Strategies in Technical Loss Reduction and Itôs Impact on Harmonic Performance of Distribution Network

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***Abstract*—This paper presents strategies in the reduction of technical losses of utility distribution network and analyze its impact on harmonic performance. A comprehensive estimation of technical losses of a distribution network is performed using analytical spreadsheet to determine loss level of major network components i.e, medium voltage (MV) feeders (33 kV and 11 kV), transformers and low voltage (LV) network against variations in load current and reactive power. Results based on simulation studies show that power factor correction capacitors (pfcc) are effective means of mitigating technical losses, particularly in LV network which supply large number of small and medium to residential and/or commercial loads. Pfcc which are appropriately sized and strategically placed in LV network is able to reduce technical losses by a significant margin without jeopardizing harmonic performance.**

***Index Terms*—Technical Losses, Harmonic Performance, Low Voltage, Distribution Network, Reactive Power, Characteristic Harmonics**

I. INTRODUCTION

Technical losses and harmonic distortions in distribution network are two issues related to the performance of distribution network which are currently of great concern to utility companies due to increasing costs of energy and the steady growth in the usage of power electronic/nonlinear loads in every electricity consumer sectors. Technical losses refers to energy loss resulting from the heating of electrical distribution components such as cables/lines and transformer windings. High technical loss level of a distribution system are typically attributed to long and highly loaded lines, low power factor, lightly loaded distribution transformers, non-strategic location of substations, etc. The accuracy in estimating technical losses in a distribution system typically require extensive network and load data for modeling. Most of the methodologies engage lots of mathematical manipulations and rely on extensive data input and accuracy of the system models to compute technical losses, particularly for large utility distribution network. Reference [1] proposed an approach whereby typical distribution feeders are modeled based on generalized load distribution profile along feeder to establish peak power loss functions associated with each of the different feeder characteristics. Energy loss in percentage terms of each feeder is then computed using the feeder load factor, loss factor [2], power factor, and its length. Technical losses for the whole distribution network, typically consisting of hundreds of feeders are then calculated by taking the sum of weighted average of all feeders in percentage terms. Weighted factors are then derived based on energy flow distribution at each feeder. For technical losses of distribution transformers resulting from the flow of energy, empirical formulas associated with transformers losses [3-4] is modified through graphical method to form an analytical expression that computes energy losses directly given the transformer capacity, peak demand and load factor. The approach is implemented using spread sheet where technical losses of each component could be estimated based on statistical load data.

The propagation of harmonic currents and harmonic voltage distortions in the distribution system are influenced by the interaction between passive elements in the network and loads (i.e, inductance, capacitance, resistors), distribution network configurations, and characteristic harmonics generated by loads [5]. The strategies applied to reduce technical losses of a distribution network may be detrimental to the improvement of harmonic performance of the same distribution network. A case example is the application of power factor correction capacitors in different parts of the network to reduce technical losses. While it is certainly effective in reducing technical losses, it is likely to results in harmonic resonance. On the other hand, there are strategies which applied to technical loss reduction without having significant impact on the harmonic performance of the network. This paper presents a comprehensive analysis of the mitigation techniques used to reduce technical losses and its influence on the harmonic performance. Measures such as strategic placement of power factor correction capacitors/passive harmonic filters in relation to loss reduction and harmonic performance is also analyzed. Other mitigations that were studied include optimization of feeder length in relation to loading and harmonic distortions. Results from this study provides clear insight for power system planning engineers in determining critical factors that needs to be addressed when dealing with technical losses and harmonic distortions in distribution networks.

II. TECHNICAL LOSSES IN DISTRIBUTION NETWORK

Technical losses in the form of I^2R in distribution network is attributed to current (I) flowing through resistive

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components (R) of cables/lines and transformers. In each of these network components, a certain percentage of its energy feeding the loads is dissipated as heat energy. As utility distribution systems typically consist of a very large number of medium and low voltage feeders and distribution transformers, it is only possible to provide an estimate of the technical loss level of the distribution network based on statistical methods [1]. Medium voltage feeders are typically characterized based on their load distribution along the feeder (e.g uniformly distributed loading, increasingly distributed loading, decreasingly distributed loading, and loading at mid-length), feeder length, load factor, and ampere capacity to statistically estimate its technical losses. In the case of transformers, energy losses can estimated based on full load and no load losses and its peak demand.

A. *Energy Losses in Distribution Feeders*

For the purpose of estimating technical losses, feeders with similar characteristics are classified into categories of feeders having the same technical loss level. An example of power loss functions based on feeder characteristics [1, 6] is shown in Fig. 1.

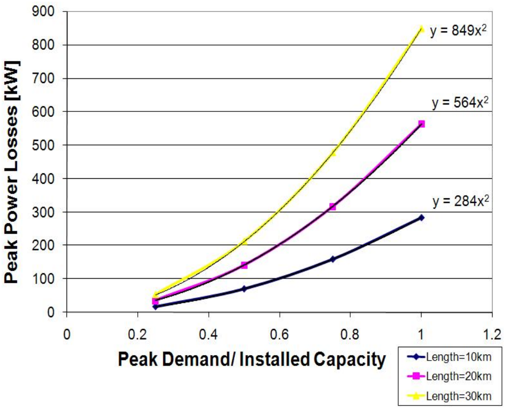

Fig. 1. Peak Power Loss Functions of 11 kV Feeders with Evenly Distributed Loads along Feeder.

It follows that the technical (energy) losses of a particular feeder, $E_{\text{Feeder}}^{\text{Loss}}$ is calculated as follows,

$$E_{\text{Feeder}}^{\text{Loss}} = \left(P_{\text{Peak}}^{\text{Loss}}\right)\left(\text{Load Factor}\right)\left(\text{Loss Factor}\right)\left(\text{Period}\right) \qquad (1)$$

where, $P_{\text{Peak}}^{\text{Loss}}$ is the peak power loss taken from the x-axis of the graph shown in Fig. 1.

B. *Energy Losses in Distribution Transformers*

Equations to compute technical losses in transformers based on no load and full load losses are well established [1] as shown in (2) and (3) below,

$$P_{\text{Tx}}^{\text{Loss}} = P_{\text{no-load}}^{\text{Loss}} + (\text{CF})^2 (P_{\text{full-load}}^{\text{Loss}}) \qquad (2)$$

Where,
$\text{CF} = \text{MD}_{\text{Tx}} / \text{VA}_{\text{Tx}}$ is the capacity ratio,
and,
MD_{Tx} is the transformer peak demand,
VA_{Tx} is the transformer capacity.

It follows that to estimate technical (energy) loss of transformers, equation (4) shown below is used.

$$E_{\text{Tx}}^{\text{Loss}} = \left(P_{\text{no-load}}^{\text{Loss}} + (\text{CF})^2 (P_{\text{full-load}}^{\text{Loss}})(\text{LossFactor})\right)(\text{Period}) \ (3)$$

III. AN EVALUATION OF TECHNICAL LOSSES - CASE EXAMPLE

Based on the methodology developed in [1], technical losses of distribution network are evaluated using spread sheet. The methodology has the advantage of being efficient and simple to use. The software is able to compute technical losses of the whole or part of the distribution network and displays the percentage losses of each network component (33 kV feeder, 33/11 kV transformers, 11 kV feeders, 11/0.4 kV transformers, and low voltage network). In this case example, technical losses of a distribution network made up of a 33 kV feeder, 2 units of 15 MVA, 33/11 kV transformers connected to four (4) 11 kV feeders and 11/0.4 kV distribution transformers/substations is evaluated. See Fig. 2. Peak demand at the 33 kV feeder is 10 MW, total installed capacity of 11/0.4 kV transformers is 35 MVA.

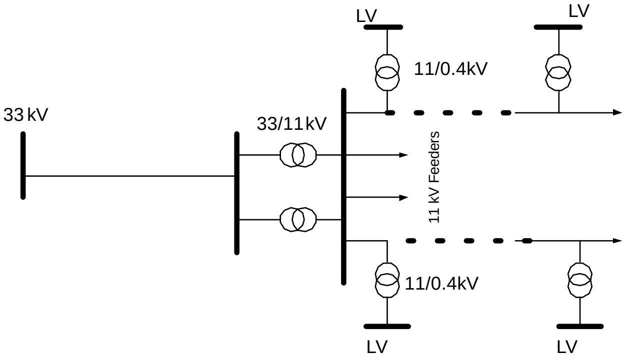

Fig. 2. Single line diagram of the network.

In this case example, technical losses of the network are assessed against the change in power factor and percentage loading (peak current/ampere capacity) of low voltage feeder. Average feeder length for 33 kV and 11 kV feeders is between 6 to 7 km. Results of the technical losses are shown in Table I - IV.

TABLE I
CASE I: SUMMARY OF TECHNICAL LOSSES OF THE VARIOUS NETWORK COMPONENTS

Case I: 50% Loading on LV Feeders			
Components	**% Technical Losses**		
	p.f = 0.75	**p.f = 0.85**	**p.f = 0.95**
33 kV Feeders	0.17	0.13	0.11
33/11 kV Transformers	0.65	0.60	0.57
11 kV feeders	0.69	0.54	0.43
11/0.4 kV Transformers	1.15	1.09	1.04
Low Voltage Network	**0.93**	**0.82**	**0.74**
Total	**3.60**	**3.18**	**2.89**

TABLE II
CASE II: SUMMARY OF TECHNICAL LOSSES OF THE VARIOUS NETWORK COMPONENTS

Case II: 75% Loading on LV Feeders			
Components	**% Technical Losses**		
	p.f = 0.75	**p.f = 0.85**	**p.f = 0.95**
33 kV Feeders	0.17	0.13	0.11
33/11 kV Transformers	0.65	0.60	0.57
11 kV feeders	0.69	0.54	0.43
11/0.4 kV Transformers	1.15	1.09	1.04
Low Voltage Network	**1.25**	**1.24**	**1.11**
Total	**3.91**	**3.60**	**3.26**

TABLE III
CASE III: SUMMARY OF TECHNICAL LOSSES OF THE VARIOUS NETWORK COMPONENTS

Case III: Variations in Losses against 33/11 kV transformer loading			
Components	**% Technical Losses**		
	7.5 MVA/Tx	**10 MVA/Tx**	**15 MVA/Tx**
33 kV Feeders	0.13	0.13	0.13
33/11 kV Transformers	**0.58**	**0.58**	**0.60**
11 kV feeders	0.54	0.54	0.54
11/0.4 kV Transformers	1.09	1.09	1.09
Low Voltage Network	0.82	0.82	0.82
Total	**3.16**	**3.16**	**3.18**

TABLE IV
CASE IV: SUMMARY OF TECHNICAL LOSSES OF THE VARIOUS NETWORK COMPONENTS

Case IV: Variations in Losses against 11/0.4 kV transformer loading			
Components	**% Technical Losses**		
	571 kVA/Tx	**714 kVA/Tx**	**857 kVA/Tx**
33 kV Feeders	0.13	0.13	0.13
33/11 kV Transformers	0.60	0.60	0.60
11 kV feeders	0.54	0.54	0.54
11/0.4 kV Transformers	**0.95**	**1.01**	**1.09**
Low Voltage Network	0.82	0.82	0.82
Total	**3.04**	**3.10**	**3.18**

From the results of the evaluation, it is evident that the 11/0.4 kV transformers and the low voltage network together contribute about 60% of the total technical losses in the network. It is also shown that transformers losses are reduced when the average loading per transformer is increased. This could be done by installing the right transformer capacity to feed its loads such that there is no lightly loaded transformer during peak load period. Additionally, it can be observed that low voltage feeder losses contribute about 30% of the total losses. Hence, there are economic justifications to reduce peak percentage loading on LV feeders, either through additional LV feeders or installing pfcc in cases where power factor is low.

IV. STRATEGIES IN TECHNICAL LOSS REDUCTION

As discussed in Section III, the amount of technical losses in the various network components is closely dependent on the current flowing through it. One of the ways to reduce the current flowing through the network components is by placing power factor correction capacitors at strategic locations of the network; the most ideal location are buses close to the loads.

A. Sizing and Strategic Placement of Low Voltage Capacitors

Low voltage feeders supplying small and medium size loads from the residential or commercial shops usually requires reactive power compensation from the utility side as these small customers are not individually responsible for their load power factor. However, due to variations in load level during different time of day, the sizing of power factor correction capacitors must be done correctly so as to avoid any harmonic resonance particularly during the light load period. In this paper, simulation studies was done on low voltage network with low voltage capacitors banks evenly placed between an average distance of about 200 meter each for evenly distributed LV loads fed by overhead line of 1000 meter. It is assumed that the average power factor is at 0.80 lagging. See Fig. 3. For economic reasons and ease of maintenance fixed capacitors are used and sized accordingly to minimize harmonic resonance during light load period. In this simulation study, fixed capacitors of 5 kVA each are used to achieve a power correction from 0.8 to 0.9 lagging. Results of the simulations are shown in Table V and VI. It can be observed that power factor correction capacitor reduces the peak load current from 302 A to 258 A (a 15% reduction) while in the case of light load current is reduced from 58A to 50 A (a 14% reduction). For both of these cases, fundamental frequency voltage is maintained within desired limits.

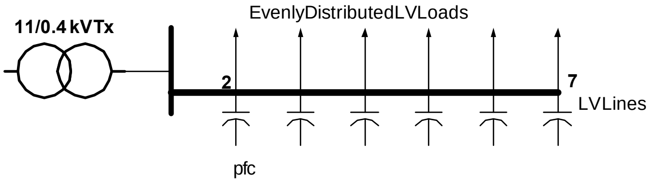

Fig. 3. Placement of Capacitors in Low Voltage Network

TABLE V
LV VOLTAGE AND CURRENT AT BUSES 2 AND 7 WITH PFCC AND WITHOUT PFCC DURING PEAK LOAD

BUS NO	VOLTAGE (V)		CURRENT (AMP)	
	Without pfcc	**With pfcc**	Without pfcc	**With pfcc**
2	238	**238**	302	**258**
7	204	**208**	58	**50**

TABLE VI
LV VOLTAGE AND CURRENT AT BUSES 2 AND 7 WITH PFCC AND WITHOUT PFCC DURING LIGHT LOAD

BUS NO	VOLTAGE (V)		CURRENT (AMP)	
	Without pfc	**With pfc**	Without pfc	**With pfc**
2	239	**240**	108	**100**
7	227	**232**	21	**20**

TABLE VII
MV VOLTAGE AND CURRENT AT BUSES 0 AND 5 WITH PFCC AND WITHOUT PFCC DURING PEAK LOAD

BUS NO	VOLTAGE (KV)		CURRENT (AMP)	
	Without pfcc	**With pfcc**	Without pfcc	**With pfcc**
0	6.4	**6.4**	263	**249**
5	5.9	**6.0**	51.5	**52**

TABLE VIII
MV VOLTAGE AND CURRENT AT BUSES 0 AND 5 WITH PFCC AND WITHOUT PFCC DURING LIGHT LOAD

BUS NO	VOLTAGE (V)		CURRENT (AMP)	
	Without pfcc	**With pfcc**	Without pfcc	**With pfcc**
0	6.5	**6.5**	30.5	**29**
5	6.4	**6.5**	6	**6.1**

B. Power Factor Correction Capacitors for MV (11kV) Feeders

Letôs consider cases where power factor of MV feeders is highly inductive and pfcc is required for reactive power compensation and is placed on the LV side of 11/0.4 kV distribution transformers. In this paper, simulation studies are done on a feeder with evenly distributed loads. See Fig. 4.

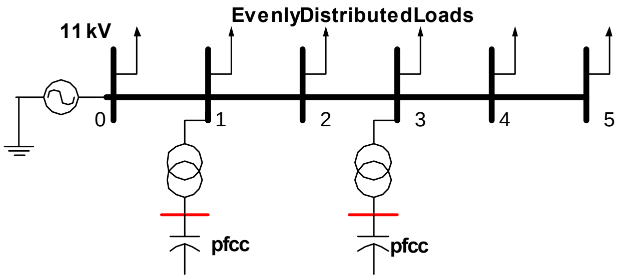

Fig. 4. Placement of Capacitors in Medium Voltage (11 kV) Feeder.

It is assumed that the aggregate loads at bus 1 and 3 are having low power factor of 0.80 lagging and therefore pfccs are placed at these two buses. Results of the simulation are shown in Table VII and VIII. Under peak load condition, connection of pfcc results in a current reduction of 5% . However, during light load period, the same pfcc causes negligible effect on the current. This has been done intentionally by setting the pfcc value so that over compensation do not occur during light load period.

V. IMPACT ON HARMONIC PERFORMANCE

One of the adverse effects of power factor correction capacitors in power system is that it interact with network inductance and results in harmonic resonance. However, the risks of a voltage resonance occurring is also dependent on the types of harmonic sources connected to the feeder. An LV feeder that feeds residential and/or commercial loads for example is likely to have harmonic sources that generate characteristics harmonics of 3rd and 5th order due to single phase power electronic loads such as television sets, personal computers, electronic ballast discharge lamps, etc. Therefore, resonance frequency of 3rd and 5th order should be avoided in LV feeders that feed residential loads in particular.

A. Frequency Scan on LV Feeders with pfcc

Frequency scan analysis is carried out to determine the frequency response of a distribution network/feeder over a range of frequencies of interest. In this study, frequency scan is performed on the LV feeder with pfcc connected to mitigate technical losses as discussed in Section IV(A). Results of the frequency scan are shown in Fig. 5. It can be observed from Fig. 5 that the resonance frequency is very close to the 7th order with a magnification of about 6 times during peak load, and 9 times during light load.

In the case of 3rd and 5th harmonics, a less significant magnification of 2 and 4 times respectively is observed from Fig .5. As 3rd and 5th order harmonics typically dominate in LV feeders that feed residential and/or commercial loads, it is crucial that the addition of pfcc for loss reduction do not results in a significant magnification at these harmonic order. In cases where there is a large penetration of single phase harmonic loads, installation of pfcc for loss reduction may be detrimental to harmonic performance.

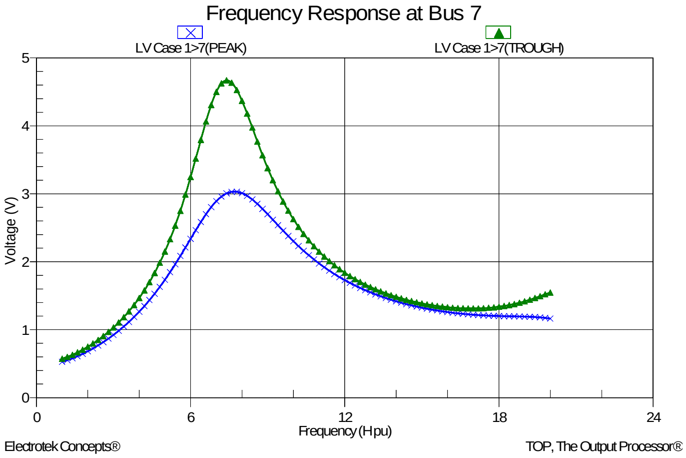

Fig. 5. Frequency Response of the LV feeder with pfcc during peak and light load period.

Simulation results of harmonic voltage distortions at LV feeder obtained using samples measurement of aggregate harmonic load currents are shown in Table IX. THDV at bus 7 is observed to have exceeded the 5% limit when pfcc are connected to the feeder.

TABLE IX
TOTAL VOLTAGE HARMONIC DISTORTION (THDV) AT BUSES 2 AND 7 WITH PFCC AND WITHOUT PFCC DURING PEAK LOAD

Bus	**Fundamental Voltage (V)**		**THDV (%)**	
No	W/O pfcc	With pfcc	W/O pfcc	With pfcc
2	227	227	0.95	0.86
7	195	203	4.1	6.48

B. *Frequency Scan on MV Feeders with pfcc*

In the case of MV feeders where pfcc are placed at bus 1 and 3, frequency scan results indicate that resonance is at around the 11th harmonic. The voltage magnification becomes more severe during light load period as can be observed in Fig. 7.

For MV feeders that are much longer, results show that resonance frequency is at lower harmonic of around the 9th order. See Fig. 8. This is detrimental in trying to maintain harmonic voltage distortions within desired level, particularly in cases where there is high penetration of harmonic loads with 5 and 7th order.

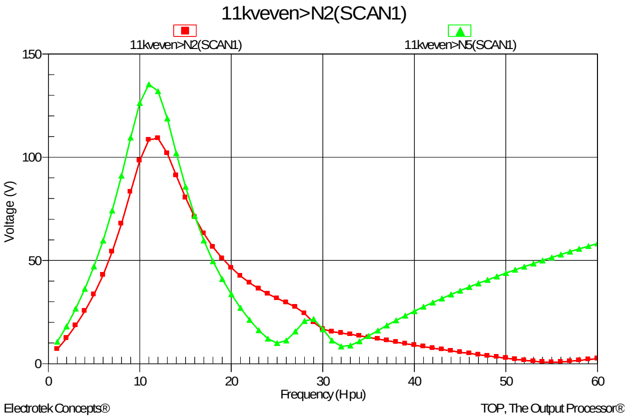

Fig. 6. Frequency Response at bus 2 and 5 during peak load period of the MV feeder with pfcc.

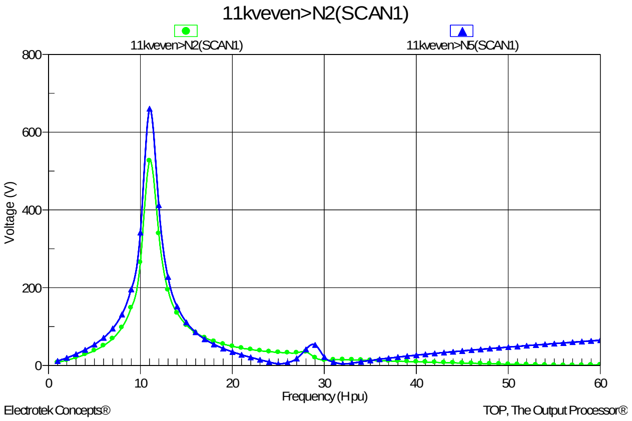

Fig. 7. Frequency Response at bus 2 and 5 during light load period of the MV feeder with pfcc.

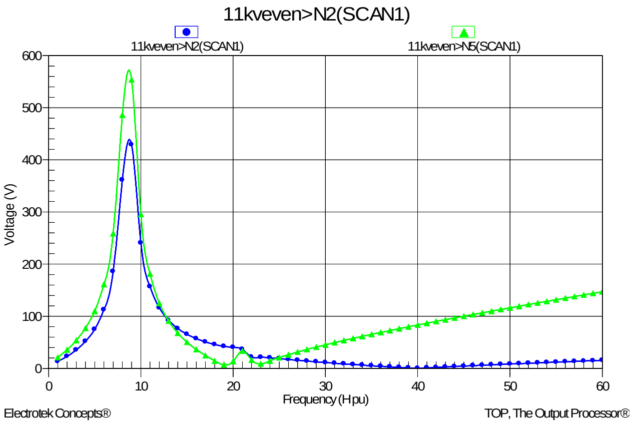

Fig. 8. Frequency Response at bus 2 and 5 for Long (30 km) MV feeder with pfcc.

VI. CONCLUSION

It is shown that the most strategic, in terms of cost and effectiveness in reducing technical losses with minimum impact on harmonic performance on distribution network, is by way of power factor correction capacitors placed strategically along LV feeders. While other approaches such as optimum loading of distribution transformers and feeders are effective in reducing technical losses, they do not significantly affect the harmonic performance of the network. Placement of pfcc for loss reduction at MV feeders is not as economical and effective as LV network. Additionally, pfcc placed at long length of MV feeders typically results in resonance at harmonic below 10th order, thereby putting the feeder at risk of higher harmonic voltage distortions.

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

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