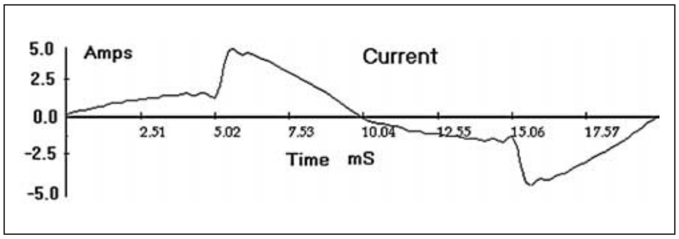

Figure 3. Mixed load

A Discount Calculation for Harmonic's Filter: From (11) to (13) and (15), (16), we can suggest the following expression for the discount calculation (Φ_d):

$$\Phi_d = cW(T)(1/m)\sum_{k=1}^{m}\delta(\tau_k)\rho(\tau_k)$$

if $\delta(\tau_k) < -\delta^*$ at least in 80% of periods τ_k (from T), and otherwise

$$\Phi_d = 0 \tag{17}$$

where m is a number of periods τ in T.

Notes: 1. All predetermined quantities from expressions (13) to (17) (i.e., τ , T, δ^*, etc.) should be established by standards. For example, δ^* should be related to the RMD accuracy and the short current impedance at PCC.

2. It is possible that $\rho(\tau_k) > \rho^*$ (where ρ^* is a predetermined quantity also) but conditions from (14), (17) are false. In this case, the power injection/consumption would be calculated for each high harmonic separately.

Experiment: In order to show the capability of the proposed penalty system an experiment is made on the simplified single-phase model (see Figure 2). The electronic dimmer (ED) with 500 W projector was used as the nonlinear load. The high accuracy standard meters (SM1- Rotek MSB100, SM2-Multi Amp SSS30) for energy measurement and the harmonic analyzer (F41-Fluke 41) for harmonic analysis were used. A 50 Hz filter selected the fundamental harmonic voltage. The example current waveform is shown in Figure 3.

The measurements for different phase angles (in each position of the ED) were made five times and the average values were used in the calculations. The results presented in Table 1 show a good correlation with the proposed formulae and the capability of the penalty system. The difference between values of fitting functions for experimental and calculated points is less than 25% for the nonlinear load (for THD**I** between 25% and 80%) and is less than 30% for the mixed load (for THD**I** between 22.5% and 55%) and δ^*=0.2%.

Conclusions: Special formulae have been obtained for the evaluation of the influence high harmonics current produced by the load in energy consumption measurement. The formulae have been verified experimentally. Formulae for the calculation of the addition/discount to the tariff were suggested.

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Potential Benefits of Using Distributed Parameter Model for Transmission Lines in Power System Analysis

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Abstract: This letter conducts load flow analysis of a five bus test systems and repeats it for various sets of transmission line lengths, each with "lumped" and "distributed" models to compare the convergence, total transmission loss, and slack generation. From this comparison, we conclude that more transmission and generation capacity can be committed if "distributed parameter" model replaces its "lumped" counterpart in such an analysis. The findings are expected to encourage the operators to take decisions through "distributed model"-based analyses so that more consumer demand can be satisfied as well as the utility's revenue substantially increased.

Keywords: Lumped versus distributed parameters, power flow analysis, enhanced transmission access, electricity market.

Introduction: Load flow analysis is a prerequisite for many real-time decision making procedures of a power system such as operational planning, static security assessment and enhancement, optimal power flow, dynamic security /transient stability analysis (for finding the pre-disturbance steady state condition), etc. Transmission lines need to be modeled accurately. Usually the nominal π circuit as in Figure 1, representing the total series impedance (Z) and shunt admittances (Y) of a transmission line on lumped basis irrespective of the line length (L) is used in load flow analysis. Lumped model does not reflect the fact that the series and shunt parameters of a transmission line are not in aggregated form but are distributed [1] uniformly throughout its length, as shown in Figure 2.

This letter proposes use of distributed parameter model and quantifies its benefits over lumped parameter model through a comparative load flow analysis on a typical five bus test system for various sets of line lengths. Such a comparison and its implications appear to have not yet been reported in the literature.

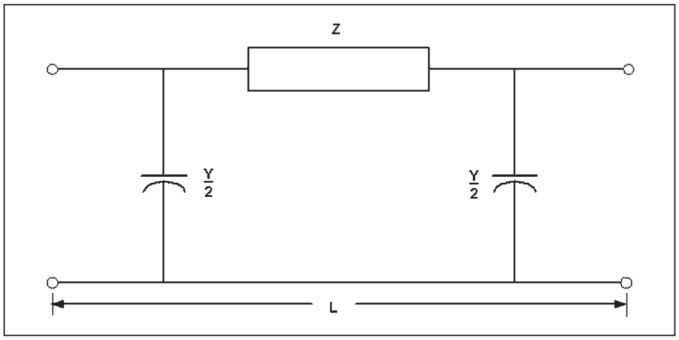

Figure 1. Equivalent π circuit of a line on lumped parameter basis

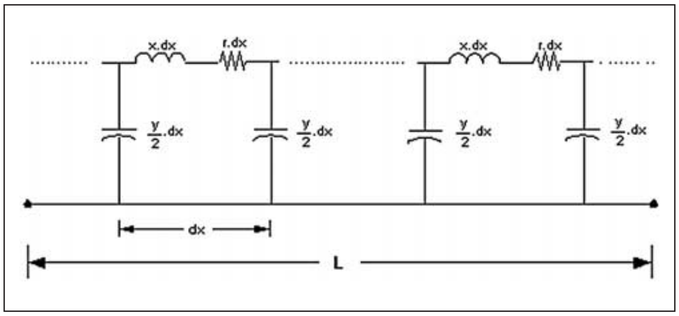

Figure 2. Distributed parameter model of a transmission line

Table 1. Line lengths of the test system in different sets

Line bus to bus	Line length (km)					
	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6
1 - 2	64.4	64.4	90	90	120	120
1 - 5	48.3	48.3	200	200	230	200
2 - 3	48.3	230	230	230	230	230
3 - 4	128.7	128.7	128.7	220	220	220
3 - 5	80.5	80.5	100	100	100	120
4 - 5	96.5	96.5	220	220	220	220
Average line length in km for each set	77.783	108.066	161.450	176.666	186.666	185.000

Equivalent Circuits for Lumped and Distributed Models: The widely used and well-documented [2] fast decoupled Newton-Raphson (FDNR) load flow method is represented in each iteration (m) by (1) and (2)

$$[\Delta\theta]^m = \left[J'_{P\theta}\right]^{-1}\left[\frac{\Delta P}{V}\right]^m \tag{1}$$

$$[\Delta V]^m = [J'_{QV}]^{-1}\left[\frac{\Delta Q}{V}\right]^m . \tag{2}$$

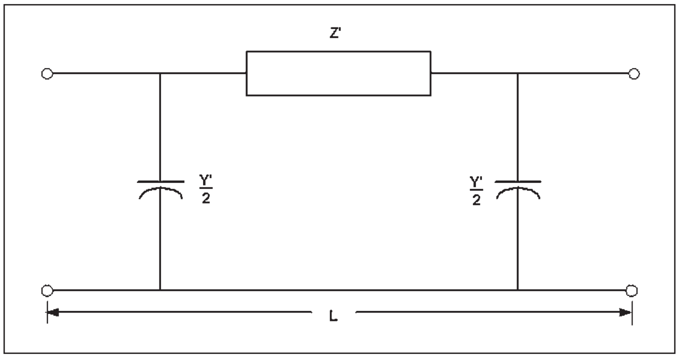

Figure 3. Equivalent π circuit for distributed model

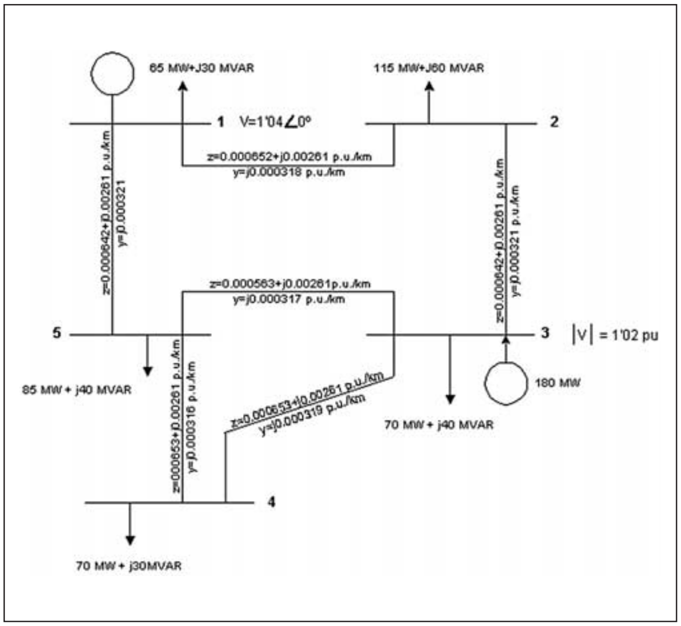

Figure 4. Test system with five buses and six lines

Computations of the modified and constant element Jacobian matrices $[J'_{P\theta}]$ and $[J'_{QV}]$, real power mismatch $[\Delta P]$, and reactive power mismatch $[\Delta Q]$ of (1) and (2) require self and mutual admittances of the buses which, in turn, depend upon the series and shunt admittances of the transmission lines in a system. For this the lumped parameter-based equivalent circuit (as in Figure 1) of a line is used. The line has a length L while its series impedance and shunt admittance per unit length per phase are, respectively, z and y. If the same line is modeled on distributed parameter basis as in Figure 2, the equivalent circuit to be used for admittance calculations is that in Figure 3, which takes into account the effect of distribution [1] in terms of the line's characteristic impedance Z_c and propagation constant γ, respectively defined by (3) and (4)

$$Z_c = \sqrt{(z/y)} \tag{3}$$

$$\gamma = \sqrt{(yz)}. \tag{4}$$

Z', the equivalent series impedance and Y', the equivalent shunt admittance shown in Figure 3 are respectively given by (5) and (6)

$$Z' = Z_c \sin h\gamma L \tag{5}$$

$$Y' = \left(1/Z_c\right)\tan h(\gamma L/2). \tag{6}$$

It should be noted that Z' and Y' of the distributed model equivalent circuit can also be obtained [1] from their corresponding counterparts Z and Y in the lumped model of Figure 1 using (7) and (8)

$$Z' = Z\left\{(\sin hL)/\gamma L\right\} \tag{7}$$

$$Y' = Y\left\{\tan h(\gamma L/2)/(\gamma L/2)\right\} \tag{8}$$

where $Z = zL$ and $Y = yL$.

Simulation Results: In order to illustrate the findings of the present study in the limited space of this letter, a typical five bus, six line sample power system [1] as in Figure 4 has been used. Bus data and each line's series impedance and shunt admittance in p.u. per km are also shown in Figure 4. Bus number 1 is the slack, bus number 3 a P-|V| while the other three buses are load bus. The total real power demand (load) in the system is 405 MW. A total of six sets (configurations) were developed from the given test system by modifying only the lengths of one or more lines at a time between 48.3 km and 230 km while keeping the bus data same for all the sets. Table 1 shows the length of each line and the

Table 2. Revenue benefits due to using distributed model

Set No. (A)	ΣP_{loss}		Power that can be committed more due to distributed model (kW) D=(B-C)*1000	Additional revenue that can be earned per day @0.05 US$/kWh (E=0.05*D*24)US$
	Lumped Model (MW)(B)	Distributed Model (MW) (C)		
1	9.671	9.631	40	48.00
2	12.086	11.988	98	117.60
3	23.521	23.105	416	499.20
4	29.174	28.451	723	867.60
5	35.021	32.355	2666	3199.20
6	34.205	31.209	2996	3595.20

average line length in each of the six sets. Each of these six sets has been subjected to a FDNR load flow analysis with "lumped" modeling and then with "distributed" modeling.

The corresponding programs were developed using MATLAB 5.3 and run on a Pentium PC. The base values were 100 MVA, 138 kV and the convergence was checked using a mismatch tolerance of 0.005 p.u. for both real and reactive powers at each bus.

Figures 5, 6, and 7, respectively, compare for each set (specified in terms of average line length) the total real power loss, slack bus real power, and the number of iterations under the "lumped" model with those under "distributed" line models. It is evident from Figures 5 and 6 that both "total loss (MW)" and "slack power generation (MW)" are less for every set with "distributed" model than that with "lumped" model. Moreover, as the average line length increases this difference becomes significant. It should be noted that similar results were obtained also for reactive power. Figure 7 shows that although for smaller average line lengths the number of iterations is the same with both models, it becomes less for the "distributed model" for the higher average line lengths.

For the same load as with the "lumped model," the line loss and, hence, the slack generation requirement become less on using "distributed" model due to its ability to represent the fact, i.e., a line comprises a number of distributed sections as in Figure 2. Because of this fact, the current while passing from one section to the next one is now divided between each section's series impedance and shunt charging admittance and thus decreases towards the receiving end resulting in lower I^2R loss.

Table 2 shows for each set the extra revenue that can be earned per day if the amount of reduction in total line loss (MW) shown by the "distributed" model is committed, i.e., this much power is made available to satisfy an equal amount of increment in the consumers' demand which could have otherwise been decided as "not servable" on using the "lumped" model. It has been assumed in Table 2 that the tariff for energy is 0.05 US$/kWhr. It is evident that if the "distributed" model is used for a system with higher average line length, a substantial amount of revenue can be earned per day due to an increase (though about 1% of the system demand) in the power that can be committed from the slack generator as well as through all the transmission lines.

The satisfied additional demand is equal to the difference of transmission loss under "lumped" and "distributed" models will be catered to by the slack generator, because the lumped model-based analysis has shown that the slack generator is able to supply this much power as "more loss." However, entertaining any increase in demand will also entail an increase in transmission loss. The question is whether this increased loss may stress the total generation and transmission capacities? Absolutely not, because the fact [1],[2] and also the results obtained as above show that at any instant of time the transmission loss in a properly planned and designed power system is at best only 10% of the corresponding demand. So if an increment in the demand itself is about 1% of the corresponding basic demand then the maximum possi-

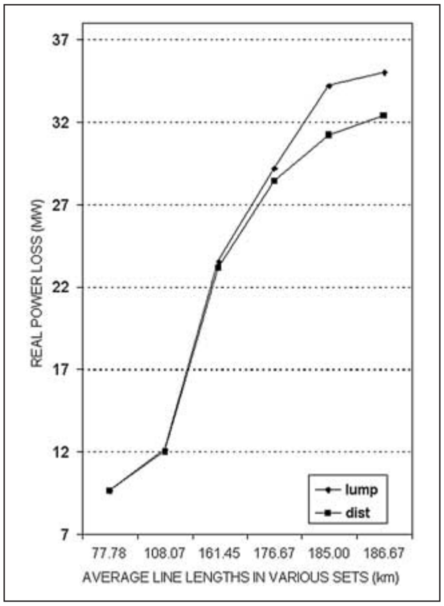

Figure 5. Real power loss versus average line lengths

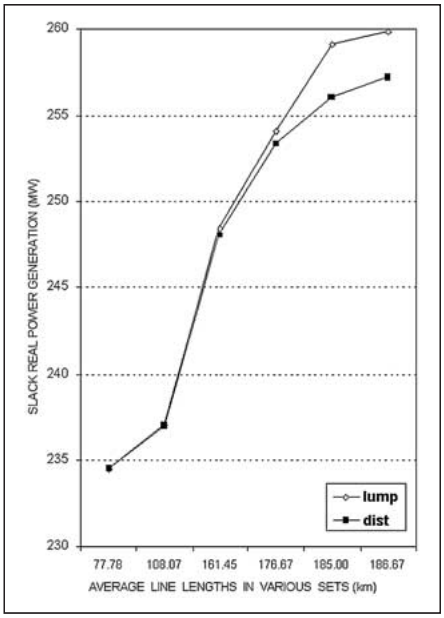

Figure 6. Slack real power generation versus average line lengths

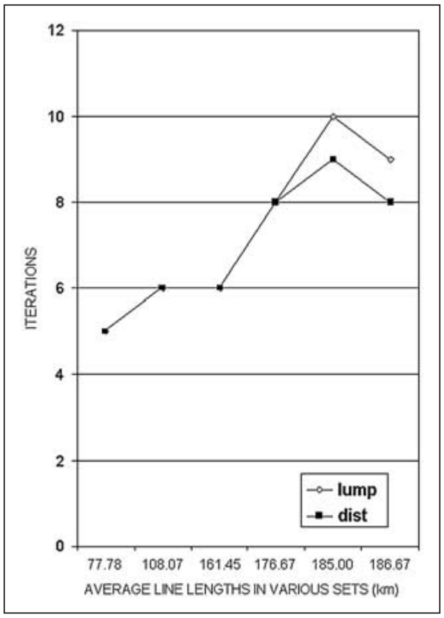

Figure 7. Iterations versus average line lengths

ble increment in loss will be only 0.1% of the basic demand, which can easily be committed from either the slack generator alone or if necessary, all the generators and can be transmitted by all the lines together. As for instance, for the considered "Set 5" this increment in demand is about 2.7 MW which is actually 0.66% of the basic demand of 405 MW. Hence, if 2.7 MW power is committed more under a decision using distributed model, the corresponding increment in loss will be at best 2.7*10% = 0.27 MW. On percentage of 405 MW this 0.27 MW is only 0.066% even not equal to the anticipated maximum of 0.1%.

Conclusions: It has been shown in this letter through an extensive load flow analysis of a typical five bus, six line system with various sets of line lengths that if the operators take decisions using "distributed parameter" model for the transmission lines even though their lengths are less than 240 km then an extra power equal to about 1% of the basic demand, can be committed more without stressing the existing generation and transmission capacities. The test system used herein had, at a certain times, a basic demand of 405 MW. But with a larger and practical system planned and designed to handle a demand to the tune of several thousand MW, this 1% means a substantial addition to the servable consumer-demand as well as to the utility's revenue achievable per day.

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