Probabilistic System Availability Model and Prevailing Factors for 33kV Primary Power Distribution Feeders in Nigeria

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Abstract – Outage and complimentary load flow analyses of a selected 33kV primary distribution network in Ughelli Delta State, Nigeria, were carried out to depict feeder availability obtainable in the country. Outage and load flow analyses were carried out using parametric statistics and Newton-Raphson computation algorithm respectively. The results provide model distribution of monthly feeder availability, contributions of outage factors and normal load flow values. It was concluded that: monthly feeder availability represented using normal probability distribution function of $\boldsymbol{p \sim N(0.78, 0.06)}$; shows that overcurrent and earth faults contribute to outage duration, taking 5% to 12% of the month outage duration respectively; coupled with significant line losses and weak voltage profile. Recommendations proposed include: replacement of weak or failed elements and insulations in the systems with new and modern ones to mitigate especially earth faults in the short term; planning for immediate increase in system capacity to accommodate the power demand effectively for present and forecast periods to eliminate load shedding, overload events, and high technical losses; maintenance practice at the planning and execution stages to mitigate failure events and repair time.

Keywords – fault, outage, probability, load flow, availability, distribution network.

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1 INTRODUCTION

Primary electricity distribution networks in Nigeria are implemented on 33kV, and are essential to supplying power to all load categories as industrial, commercial, municipal administrative buildings and facilities, communication stations, health care establishments and infrastructure, and public recreational facilities. In Nigeria, the available electrical energy generated is not enough to meet the demands of the users, leading to constant load shedding, especially at the secondary distribution networks (Melodi & Temikotan, 2011; Melodi & Adu, 2016). The generated electricity and network capacity deficits, coupled with random fault events lead to constant blackouts or power outage events in the entire systems. Reliability of these networks is crucial to customer satisfaction and revenue generation for the utility and businesses of the customers, public security, and energy saving or conservation. In view of the above, pre-planning situational evaluation of the system are relevant to planning short, medium, and long term reliable power supply and continuity of same.

Some observed studies on distribution feeder reliability in Nigeria applied Markov chain method, conventional and customer-oriented reliability indicators on specific feeders as in Opara et al. (2015). Whereas, this study proposes deployment of probabilistic distribution modelling of categorized outage data and substantiated by load flow analysis. This approach considers pre-planning evaluation of the operating mode of a typical 33kV distribution network; specifically, investigating outage causes and network capacity for improved system planning and operation.

The location of the 33kV network is in the Niger-delta region because of its closeness to one of the country's major gas fired generating stations, Delta I-II, Nigeria. This eliminates the consideration for the additional effect of the reliability of in-coming 132 kV lines supplying remote 33kV networks. In order words, the selected network is unique in that it is fed directly from a major gas fired generating station, eliminating the need for the consideration for sub transmission contingencies and it signifies the prevailing divergent radial networks in the country. The single line model of the test system is presented in Figure 1. The network comprises of six feeders, five of which are supplied by 60MVA, one by 30MVA. In order to characterize the system, two objectives are set. They are: analyses of the outage and load flow.

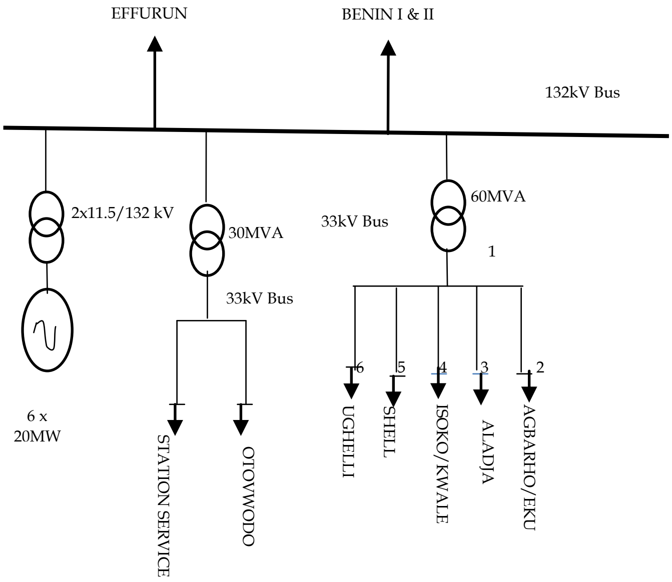

Fig. 1: Delta I-II transmission station and network, Ughelli, Niger Delta, Nigeria

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2 METHODOLOGY

In order to measure and characterize the prevailing system reliability or availability, the following algorithm was applied:

2.1 ASSESSMENT OF OUTAGES OR SYSTEM FAILURE

Outage data, which comprises of daily time series of overcurrent and earth fault frequencies and durations were observed and obtained from available system records, from 2010 to 2015. These data were described using normal distribution function statistics, where choice of distribution function is based on relative frequency histograms (Warrack, 2003; Mendenhall, Beaver, & Beaver, 2003; Robert & Casella, 2004).

It is considered that the outage variables are continuous, random and a sample set can be mapped or described by normal distribution function. The selected distribution is based on the shape of obtained relative frequency distribution of data. In a Normal distribution, we have the probability density function (PDF) and cumulative distribution function (CDF) of continuous random variable x, with mean μ and standard deviation σ of the distribution. The PDF is given as

$$Outage\ variable\ x \sim f(x,\mu,\sigma)\ =\frac{1}{\sqrt{2\pi\sigma}}e^{-\left[\frac{(x-\mu)^2}{2\sigma^2}\right]} \quad (1)$$

Probability that the variable fall within the interval [,]is expressed as:

$$P(x\in[a,b]) = CDF(x,\mu,\sigma) = \int_a^b f(x,\mu,\sigma)dx \quad (2)$$

From (2), the probability of an event having values in the interval [a,b] is expressed as:

$$p([a,b]) = CDF(b,\mu,\sigma) - CDF(a,\mu,\sigma) \quad (3)$$

where a and b are boundaries of given interval of variable . The specific monthly outage is obtained from data obtained from system operation records as (4)

$$Outage\ data = \{EFD(t), EFF(t), OCD(t), OCF(t)\}, \quad (4)$$

where $EFD(t), EFF(t), OCD(t), OCF(t)$, are respectively, earth fault duration, earth fault frequency, overcurrent fault duration, overcurrent fault frequency in time t (month). Derived and evaluated outage parameters are as shown in the following algorithms of Equations (5) to (8):

Earth fault duration per event,

$$EFD'(t) = \frac{EFD(t)}{EFR(t)}; \quad (5)$$

Overcurrent fault duration per event,

$$OCD'(t) = \frac{OCD(t)}{OCF(t)}; \quad (6)$$

Implemented relative frequency distributions of parameters are implemented,

$$RF\big(EFD(t)\big);\ RF\big(EFF(t)\big);\ RF(EFD')(t); \quad (7a)$$

$$RF\big(OCD(t)\big);\ RF\big(OCF(t)\big); RF\big(OCD'(t)\big) \quad (7b)$$

Single Feeder monthly unavailability (q_{mth}) and availability (p_{mth}):

$$q_{mth} = \frac{T_{O,mth}}{T_{op,mth}} = \frac{T_{EF,mth}+T_{OC,mth}}{D_{mth}(24-T_{LS,dy})} \quad (8a)$$

$$p_{mth} = 1 - q_{mth} \quad (8b)$$

where $T_{O,mth}$ is monthly outage duration on a feeder (hrs), $T_{op,mth}$ is monthly normal operation time (hrs), $T_{EF,mth}$ is monthly outage duration due to earth fault per feeder (hrs), $T_{OC,mth}$ is monthly outage duration due to overcurrent per feeder (hrs), D_{mth} number of days in month mth, $T_{LS,dy}$ is daily outage duration due to load shedding per feeder (hrs).

Selection of distribution functions of unavailability and availability:

$$q_{mth} \sim f(x)\ \forall\ RF(q_{mth}) \equiv f(x) \quad (9a)$$

$$p_{mth} \sim f(x)\ \forall\ RF(p_{mth}) \equiv f(x)\,, \quad (9b)$$

where $f(x)$ is any suitable PDF of continuous random variable x with corresponding PDF parameters.

2.2 POWER FLOW ANALYSIS OF 33KV PRIMARY DISTRIBUTION LINE

Power flow analysis is carried out on the primary distribution network shown in Figure 1 using Power System Toolbox in MATLAB software. The generic concept, framework and algorithm for the Newton Raphson (NR) method in the software is as described in (10) – (18). The study is carried out to analyse mode parameters such as node voltages, line loses, system demand etc. The network supplies five delivery points, four towns and an oil company-community (Aladja, Ughelli, Agbarho/Eku, Isoko/Kwale, and Shell), using separate 33kV feeders with loads ranging from 6 to12 MW. System parameters for the load flow computation are defined and evaluated or derived from obtained system data using (10).

$$System\ data = \{r_{oij}, x_{oij}, l_{ij}, D_{GMD}, U_{nom}\ , P_i\ , Q_i, F_{ij}, M_{ij}\} \quad (10)$$

where M_{ij} is conductor material, F_{ij} is conductor size (mm^2), l_{ij} is conductor length in km, r_{oij} is 'per km' active resistance, x_{oij} is per/km reactive resistance between nodes i and j; D_{GMD} is geometric mean distance between line phases, and U_{nom} is nominal network voltage (kV), P_i is active load (MW), Q_i is reactive load (MW).

In Saadat (2002) and Nagrath and Kothari (2003), complex power injected into the distribution lines (S_i, MVA) is expressed as:

$$S_i = V_i^* I_i = P_i - jQ_i = V_i^* \sum_{j=1}^{n} Y_{ij} V_j \quad (11)$$

where I_j is injected current into node i, V_i is the voltage at the i-th bus, I_i^* is the complex conjugate of the current injected at the i-th bus, P_i and Q_i are injected real and reactive powers at the i-th bus; Y_{ij} is the bus admittance between the nodes i and j, and is a function of r_{oij}, x_{oij}, l_{ij} using the procedure described in Saadat (2002), and V_j is the voltage at load node j.

Letting $Y_{ij} = Y_{ij}\angle\theta_{ij}\ and\ V_i = V_i\angle\delta_i;$ θ_{ij} and δ_i represent the admittance and voltage angles respectively.

From (11) it follows that:

$$P_i - jQ_i = \sum_{j=1}^{n}|Y_{ij}|\,|V_i||V_j|\angle(\theta_{ij} + \delta_j - \delta_i) \qquad (12)$$

Where (12) implies that:

$$P_i = \sum_{j=1}^{n}|Y_{ij}|\,|V_i||V_j|cos(\theta_{ij} + \delta_j - \delta_i) \qquad (13)$$

$$Q_i = -\sum_{j=1}^{n}|Y_{ij}|\,|V_i||V_j|sin\,(\theta_{ij} + \delta_j - \delta_i) \qquad (14)$$

There are 4 variables that are associated with each bus: P, Q, V, δ which are the real power, reactive power, bus voltage and voltage angle respectively. Each bus in a power system is classified as one of three types: Load bus or P-Q bus (where V and δ are unknown); Generator bus or P-V bus (where Q and δ are unknown); and Slack bus or swing bus (where P and Q are unknown).

According to Saadat (2002), equations (13) and (14) constitute a set of nonlinear algebraic equations in terms of the independent variables, voltage magnitude in per unit, and phase angle in radians. We have two equations for each load bus, which is given by (13) and (14) and one equation for each voltage-controlled bus, which is (13). The Jacobian matrix J gives the linearized relationship between small changes in voltage angle $\Delta\partial_i^{(k)}$ and voltage magnitude $\Delta|V_i^{(k)}|$ with the small changes in real and reactive power $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$. Elements of the Jacobian matrix are the partial derivatives of (13) and (14) evaluated by $\Delta\partial_i^{(k)}$ and $\Delta V_i^{(k)}$. In a short form, it can be written as

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix};\ J_1 = \frac{dP}{d\delta};\ J_2 = \frac{dP}{dV};\ J_3 = \frac{dQ}{d\delta};\ J_4 = \frac{dP}{dV} \qquad (15)$$

The term $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are the respective differences between the scheduled and the calculated values of injected active and reactive powers at the i-th bus and k-th iteration:

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)};\quad \Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \qquad (16a)$$

For clarity, P_i^{sch} and Q_i^{sch} are specified injected or net active and reactive powers respectively at i-th bus. Whereas, $P_i^{(k)}$ and $Q_i^{(k)}$ are the calculated injected active power and reactive power for assumed, obtained, or given values of V_i and δ_i. Mathematically,

$$P_i^{sch} = P_{G(i)} - P_{L(i)};\ Q_i^{sch} = Q_{G(i)} - Q_{L(i)} \qquad (16b)$$

where $P_{G(i)}$ and $Q_{G(i)}$ are specified (or installed) active power and reactive power generations respectively at i-th bus; $P_{L(i)}$ and $Q_{L(i)}$ are specified active load and reactive load respectively at i-th bus.

The new estimates for bus voltages and angles are:

$$|V_i^{(k+1)}| = |V_i^{(k)}| + \Delta|V_i^{(k)}|\ ;\ \delta_i^{(k+1)} = \delta_i^{sch} + \Delta\delta_i^{(k)} \qquad (17)$$

The procedure for power flow solution using the Newton-Raphson method is as follows:

For load buses, where $P_i^{(sch)}$ and $Q_i^{(sch)}$ are specified, initial voltage magnitudes and angles are set at 1.0 per unit (p.u.) and 0.0 radian respectively, i.e., $|V_i^{(0)}|$=1.0 p.u. and $\delta_i^{(0)}$=0.0 radian.

For voltage-regulated buses, where $|V_i|$ and P_i^{sch} are specified, initial angles are set at 0.0 radian (i.e., $\delta_i^{(0)}$=0.0 rad.).

For load buses, $P_i^{(k)}$ and $Q_i^{(k)}$ are calculated using (13) and (14) respectively, and $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are calculated using (16).

For voltage-controlled buses, $P_i^{(k)}$ and $Q_i^{(k)}$ are calculated using (13) and (14) respectively.

The element of the Jacobian matrix ($J_1, J_2, J_3, and\ J_4$) are calculated from (15).

The resulting system of linear equation expressed by (15) is solved directly by optimally ordered triangular factorization and Gaussian elimination.

The new voltage magnitude and phase angles are computed from (17)

The process is continued until the residual $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are less than the specified accuracy (ϵ):

$$|\Delta P_i^{(k)}| \le \epsilon;\ |\Delta Q_i^{(k)}| \le \epsilon \qquad (18)$$

In Figure 1, bus 1 is the slack while 2, 3, 4, 5, 6 are the load buses.

3 RESULTS AND DISCUSSIONS

3.1 SYSTEM OUTAGE ANALYSIS

Using the PDF algorithm mentioned in the previous section above, plots of RF, PDF and CDF for monthly outage duration per earth fault event obtained are as shown in Figure 2. Figure 2 shows that the empirical range of outage duration per earth fault event is 1 to 12 hours. The most frequently observed interval is (5,7] hrs. That is, it usually takes 5 to 7 hours to restore a system after an earth fault event.

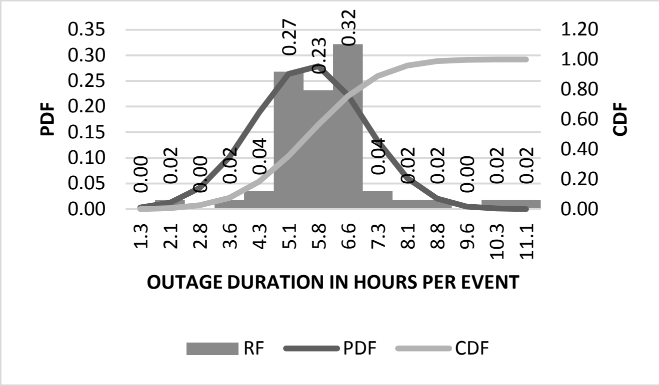

Fig. 2: RF, PDF and CDF of monthly outage duration per Earth Fault event (July 2010-February 2015)

Also, plots of RF, PDF and CDF for monthly outage duration per over current (OC) fault event obtained are as shown in Figure 3. Figure 3 shows that the empirical range of outage duration per over current fault event is 1 to 6 hours. The most frequently observed interval is (2,3) hrs. That is, it usually takes 2 to 3 hours to restore the system after an over current fault event.

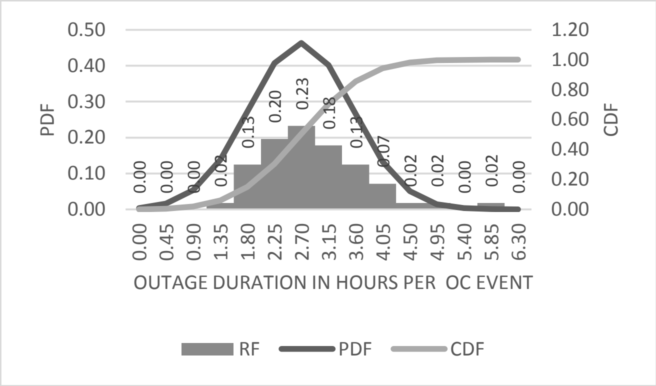

Fig. 3: RF, PDF and CDF of overcurrent Fault (July 2010-February 2015)

The obtained distributions for system monthly unavailability due to EF and OCF are as shown in Figure 4. The RF plots show that the system is mostly unavailable between 5% to 11% (with probability of 0.35) of the time due to OCF and 6% to 12% (with probability of 0.29) of the time due to EF. This means that OCF and EF contributes to system outage at 33kV.

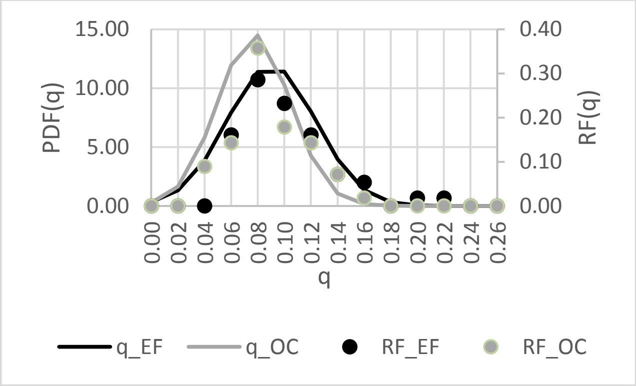

Fig. 4: System Unavailability due to earth faults and overcurrent faults respectively

The distributions for feeder availability and complementary unavailability obtained are presented in Figure 5. Figure 5 shows that the most frequent interval of monthly reliability p_{mth} is (0.76, 0.81) and q_{mth} is (0.20, 026). These values depict substandard feeder reliability.

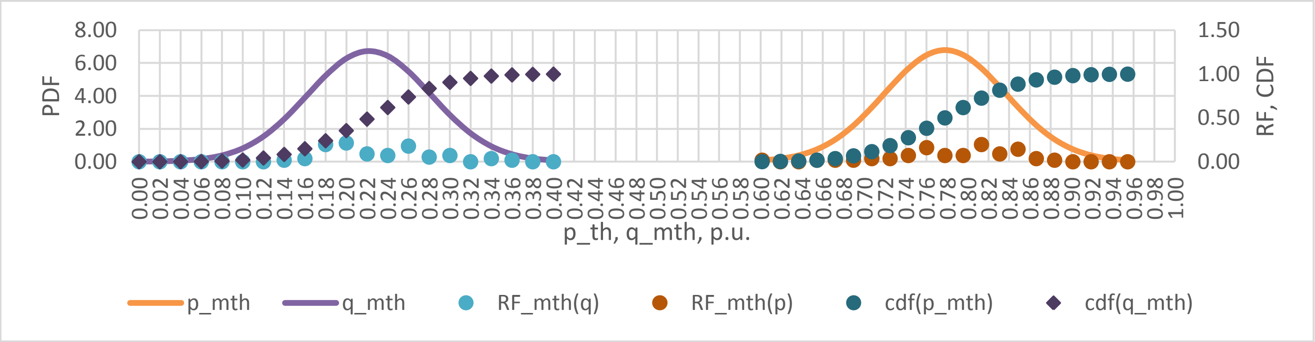

Fig. 5: distribution of monthly system availability or reliability

3.2 POWER FLOW ANALYSIS

From empirical system data, the derived values of network parameters are as shown in Table 1. The obtained power Flow results are as shown in Table 2 and Table 3. Also, a scatter plot of the loading coefficients and line lengths versus the receiving end node voltages are presented in Figure 6. Table 2 and Table 3 show that the total load is $54.0 + j40.5MVA$ ($67.5MVA$) with a loss of $8.289 + j11.696\ MVA$ and System demand of $62.274 + j52.179MVA$ ($81.245MVA$). In view of these values and given that the available power supply from the power station is 48MW and injection substation capacity is 60MVA, the system demands exceeds the injection transformer by 35.4%, the effect of such condition is load shedding.

Figure 6 shows that the voltage profile for lines in a particular range needs to be stabilized, the load node over the 16km distance from the system bus, with loading coefficient ranging from 0.49 to 1.19 having voltages in the range of 0.73 to 0.95p.u., this can be done by load control or reinforcing the affected lines.

From the load flow, the contribution to feeder poor availability can be identified: load shedding due to undersized transformer; and overcurrent faults due to overload events in overloaded lines. Solving line overloading problems by the line re-conductoring will significantly increase system availability as OCF will be eliminated. Consequently, the overall q_{mth}will be approximately 5% to 11%, as against 20% to 26%.

The load flow results could not indicate the possible cause of EF event. However, EF can be mitigated through known clearing Right-of-Way of line threatening vegetation, standard maintenance of insulation, monitoring of insulator elements for weakness using smart technology in order to prevent failure. The total power losses on the line is 8.289MW which is enough to power a town, these loses makes the supply power not to be adequately utilized. This suggests a network optimization problem for energy conservation

Table 1. 33kV line Parameters

LINE	TOWN NAME	A(m^2)	r(m)	D_{GMD} (m)	L (km)	$r_o\ (\frac{\Omega}{km})$	$x_o\ (\frac{\Omega}{km})$	R(Ω)	X (Ω)	Z_{actual} (Ω)	Z_{base}	Z_{pu}
1-2	Agbarho	0.01	0.00564	1.726	31.6	0.265	0.3739	8.374	11.815	8.374 + j11.815	10.89	0.769 + j1.085
1-3	Aladja	0.01	0.00564	1.726	45	0.265	0.3739	11.925	16.826	11.925 + j16.826	10.89	1.095 + j1.545
1-4	Isoko	0.01	0.00564	1.726	38.2	0.265	0.3739	10.123	14.283	10.123 + j14.283	10.89	0.9296 + j1.3116
1-5	Shell	0.01	0.00564	1.726	16.2	0.265	0.3739	4.293	6.027	4.293 + j6.027	10.89	0.3942 + j0.536
1-6	Ughelli	0.01	0.00564	1.726	0.25	0.265	0.3739	0.06625	0.0935	0.06625 + j0.0935	10.89	0.00608 + j0.00859

Table 2. Result of power flow in Power System toolbox in Matlab software format

```
basemva = 100;      accuracy = 0.0005;      accel = 1.8;      maxiter = 100;
% DELTA TS 33KV FEEDER
% Bus DATA
%        Bus  Bus  Voltage  Angle   ---load---   ---generator-------   -injected-
%         No  code   mag.   Degree   MW    Mvar   MW   Mvar Qmin Qmax     Mvar
busdata=[1    1    1.05     0       0.0   0.0    0.0  0.0   0    0      0
         2    0    1.0      0       12.0  9.0    0.0  0.0   0    0      0
         3    0    1.0      0       6.0   4.5    0.0  0.0   0    0      0
         4    0    1.0      0       12.0  9.0    0.0  0.0   0    0      0
         5    0    1.0      0       12.0  9.0    0.0  0.0   0    0      0
         6    0    1.0      0       12.0  9.0    0.0  0.0   0    0      0];
% LINE DATA
%%         bus bus    R         X         0.5B     line code or
%          nl  nr     pu        pu        pu      tap setting
linedata=[1   2    0.7689    1.085      0           1
          1   3    1.095     1.545      0           1
          1   4    0.9296    1.3116     0           1
          1   5    0.3942    0.556      0           1
          1   6    0.00608   0.00859    0           1];

% Calculation of the admittance
lfybus
% Calculation using power flow
lfnewton
% Output of Power Flow Solution
busout
% Output of Lineflow and loss
Lineflow
Result:                   Power Flow Solution by Newton-Raphson Method
                        Maximum Power Mismatch = 6.76701e-05
                               No. of Iterations = 4

    Bus  Voltage  Angle     ------Load------    ---Generation---   Injected
    No.  Mag.     Degree      MW        Mvar       MW        Mvar      Mvar

     1   1.050    0.000     0.000     0.000    62.274    52.179     0.000
     2   0.814   -4.093    12.000     9.000     0.000     0.000     0.000
     3   0.898   -2.639     6.000     4.500     0.000     0.000     0.000
     4   0.731   -5.511    12.000     9.000     0.000     0.000     0.000
     5   0.947   -1.801    12.000     9.000     0.000     0.000     0.000
     6   1.049   -0.025    12.000     9.000     0.000     0.000     0.000

    Total                  54.000    40.500    62.274    52.179     0.000
                           Line Flow and Losses
     --Line--  Power at bus and line flow    --Line loss--  Transformer
     from  to    MW      Mvar      MVA       MW       Mvar      tap

     1         62.274   52.179   81.245
           2   14.611   12.684   19.349    2.611    3.684
           3    6.763    5.577    8.766    0.763    1.077
           4   15.913   14.521   21.543    3.913    5.521
           5   12.990   10.396   16.638    0.990    1.396
           6   12.012    9.018   15.021    0.012    0.018
```

```
   2        -12.000   -9.000   15.000
         1  -12.000   -9.000   15.000    2.611    3.684

   3         -6.000   -4.500    7.500
         1   -6.000   -4.500    7.500    0.763    1.077

   4        -12.000   -9.000   15.000
         1  -12.000   -9.000   15.000    3.913    5.521

   5        -12.000   -9.000   15.000
         1  -12.000   -9.000   15.000    0.990    1.396

   6        -12.000   -9.000   15.000
         1  -12.000   -9.000   15.000    0.012    0.018
 Total loss                              8.289   11.696
```

Table 3. Summary of operating mode parameters

I	j	L_{ij}, km	P_{ij}, MW	Q_{ij}, Mvar	S_{ij}, MVA	ΔP_{ij}, MW	ΔQ_{ij}, Mvar	U_j, p.u.	δ, deg	P_j, MW	Q_j, Mvar	Pg_j, MW	Qg_j, Mvar	Q_j, Mvar
1	1							1.050	0.000	0.000	0.000	62.274	52.179	0.000
1	2	31.6	14.611	12.684	19.349	2.611	3.684	0.814	-4.093	12.000	9.000	0.000	0.000	0.000
1	3	45	6.763	5.577	8.766	0.763	1.077	0.898	-2.639	6.000	4.500	0.000	0.000	0.000
1	4	38.2	15.913	14.521	21.543	3.913	5.521	0.731	-5.511	12.000	9.000	0.000	0.000	0.000
1	5	16.2	12.990	10.396	16.638	0.990	1.396	0.947	-1.801	12.000	9.000	0.000	0.000	0.000
1	6	0.25	12.012	9.018	15.021	0.012	0.018	1.049	-0.025	12.000	9.000	0.000	0.000	0.000

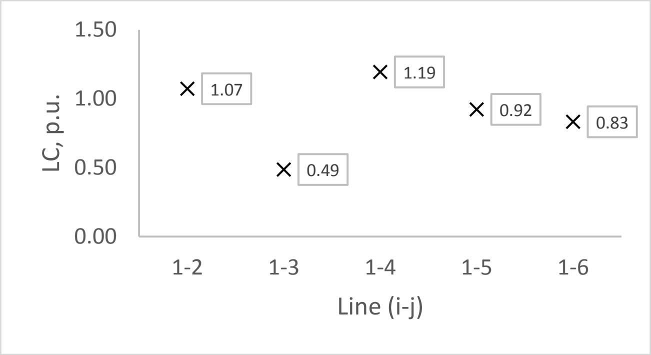

Fig. 6: Scatter plot of loading coefficients and line lengths

4 CONCLUSION

The application of parametric statistical analysis method and Newton-Raphson load flow method has been useful in modelling and evaluating the outage duration of overcurrent and earth fault per month in a year, and contribution of prevailing load flow on the delta 33kV primary distribution lines respectively. From analysis of the results obtained, the following contributions are made: monthly feeder availability represented using normal probability distribution function of $p{\sim}N(0.78,0.06)$ shows that overcurrent and earth faults contributes to outage fault, taking 5% to 12% of the month outage duration; coupled with significant line losses and weak voltage profile. The overload events during load flow is a substantiated cause for overcurrent or overload outages and earth faults can only be attributed to known insulation failures, lines' supports failures or collapse and vegetation encroachments on the lines.

Recommendations proposed include: replacement of weak or failed elements and insulations in the systems with new and modern ones to mitigate especially earth faults in the short term; planning for immediate increase in system capacity to accommodate the power demand effectively for present and forecast periods to eliminate load shedding, overload events, and high technical losses; maintenance practice at the planning and execution stages to mitigate failure events and repair time. Installation of modern state-of-the-art protection system for preventive controlling of short circuit events. This could incorporate smart technology.

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