$$I_T = \frac{I_f}{I_s},$$

I_f: Fault current (A)

I_S: Relay Pickup current setting (A)

TMS: Time Multiplier Setting

Assuming that breaker operating time is 50 ms, then the duration of voltage sag is relay operating time plus breaker operating time. As such the full characteristic of a voltage sag i.e. magnitude and duration can easily be derived from the dual-axis graph developed from fault simulations.

On top of the visual dual-axes graphs, formulation of the curves is done using regression [16] analysis. A summary of the formulas derived are shown in Table 4 for 3-phase fault of 132/11kV 2x30 MVA configuration and Table 5 for 3-phase fault of 132/3/11 kV 2x90/2x30 MVA configuration. The formulas for 2-phase faults and other network configurations can be derived using similar method.

Key variable that must be known for using the formulas is the fault distance x in the formulation. By knowing the fault distance and type of 11kV cable, remaining voltage magnitude and duration can be quickly derived for areas without online monitoring. PQ report can be completed on time without delay and having to send protection personnel to download relay data which is a time consuming effort.

TABLE IV
DERIVED EQUATIONS FOR CASE I CONFIGURATION WITH 3-PHASE FAULT AT 11KV FEEDER.

Network configuration: Bus-Section "OPEN"	
Voltage/Fault Current	Derived Equations
Remaining Voltage (p.u)	$1.094\text{x}10^{-5}x^5 - 3.992\text{x}10^{-4}x^4 + 6.161\text{x}10^{-3}x^3 - 5.318\text{x}10^{-2}x^2 + 2.866\text{x}10^{-1}x - 2.367\text{x}10^{-4}$
Fault Current (kA)	$9.484\text{x}10^{-5}x^5 - 1.976\text{x}10^{-3}x^4 + 6.601\text{x}10^{-3}x^3 + 1.532\text{x}10^{-1}x^2 - 1.977\text{x}10^{-1}x + 11.492$
Network configuration: Bus-Section "CLOSE"	
Voltage/Fault Current	Derived Equations
Remaining Voltage (p.u)	$8.460\text{x}10^{-5}x^5 - 2.434\text{x}10^{-3}x^4 + 2.762\text{x}10^{-2}x^3 - 1.560\text{x}10^{-1}x^2 + 5.193\text{x}10^{-1}x + 3.441\text{x}10^{-3}$
Fault Current (kA)	$-3.349\text{x}10^{-4}x^5 + 1.269\text{x}10^{-2}x^4 - 1.950\text{x}10^{-1}x^3 + 1.585x^2 - 7.508x + 21.88$

TABLE V
DERIVED EQUATIONS FOR CASE II CONFIGURATION WITH 3-PHASE FAULT AT 11KV FEEDER.

Network configuration: Bus-Section "OPEN" (Equations for 11kV)	
Voltage/Fault Current	Derived Equations
Remaining Voltage (p.u)	$1.505\text{x}10^{-5}x^5 - 5.193\text{x}10^{-4}x^4 + 7.532\text{x}10^{-3}x^3 - 6.079\text{x}10^{-2}x^2 + 3.057\text{x}10^{-1}x + 1.527\text{x}10^{-5}$
Fault Current (kA)	$8.027\text{x}10^{-5}x^5 - 1.485\text{x}10^{-3}x^4 - 9.916\text{x}10^{-4}x^3 + 2.202\text{x}10^{-1}x^2 - 2.311x + 12.29$
Network configuration: Bus-Section "CLOSE" (Equations for 11 kV)	
Voltage/Fault Current	Derived Equations
Remaining Voltage (p.u)	$6.982\text{x}10^{-5}x^5 - 2.039\text{x}10^{-3}x^4 + 2.364\text{x}10^{-2}x^3 - 1.414\text{x}10^{-1}x^2 + 4.825\text{x}10^{-1}x + 2.742\text{x}10^{-3}$
Fault Current (kA)	$-2.129\text{x}10^{-4}x^5 + 8.859\text{x}10^{-3}x^4 - 1.471\text{x}10^{-1}x^3 + 1.279x^2 - 6.463x + 20.17$
Network configuration: Bus-Section "OPEN" (Equations for 33kV)	
Voltage/Fault Current	Derived Equations
Remaining Voltage (p.u)	$-8.337\text{x}10^{-6}x^5 + 1.942\text{x}10^{-4}x^4 - 1.417\text{x}10^{-3}x^3 + 7.319\text{x}10^{-4}x^2 + 4.021\text{x}10^{-2}x + 0.7792$
Network congiguration: Bus-Section "CLOSE" (Equations for 33 kV)	
Remaining Voltage (p.u)	$-2.994\text{x}10^{-6}x^5 - 1.741\text{x}10^{-5}x^4 + 1.806\text{x}10^{-3}x^3 - 2.329\text{x}10^{-2}x^2 + 1.303\text{x}10^{-1}x + 0.6360$

III. Results and Discussion

A. *Validation of simulation with calculation*

The accuracy of formulation based on simulation is being validated by comparing the values from simulation with calculation using equation (1) for 3-phase fault as shown in Table 6 for remaining voltage (Case I – Bus-section "CLOSE") [16][17].

TABLE VI
% DIFFERENCE BETWEEN SIMULATION AND CALCULATION FOR REMAINING VOLTAGE (CASE I – BUS-SECTION "CLOSE")

d (km)	Vsag (pu) 2Txs (Simulation)	Vsag (pu) 2Txs (Calculation)	Difference (%)
0.2	0.100	0.098	-2.04%
0.4	0.190	0.179	-6.15%
0.6	0.260	0.246	-5.69%
0.8	0.330	0.303	-8.91%
1.0	0.380	0.352	-7.95%
1.5	0.490	0.449	-9.05%
2.0	0.570	0.521	-9.40%
2.5	0.630	0.576	-9.38%
3.0	0.680	0.620	-9.68%
3.5	0.710	0.656	-8.23%
4.0	0.740	0.685	-8.03%
4.5	0.770	0.710	-8.45%
5.0	0.790	0.731	-8.07%
5.5	0.800	0.749	-6.81%
6.0	0.820	0.765	-7.19%
6.5	0.830	0.780	-6.41%
7.0	0.840	0.792	-6.06%
7.5	0.850	0.803	-5.84%
8.0	0.860	0.813	-5.78%
8.5	0.870	0.822	-5.84%
9	0.877	0.830	-5.66%

The percentage difference is marginal with highest being 9.68%. The Root Mean Square Error (RMSE) calculated for remaining voltage formulation is 0.0461 (4.61%), which is small.

B. Validation of simulation with online measurement

The result for % remaining voltage from simulation is being compare with voltage sag (% V) from actual event captured by online measurement as shown in Table 7.

TABLE VII
% DIFFERENCE BETWEEN FORMULA FROM SIMULATION AND ONLINE MEASUREMENT FOR REMAINING VOLTAGE (CASE I – BUS-SECTION "CLOSE")

Point of common coupling	Date & time of event	d (km)	Vsag (pu) 2Txs (Online measurement)	Vsag (pu) 2Txs (formula)	Difference
SMRK	29/11/14, 03:55AM	4.0	0.70	0.75	-7.14
TKLG	17/01/16, 10:50AM	3.0	0.65	0.69	-6.15
BBRU	02/08/16, 02:55PM	1.5	0.46	0.50	-8.69
RBDR	06/07/17, 06.19PM	0.4	0.18	0.19	-5.5

The percentage difference is between -5.5 % and -8.69% for fault distance between 0.4 to 4.0 km. This showed that the formulation for characterization of voltage sag using fault simulation and regression analysis is fairly accurate.

IV. CONCLUSIONS

The authors have formulated equations for deriving voltage sag characteristics for distribution system under two (2) different configurations 132/11kV and 132/33/11kV and two (2) operating condition i.e. bus-section "OPEN" and "CLOSE". The formulation is done using short circuit simulations of DIgSILENT Power Factory commercial software and regression analysis for two (2) types of impactful faults i.e. 3-phase and phase-to-phase faults.

The fast derivation method enables voltage sag characteristic to be made known to affected customers in areas without online monitoring. The characteristic of % remaining voltage and duration can be evaluate against standard like MS IEC 61000-4-34 (Class 3) to understand the immunity level of these customers. With this simplified and fast method, utility like TNB can not only meet the timeframe imposed by the regulator on PQ event reporting but also provides full detail on the voltage sag characteristic fairly accurately.

Further research is ongoing to extend the formulation for other distribution network configuration such as 132/33kV 2x90 MVA with 33kV cables of various lengths to 33/11kV 2x30 MVA substation.

REFERENCES

[1] S. Naderian and A. Salemnia, "Method for classification of PQ events based on discrete Gabor transform with FIR window and T2FK-based SVM and its experimental verification," IET Gener. Transm. Distrib., vol. 11, no. 1, pp. 133–141, 2017.

[2] L. E. Weldermariam, V. Cuk, J. F. . Cobben, and W. L. Kling, "The Influence of Critical Distance on Monitoring Dips in the MV Network," IEEE, 2014.

[3] M. F. Faisal and a. Mohamed, "Integrating the S-PQDA software tool in the utility power quality management system," 2011 IEEE Int. Electr. Mach. Drives Conf. IEMDC 2011, pp. 966–970, 2011.

[4] M. F. Faisal, A. Mohamed, and H. Shareef, "Prediction of incipient faults in underground power cables utilizing S-transform and support vector regression," Int. J. Electr. Eng. Informatics, vol. 4, no. 2, pp. 186–201, 2012.

[5] S. Khan, Industrial Power Systems. New York: CRC Press, 2008.

[6] W. N. W. Mahmood, R. N. Mukerjee, and V. K. Ramachandaramurthy, "Identification of voltage sag origin in a measurement deficient power network," Proceedings. Natl. Power Eng. Conf. 2003. PECon 2003., pp. 0–4, 2003.

[7] S. P. A. Karim, A. Asuhaimi, and M. Zin, "The Application of Fault Signature Analysis in Tenaga Nasional Berhad Malaysia," IEEE Trans. Power Deliv., vol. 22, no. 4, pp. 2047–2056, 2007.

[8] S. Kamble and C. Thorat, "Classification of voltage sags in distribution systems due to short circuit faults," Proc. Int. Conf. Optim. Electr. Electron. Equipment, OPTIM, pp. 257–264, 2012.

[9] M. Bollen, Understanding Power Quality Problems –voltage sags and interruptions. IEEE Press series on Power Engineering, 2000.

[10] M. H. J. Bollen, "Fast assessment methods for voltage sags in distribution systems," IEEE Trans. Ind. Appl., vol. 32, no. 6, pp. 1414–1423, 1996.

[11] M. Bollen, "Method of critical distances for stochastic assessment of voltage sags," vol. 145, no. 1, 1998.

[12] M. H. J. Bollen, "Additions to the method of critical distances for stochastic assessment of voltage sags," IEEE Power Eng. Soc. 1999 Winter Meet. (Cat. No.99CH36233), vol. 2, pp. 1241–1246, 1999.

[13] H. Saadat, Power System Analysis. McGraw Hill International Editions, 1999.

[14] M. H. J. Bollen, "Characterisation of voltage sags experienced by three-phase adjustable-speed drives," IEEE Trans. Power Deliv., vol. 12, no. 4, pp. 1666–1671, 1997.

[15] TNB, TNB Distribution Engineering Fundamentals, no. May. 2014.

[16] Amiruddin Ismail and Adel Ettaieb Elmloshi,"Logistic Regression Models to Forecast Travelling Behaviour in Tripoli City," International Journal on Advanced Science, Engineering and Information Technology, vol. 1, no. 6, pp. 618-623, 2011. [Online]. Available: http://dx.doi.org/10.18517/ijaseit.1.6.124.

[17] Moaath Shatnawi,Mohammad Faidzul Nasrudin and Shahnorbanun Sahran,"A new initialization technique in polar coordinates for Particle Swarm Optimization and Polar PSO," International Journal on Advanced Science, Engineering and Information Technology, vol. 7, no. 1, pp. 242-249, 2017. [Online]. Available: http://dx.doi.org/10.18517/ijaseit.7.1.1794.

[18] Suhaila Zainudin,Dalia Sami Jasim and Azuraliza Abu Bakar,"Comparative Analysis of Data Mining Techniques for Malaysian Rainfall Prediction," International Journal on Advanced Science, Engineering and Information Technology, vol. 6, no. 6, pp. 1148-1153, 2016. [Online]. Available: http://dx.doi.org/10.18517/ijaseit.6.6.1487.