THE IMPACT OF SMALL SCALE EMBEDDED GENERATION AND EEDSM ON HISTORICALLY DESIGNED NETWORKS AND HOW IT WILL AFFECT NETWORKS OF FUTURE CITIES

LEADING THE ELECTRICITY DISTRIBUTION INDUSTRY

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Abstract

Load forecasting methods are based on selecting ADMD values for various load classes, summating the load class load profiles and the application of diversity factors while looking 10 to 20 years into the future. These factors, especially diversity, are altered through EEDSM and small scale embedded generation initiatives. Distribution networks are not designed to cater for reverse power flow or a diversity-less scenario (e.g. solar PV power injection at rooftop level into the grid). The paper will investigate the impact EEDSM and small scale embedded generation may have on these parameters used for master planning and designs, how it will affect existing networks and which concerns we should address for our future cities in this regard.

1. Introduction

Throughout the world there is a drive to improve energy efficiency, reduce electricity demand and encourage renewable energy generation. The public is generally informed through media that this is good for the environment, will prolong generation and grid assets as well as natural resources such as fossil fuels and water. However, it may be possible that these initiatives change the performance of planned (future) and designed (existing) networks without engineers reconsidering past assumptions or traditional methods. Quite a number of assumptions are made in the selection of suitable parameters and combinations of parameters to predict future load and to plan and design infrastructure accordingly. If parameters are affected and the impact of a change is not considered, unexpected or even degraded performance of networks may result while utilities and municipal electricity re-sellers may have to lay out unplanned capital to rectify or address problems caused.

The South African Grid Code has defined several classes of embedded generation [1]. For this paper, embedded generation of Class A1 (i.e. <13.8 kVA) and EEDSM initiatives for the low voltage domestic load class will be considered.

This form of generation is called embedded generation, because it cannot be controlled by the national System Operator.

In this paper, only the technical impact on distribution network design and planning parameters are considered. Power quality and financial impact to revenue streams are not considered. While energy saving and demand side management (EEDSM) initiatives are fairly well implemented by many utilities, most utilities do not allow the connection of small scale embedded generators at present to their distribution networks pending further regulations, by-laws and certainty about the impact it will have on their networks and revenue streams. In spite of utilities not allowing small scale embedded generation, it exists in the distribution networks already in South Africa, and the location thereof in the networks are not only unknown to utilities, but can also not be controlled by utilities.

NRS 097-2-1:2010 Grid Interconnection of Embedded Generation [2] attempts to provide some guidance to the implementation and compliance of embedded generation.

2. Load forecasting, related planning and design parameters

In electricity distribution network designs and master planning, various assumptions have to be made while the designer or planner considers future loading and scenarios. Load forecasting is an integral part of any network design and considers a saturated maximum demand state 15 to 20 years into the future. The load forecast is determined by considering a combination of diversity factors, load factors, load profiles, loss factors, growth rate and after diversity maximum demand (ADMD). Once the end state load is known, network elements can be sized based on voltage drop, current carrying capability and fault level considerations.

Much work has been done internationally over the years to develop tools and formulae to predict and calculate diversity from as early as the late 1930s [3] on domestic loads for LV network design and to calculate maximum demand from ADMD during the early 1950's [4] (deterministic methods).

Coincidence and diversity by definition are:

$$Coincidence = \frac{total\ MD}{\sum Indiv.MD's} \qquad \dots (1)$$

Where MD = Maximum demand,

and

$$Diversity = \frac{1}{Coincidence} \qquad \dots (2)$$

Boggis [4] and Mcqueen [5] related maximum demand, ADMD and diversity factor (DF) as:

$$MD = N \times DF \times ADMD \qquad \dots (3)$$

$$ADMD = \lim_{N \to \infty} \frac{1}{N} \sum_{i=0}^{N} MD_i \qquad \dots (4)$$

$$DF = 1 + \frac{k}{N} \qquad \dots (5)$$

Where   k = Coincidence, and
N = Number of consumers

Later theory suggested that a homogenous group as small as 100 consumers were sufficient to produce an accurate ADMD value. However, the CSIR [6] suggests that a 1000 consumers form a representative sample size to determine an accurate ADMD.

In some cases, as described in [4], equation 5 also existed in the form

$$DF = 1 + \frac{k}{\sqrt{N}} \qquad \dots (6)$$

Voltage drop calculations were initially based on empirical formulae (deterministic methods) such as British and AMEU diversity correction curves with neutral unbalance compensation), followed by statistical distribution curves (probabilistic methods) such as the Herman-Beta method [7], [8]. Lately, the USA and Australia are considering stochastic methods as opposed to the probabilistic methods, considering a larger dependency on other factors such as time, temperature, humidity, cloud cover etc. [9].

The Herma-Beta distribution curve [7] still relies on an ADMD parameter to be selected, while diversity correction is applied through the selection of α and β parameters to model the probability of a consumer drawing a specific current at peak time.
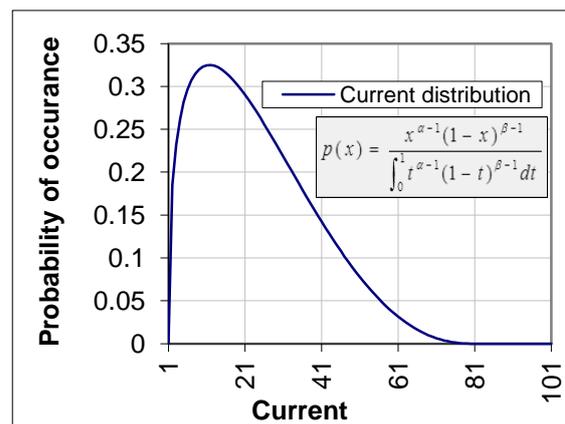

Figure 1: Beta distribution curve with parameters α=1.37, β=3.39, c=80, ADMD=5.3 kVA (NRS034 Table 2 LSM 8 high end)

Present ADMD is still the best determined by measurement, while future ADMD draws on the experience of the planner to combine load growth, income level and other factors to produce a suitable figure. Consider the following 1-minute domestic load profile:
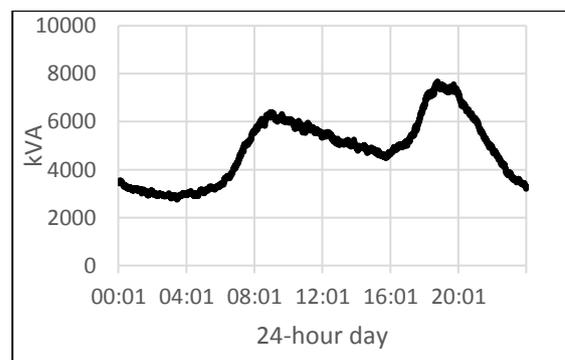

Figure 2: Domestic 24-hour load profile

For this load profile, the maximum demand of 7 617 kVA was recorded at 18:47 on a given day. For 1 511 domestic consumers and streetlight load of 62 kVA, the present ADMD is:

(7 617 – 62) / 1 511 = 5.0 kVA / household.

It is to be noted that the measurement interval plays a significant role in the ADMD measurement. The longer the measurement interval, the larger the error between the integrated peak and the instantaneous peak.

The projection of this ADMD into the future requires the application of S-curve load growth theory, as well as knowledge of network load maturity. If this network was designed at a 5.3 kVA ADMD, it is 94% mature at present.

Following determination of a final load, the network can be designed. What happens when design parameters change? The following two sections of this paper examine simple changes to e.g. ADMD through residential load control, such as ripple controlled geyser switching, as well as small scale embedded generation such as solar PV.

3. EEDSM

EEDSM generally refers to energy efficiency and demand side management. Generally, the following figure is used to explain the various techniques:
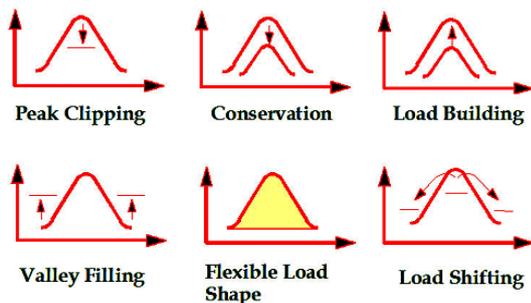

Figure 3: Impact of EEDSM initiatives on load profiles

Energy efficiency, or conservation generally reduces the demand and energy, which does not have a negative effect on the distribution network. This is already deployed by many utilities and customers, such as more energy efficient streetlights, domestic CFL roll-out, replacement of fluorescent lamps in offices with more efficient lamps, replacement of conventional geysers with heat pumps and solar geysers etc.

Demand side management usually involves load shifting, which is in effect a combination of peak clipping and valley filling. Domestic ripple control is one such an example rolled out to domestic users to reduce the maximum demand during the morning and evening peak. In this case, no energy is conserved, just moved. When load profiles containing ripple controlled geysers are investigated, it has been observed that the cold load pick-up resulting from the load shift sometimes exceeds what would have been the original peak. By definition, the ADMD has increased and the load factor decreased due to a lack of diversity on a certain load portion of the network, in this case the geyser load. In many cases, the utilities save on their revenue bills purely by consuming the energy at a more cost effective time. Consider a typical recent example, Figure 2, where the load profile a controlled day is superimposed on the profile of an uncontrolled day.
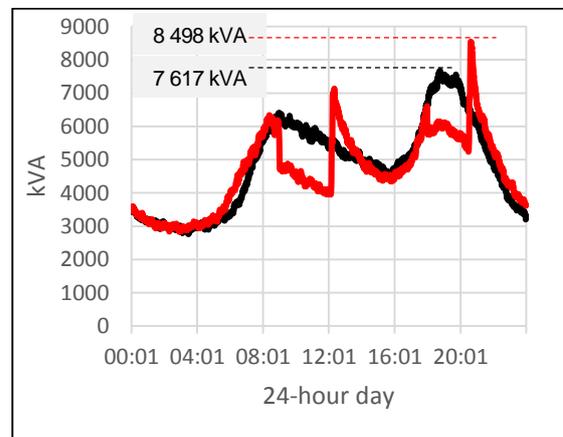

Figure 4: Effect of cold-pickup load on a ripple control system, indicating an ADMD increase

From this observation, the ADMD has increased by 11.6% while studies by an Italian Distributor have indicated as much as a 25% increase [8]. Very often, control does not take place at the 11 kV level, but at the billing level, e.g. 132 kV, in which case occurrences such as these can be expected. The discussion of improved control algorithms at multiple network levels are excluded from this study.

It must be noted that measurement error, when considering for instance 30-minute integrated data vs. 1-minute integrated data, can be as high as 15% (specifically observed for the load-controlled profile in Figure 4).

By considering an example low voltage feeder, designed at 5.3kVA ADMD, the impact of an ADMD increase can easily be observed through load flow analysis.

The Beta distribution curve parameters based on the design ADMD as well as the revised ADMD for

two scenarios, should an increase of 11.6% and 25% respectively occur to present day ADMD of 5 kVA, are as follows:

Table 1: Ripple control impact to Beta distribution curve modelling parameters

ADMD change	Revised ADMD kVA	α	β	C
5.3 kVA Designed	5.3	1.37	3.39	80
5.0 kVA + 11.6%	5.8	1.29	2.83	80
5.0 kVA + 25%	6.25	1.21	2.37	80

For an example low voltage (LV) feeder system, two scenarios are considered:
- A- A tapered LV feeder with only certain cable sizes used. Here, a circuit breaker is required at each change in cable size.
- B- An LV feeder with the same size right through. Here, a circuit breaker is only required at the transformer to protect the cable.

All LV cables in these two scenarios are copper cables. Service connections are 16 mm^2 two-core, 30 m when on the same side of the road as the LV distribution or metering kiosk, and 43 m when on the opposite side of the road.
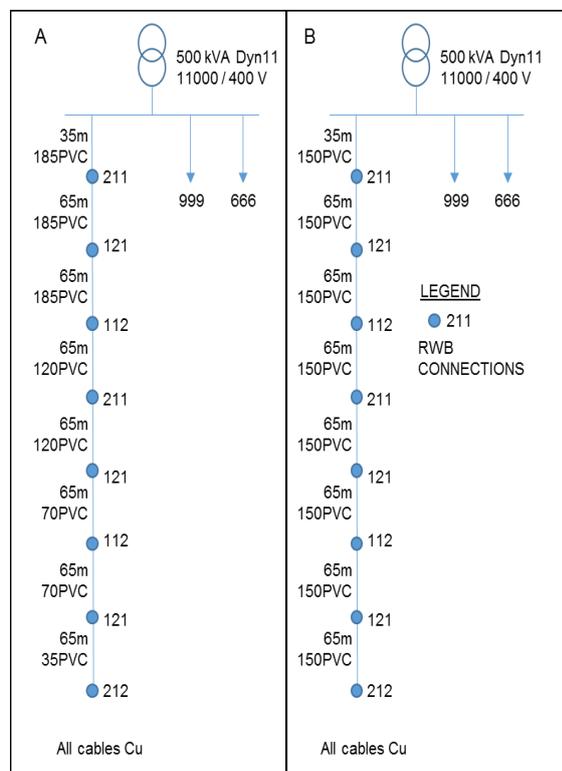

Figure 5: Sample LV feeder for two scenarios: Tapered LV feeder (A) and the same cable size used right through (B)

Two additional feeders are shown connected to transformer secondary in order to correctly simulate voltage drop across the transformer.

The phase allocation is such that each feeder contains an equal number of consumers per phase, although the three feeders are of different length. For Scenario B, the feeder is designed to include as many domestic customers as possible to be just within the maximum allowed voltage drop, considering nominal tap transformer settings and assuming a 1 p.u. MV voltage. The cables were then changed for Scenario A, and covered only four types of cables, as many utilities only stock a certain number of cable sizes in their stores.

The results of a load flow analysis are as follows:

Table 2: Results of load flow for two sample feeder designs at 11.6% and 25% ADMD increase

ADMD (kVA)	Trans-former load (kVA)	Min V (% of nominal)	Highest loaded cable (% of rated current)	% distance reach of LV feeder @ 90% V
Tapered LV cable feeder (A)				
5.3	478	90.14	77	100
5.8	519	89.28	84	73
6.25	560	88.44	90.9	60
One size LV cable feeder (B)				
5.3	478	91.34	88	100
5.8	519	90.59	96	100
6.25	560	89.85	103.5	85

These results demonstrate that:
- a) The lowest voltage at a customer distribution board drops below the minimum allowed voltage of 0.9 p.u.
- b) Transformer loading increased by 17%, although in this example the loading is still within the overload conditions allowed by the transformer manufacturer, provided that the overload duration remains below 4 hours in a 24-hour cycle.
- c) For scenario B, the conductor section closest to the transformer has exceeded rated capacity.
- d) For Both scenarios, at significant ADMD increase, the allowed maximum voltage drop is reached before the end of the feeder.

4. Embedded generation

Embedded generation in the LV network regions of distribution networks are difficult to control by utilities. With rising electricity prices, it is possible that the levelized cost to install e.g. solar PV may

soon outweigh the cost when purchasing from the utility. There are already solar PV panels installed on distribution networks with the possibility of reverse power flow in the case of excess power. Distribution networks were traditionally not designed for reverse power flow since almost all LV feeders in South Africa are radial feeders.

During low load, conditions are such that any excess energy not consumed by the premises itself could flow into the network. According to impedance paths and phase injected on, the energy will flow to the nearest load on that phase. This in itself creates unbalance elsewhere in the network, which increases voltage drop. Generally, the voltage rises where a generator is connected while the distribution network is traditionally designed to mitigate voltage drop. Distribution transformers are on fixed taps, and cannot adjust itself to compensate for increased voltages on the LV network. The networks are further designed with diversity between loads in mind. If the amount of energy injected into the network during low load conditions is not controlled, there exists the possibility of overloading sections of the LV cable network due to a lack of diversity between multiple solar PV embedded generators.

The effect of solar PV power injected into the network from house-hold level on voltage rise will be demonstrated through load flow analysis. Although fault level generally should increase when generators are connected to the network, the effect on fault level will not be illustrated or discussed further in this paper.

Consider a 5.3 kVA load profile, averaged for a single consumer, with a 3 kW solar PV plant (at unity power factor):
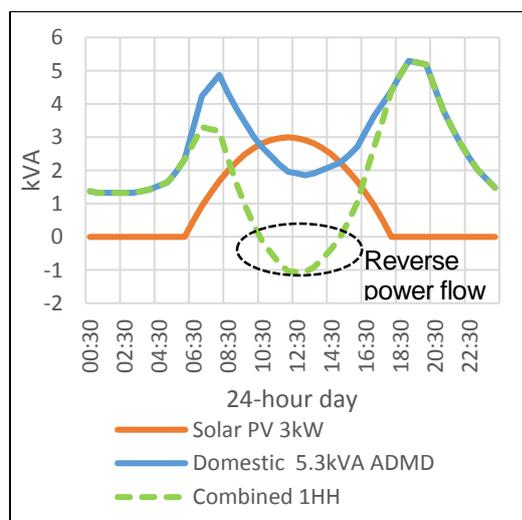

Figure 6: Impact of solar PV to an averaged domestic load profile

From this graph, it is evident that a surplus energy could exist during low load conditions when the energy produced by the solar PV cell cannot be utilized by the household. In reality, the load profile of a single consumer is not as smooth, and the solar output can be affected by ambient temperature or cloud cover. During reverse energy flow conditions, voltage rise can take place. This is especially a concern where solar PV embedded generation takes place close to transformers with internal boost (3.75% for 415V secondary or 5% for 420V secondary side transformers), or raised taps.

It is also clear from the vertical scale in this graph that any larger embedded PV system will send larger amounts of energy back into the network.

It is further clear that the impact during the evening peak will be virtually zero (the solar curve has been drawn for a 06:00 to 18:00 solar day), while the morning peak can be considerably reduced.

It must be noted that if another form of generation, e.g. micro wind turbines or systems with excess storage would inject single phase power during the peak period resulting in unbalanced conditions occurring on a previously balanced feeder designed to its limits, voltage regulation violations could occur.

The effects of voltage rise and the impact to feeder ampacity are illustrated considering the two feeder systems in **Error! Reference source not found.** through a load flow analysis.

For Scenario's A and B (**Error! Reference source not found.**), the following solar PV scenarios are considered at maximum reverse power flow conditions:
1) 3 kW solar PV embedded generators for a transformer with 3.75% internal boost (i.e. a 415 V system)
2) 9 kW solar PV embedded generators (415 V system)

For the 415V system, voltage drop per phase is still measured relative to the declared nominal voltage of 230V in South Africa.

The results are as follows:

Table 3: Solar PV embedded generation load flow results. (Negative transformer load indicates reverse flow)

Scenario	Trans-former load (kVA)	Min V %	Max V %
3kW solar PV embedded generator systems			
Tapered LV feeder:			
No generator connected	150	101.40	103.42
Single generator close to transformer	147	101.47	103.44
Single generator at end of feeder	147	101.32	103.44
25% penetration close to transformer	90	101.60	103.56
25% penetration at end of feeder	90	102.02	103.76
100% penetration	-68	103.67	105.33
One size LV feeder:			
No generator connected	150	101.64	103.42
Single generator close to transformer	147	101.72	103.29
Single generator at end of feeder	147	101.58	103.44
25% penetration close to transformer	90	101.85	103.56
25% penetration at end of feeder	90	102.12	103.58
100% penetration	-77	103.68	105.23
9kW solar PV embedded generator systems			
Tapered LV feeder:			
No generator connected	150	101.40	103.42
Single generator close to transformer	141	101.61	103.48
Single generator at end of feeder	141	100.39	104.39
25% penetration close to transformer	42	101.82	103.90
25% penetration at end of feeder	42	102.95	107.34
100% penetration	-247	104.15	111.96
One size LV feeder:			
No generator connected	150	101.64	103.42
Single generator close to transformer	141	101.88	103.48
Single generator at end of feeder	141	100.77	104.09
25% penetration close to transformer	42	102.09	103.95
25% penetration at end of feeder	42	102.93	106.48
100% penetration	-255	104.17	111.26

From these results, it is noted that:-
a) Voltage rises as generators are added.
b) Under higher embedded generation load, and high penetration, the maximum voltage limits can be exceeded and excess power flows across the transformer into the MV network.

c) Although no cables were overloaded under any reverse power flow conditions in these examples, under very high embedded generation load (e.g. each house inject 60A after own utilization) LV feeder sections will become overloaded due to a lack of diversity between generators.

5. Conclusion

In this paper, the following has been demonstrated:
a. The simple act of load shifting through e.g. ripple control can increase the ADMD, with possible overloading of LV feeders and transformers while the voltage has dropped below compliance limits.
b. The addition of one single phase embedded generator will increase unbalance.
c. The addition of embedded generators can cause the voltage under low load conditions to increase above compliance limits.

Based on the findings, it is necessary for utilities to contemplate:
• the additional burdens they unknowingly have placed on their distribution networks already
• the future burdens over which they will not easily have control
• how they will deal with the technical implications of future EEDSM and embedded generation aspects.

Much work must still be done to increase our understanding of the impact of new technology and to develop new design methods in order to ensure continuous robust, compliant and safe networks.

6. Bibliography

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