as a constant impedance model with a negligible reactive power component. However studies would suggest that the reactive components becomes more substantial at lower load levels (stand by) [9]. This can be a very difficult load to model with respect to time over a day, it is really a combination of a composite load with some fuzzy logic as oppose to a continuous function. A polynomial representation would be greater than a 13th order to have an appreciable correlation. A discrete model would be more suitable.

E. Restaurant

A restaurant falls within the service industry which is centered on customer comfort and experience. Thus the major loads are air-conditioning, extraction fans, ovens and stoves. These loads may include induction type ovens and motors running throughout the working hours. This pattern is evident in Figure 5.

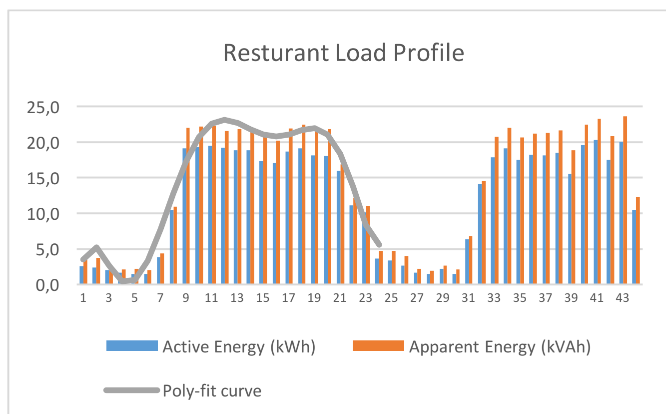

Figure 5: Restaurant load measured over 44 hours

This load profile would be best described as a constant power model with varying apparent power with respect to a relatively stable power, like a step function a simple discrete function. A polynomial function for a reasonable fit would be an 8th order as in equation 8.

$$Polyfit_{car} = 5.77\times10^{-6}t^7 - 4.77\times10^{-4}t^6 + 0.015t^5 - 0.244t^4 + 1.92t^3 - 6.23t^2 + 6.487t + 3.485 \quad (8)$$

Table 5: Load characteristics for the restaurant

Load Characteristics	Value
Maximum demand	23.62
Load factor	0.60
Power factor (average)	0.83

F. *Spar*

A spar is a typical grocery store and thus will have a baseline level of security and refrigeration loads and lighting with increased computer, HVAC and lighting loads during working hours as can be seen in Figure 6.

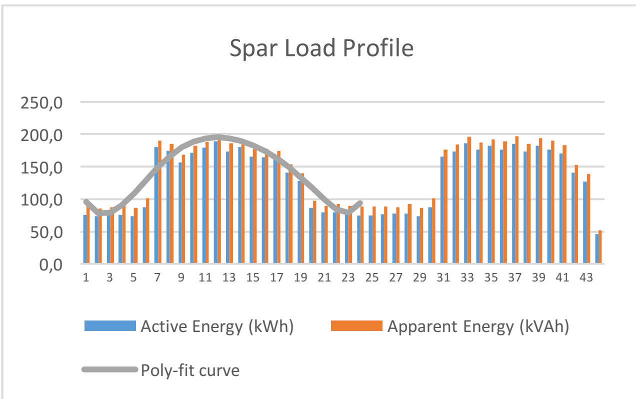

Figure 6: Spar load measured over 44 hours

It can be seen that the load is distinctly cyclical. This load profile would be best described as a constant impedance model combined with a step function with a constant off-set. A 8th order polynomial function to map this is represented in equation 9.

$$Polyfit_{car} = 3.55\times10^{-6}t^7 - 2.1\times10^{-4}t^6 + 3.593\times10^{-3}t^5 + .016t^4 - 1.179t^3 + 12.175t^2 - 28.303t + 95.891 \quad (9)$$

Other characteristics are summarized in Table 6.

Table 6: Load characteristics for a Spar

Load Characteristics	Value
Maximum demand	199.70
Load factor	0.71
Power factor (average)	0.91

G. *Tile Retailer*

A tile retailer typically will have lighting, computing and perhaps some motorized equipment in the storage area. It is low risk so baseline lighting and security loads are expected to be low as it is in Figure 7.

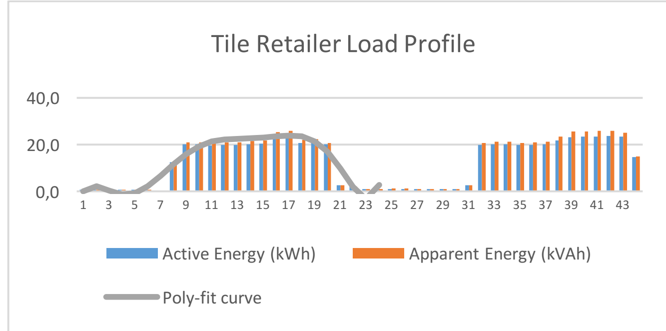

Figure 7: Tile retailer load measured over 44 hours

It can be seen that the load is most distinctly bi-modal with minimal load outside working hours and a relatively constant power consumption during work. This could be represented by a very basic step (discrete) function which would approximate to a constant power load. A polynomial function as represented in the Figure 7 for a 24 hour period is of the 7th order and represented by equation 10.

$$Polyfit_{car} = 7.23\times10^{-6}t^6 - 5.65\times10^{-4}t^5 + 0.0173\times 10^{-3}t^4 - .262t^3 + 1.98t^2 - 6.496t + 0.2084 \quad (10)$$

Other characteristics are summarized in Table 7.

Table 7: Load characteristics a tile retailer

Load Characteristics	Value
Maximum demand	25.99
Load factor	0.52
Power factor (average)	0.95

VII. OPTIMSATION OF LOADS

Without altering the technology employed, i.e. substitution with energy efficient equipment or control systems for each system, there are other means to improve the load characteristics and/or reduce energy consumption. This may lead to a reduction in technical losses and non-technical factors (cost of electricity) for the consumer and/or the electricity operator.

These methods at the load/consumer end, include:

- Power factor correction – which reduces reactive current (with associated losses) and apparent power is minimized.
- Change in schedule/sequencing of equipment such that a flatter, more consistent load is achieved such that maximum demand is minimized and load factor is maximized. Understanding the operational characteristics of the entity is crucial to make this relevant.
- Reduction in waste/consumption, i.e. only using energy when required.

It is also possible to optimize loading at a node supplying the mixture of loads, i.e. changing the aggregate load profile and balancing loads from a feeder. However this is out of the scope of this paper, which serves only to identify the opportunities where Smart Grids could be employed.

Finer control and protection, as supported by Smart Grid technologies would allow for optimal usage of the capacity of installed infrastructure based on thermal control, allowing for the "sweating" of assets. Part of the information that feeds into and emanates from Smart Grids, load models and load profile data would assist in more accurate network planning as opposed to crude diversity factors and other estimates made in the absence of such detailed information.

The options for optimization looking at alternative generation options for each of the load types/profile are analyzed in section VII are discussed below.

A. 5 Star Game Lodge

The Game Lodge, it is a relatively small load. Depending on the load, it may be necessary to switch certain equipment out of sequence to stagger the load. However with food preparation and lighting, this is difficult to do. Thus the only way to improve the load profile may be to make the use of energy storage options like a UPS which would not require a large capacity or power output, e.g. a UPS with a rating of 2 kW with a battery bank of 2000 VAh capacity.

B. Courier Company

The courier company has a fairly constant load in comparison. A combination of power factor correction and perhaps a photo-voltaic system with appropriate automatic change-over or switching to clamp that daytime peak. A system that can deliver approximately 30 kW would provide a significant improvement. This is obviously a substantial investment decision. However this is more in the way of reducing grid energy usage as oppose to load optimization.

C. Car Dealership

The car dealership is not very different from the Courier Company load profile and thus a similar approach should be used to reduce the maximum demand. There should be sufficient surface area over the roof to cater for say a 40 kW photo-voltaic system.

D. Residential Customer

The residential load could benefit from changing the scheduling of items like washing machines, putting the geyser on a timer etc. The load profile would also benefit from a solar heating solution and perhaps the use of a UPS to flatten the load profile.

E. Restaurant

The restaurant probably does not have flexibility to the timing of loads. However the introduction of power factor would improve the maximum demand and reactive energy consumption (and any billing) appreciably. Since the load is only in the day, a photovoltaic type solution may be worthwhile but this wouldn't be the strongest candidate comparatively.

F. Tile Retailer

For the tile retailer, the load is quite constant when in use, so aside from power factor correction, there is little that can be done. A UPS would have to be specified with a capacity for the entire load and would thus be very costly as would a photo-voltaic solution.

VIII. CONCLUSION

Load modelling and load profiling are key in understanding how an electrical load/network behaves, on a transient and steady-state time scales. Some of these factors, the methods for obtaining them and the significance of them are presented and are crucial to load modelling and load profiling. Among the several measures are loss factors, load factors and power factors.

With the information available, 7 data sets (consumer sets) are analyzed to determine the factors that are possible. A time based polynomial model has been fitted to each profile. Using this continuous function for a 24 hour period is produced per a data set. This type of information provides key information for more accurate load analysis and the corresponding design of networks whether it form part of a Smart Grid or not. Such profile could be aggregated and controlled through a Smart Grid to improve the aggregate factors, balance loading, improve efficiency and even maximize capacity utilization.

High level options for improving the load characteristics and load profile is explored considering servicing peak loads with alternative energy sources (which would naturally imply the corresponding control). This paper provides an appreciation of the theory and application of load analysis against the backdrop of operating constraints and cost to optimize loading and network design.

IX. ACKNOWLEDGMENT

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