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The Propagation of Disturbances in Power Distribution Systems

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Abstract: The propagation of power quality disturbances in distribution systems is investigated in this paper. Simulations of disturbances are accomplished using mathematical and PSpice modeling. Disturbances instrumented in the field are compared with PSpice calculations. Each component in the distribution system is modeled in detail using all available information. Measurements are used to refine the simulations, and having obtained a validated simulation, studies are made as to the effects of system components on the severity of power quality disturbances. The effects of disturbances on the system components, such as transformers, distribution lines and load models, are analyzed. It is shown that when disturbances propagate through a delta / wye transformer, many indices, such as unbalance factor, voltage regulation, and zero sequence levels, decrease.

Index terms: Distribution engineering, power quality, disturbances, voltage sags.

I. INTRODUCTION

THE VOLTAGE and the current in power systems are rarely fixed at their nominal values. Voltages and currents usually have variations and each of these variations can create problems for customers depending on how severe the level of variations may be and the vulnerability of the loads. Such fluctuation phenomena are called "power quality disturbances." Power quality disturbances are caused by many events, such as starting a motor, switching equipment in the system, lightning, and balanced/unbalanced faults. Many researchers have sought to evaluate the cost of the supply interruptions. Some electric utility companies realize the importance of the power quality problem, and they invest in making their power systems as robust as possible. In order to solve power quality problems, the effects of the disturbances need to be understood clearly. According to IEEE Standard 1159-1995 [1], a voltage sag is a momentary voltage drop from 0.1 to 0.9 per unit in rms with a duration of 0.5 cycle to one minute. The analysis in this paper is the examination of disturbances measured upstream from the point of end users. Observations are used to estimate and calculate how these 'upstream' disturbances propagate to the end user.

Voltage sags are the short duration, shallow reduction in rms voltage caused by faults in the electric system and starting large loads, such as motors. The propagation characteristics describe the disturbance severity at locations far from the origin of the disturbance. Voltage sags are widely recognized as one of the most important power quality disturbances [2]. Customers worldwide experience similar problems due to voltage sags. Computer, industrial control systems, and adjustable speed drives are especially notorious for their sensitivity. According to IEEE Standard 1159-1995 [1], voltage variations can be categorized as instantaneous, momentary, or temporary depending on their durations as defined. An interruption occurs when the supply voltage decreases below 0.1 pu for a period of time within one minute. Generally, recloser limits a non-permanent fault to less than 30 cycles (a half cycle) [1].

Tang, Lamoree, McGranaghan, and Mehta [3] presented the effect of voltage sags on motors and drives. When a single line to ground fault (SLGF) occurs at phase A, the voltage across phase A-B and A-C are gradually changed by the result of the interaction between the system and the induction motor. The customer bus voltage is reduced when the fault is initiated and the voltage sag remains for a couple cycles after the fault is cleared. Collins and Mansoor [4] analyzed the effects of voltage sags and the impact of phase jumps on the operation of AC motor drives. The typical AC drive has a three-stage topology: diode rectifier, DC link (filtering), and inverter. The AC drive has some energy storage in the DC link capacitor, which enables the AC drive to tolerate voltage sags. The momentary unbalance in the supply voltage, both magnitude and phase angle, can lead the AC drive to failure or direct the protective devices to some fault operations due to excessive current unbalance in the line side of the AC drive. During an SLGF, diodes of the rectifier do not stay forward biased as in normal operation. Until the voltage peak is high enough to produce forward bias, the DC link capacitor will discharge more than under normal operation. During a voltage sag, the rms current drawn from the AC mains to AC motor drives might exceed 200% of their normal current rating.

To provide voltage sag ride-through capability, mitigation devices require some kind of energy storage.

Reference [5] categorizes mitigation devices into three major types: motor generator sets, transformer based solutions, and inverter-based solutions. Gnativ and Milanovic [6] proposed a new set of indices used to study the influence of distribution network topology on voltage sag propagation in distribution systems. It is shown that the network topology and the propagation of voltage sags in distribution systems have a very strong correlation. Sags in meshed networks are generally more severe than sags in radial systems. Collins and Zapardiel [7] presented the impact of voltage sags on an AC contactor.

References [2, 8, 9] analyze the characteristics of voltage sags and phase angle shifts in power systems with symmetrical components. A generalized rule is built for both balanced and unbalanced sags taking into account the fault types, transformer types, and load connections. From two types of faults (the single line to ground and the double line to ground) and three symmetrical phases, unbalanced sags can be classified as six different types. The details of these subtypes are proposed in reference [10].

II. SAG INDICES AND MEASURES OF POWER QUALITY EVENTS

Many voltage sag indices have been developed. A few are reviewed below:

- A sag severity index was developed by the Detroit Edison company as simply the mean of the rms value per unit (V_a, V_b, and V_c) [9],

$$Sag\ score = 1 - \frac{|V_a| + |V_b| + |V_c|}{3}.$$

- Other methods, which are similar to the reliability indices, are proposed by Brooks, Waclawiak, and Sundaram [11]. Four types of indices in reference [11] depend on the combination of the magnitude and duration shown in the following paragraph.
- The System Average rms (Variation) Frequency Index$_{Voltage}$ (SARFI$_x$) represents the average number of customers experiencing the voltage variation that occurs over the assessment period,

$$SARFI_X = \frac{\sum N_i}{N_T},$$

where x is the rms voltage threshold, N_i is the number of customers experiencing short-duration voltage deviations due to measurement event i and N_T is the number of customers served from the section of the assessed system [11].

- Other indices used to assess the rms variation are the System Instantaneous Average RMS Frequency Index (SIARFI$_x$), the System Momentary Average RMS Frequency Index (SMARFI$_x$), and the System Temporary Average RMS Frequency Index (STARFI$_x$).
- Thallam and Heydt [9] proposed a method called Voltage Sag-Lost Energy Index (VSLEI). The concept is based on the energy that was not delivered during the sag event. The lost energy in a sag event, W, can be calculated as,

$$W = (1 - V_{pu})^{3.14} t \qquad (1)$$

where V_{pu} is the phase voltage in per unit of nominal voltage during a sag event, and t is the sag duration in milliseconds. Equation (1) is derived by using the curve fitting method to the CBEMA curve.

- Gnativ and Milanovic [12] proposed a method called Sag Propagation Index (SPI),

$$SPI^{n}_{\%V} = \frac{\sum N_{Bi}}{\sum N_{Bt}}$$

where n is the network configuration, $\%V$ is the rms voltage threshold (e.g., 90%, 80%, …), $\sum N_{Bi}$ is number of buses that experience voltage sags with magnitudes less than $\%V$, and $\sum N_{Bt}$ is the total number of buses in the distribution system. Gnativ and Milanovic also introduced an index called Sag Propagation Index for Asymmetrical Faults (SPIA).

- Kyei, Ayyanar, Heydt, Thallam, and Blevins [13] have proposed a sag index based on compliance with a CBEMA-like curve. The index seems to be useful for a range of single phase and three phase loads, and the index is load dependent.

In this study, several simply calculated indices are used to assess the severity of sag-type disturbances. The indices used in the analysis consist of unbalance factor (U), voltage regulation (VR), the lowest phase voltage during fault (V_{lowest}), zero sequence factor (V_0/V_{rated}), maximum fault current and sag energy index (SEI). The unbalance factor, voltage regulation and sag energy index [14-16] are,

$$U_V = \frac{V^-}{V^+} \qquad U_I = \frac{I^-}{I^+} \qquad VR = \frac{|V_a| + |V_b| + |V_c|}{|Vrated|}$$

$$SEI = [100 - E_a + 100 - E_b + 100 - E_c][Time\ duration]$$

where E_a, E_b, and E_c are phase energy values computed in each phase. E_a is calculated as,

$$Ea = \frac{\int_{event\_start}^{event\_end} Va\_event^2 dt}{\int_{event\_start}^{event\_end} Va\_nom^2 dt} \times 100$$

And the remaining phase quantities are similarly calculated.

III. ANALYSIS METHODS

In order to analyze the consequences of short circuits in distribution systems, the major components in the distribution system need to be modeled. Three generalized equations, which represent the relationship between voltages and currents at the primary and secondary side are given by [14],

$$[VLN_{ABC}] = [a_t][VLN_{abc}] + [b_t][I_{abc}]$$
$$[I_{ABC}] = [d_t][I_{abc}]$$
$$[VLN_{abc}] = [A_t][VLN_{ABC}] - [B_t][I_{abc}]$$

where $[a_t]$, $[b_t]$, $[d_t]$, $[A_t]$, and $[B_t]$ are five generalized matrices calculated on the basis of transformer connections, $[VLN_{ABC}]$ is the matrix representing line-to-neutral voltages at source side, $[I_{ABC}]$ is the line currents at source side matrix, and $[I_{abc}]$ is the line currents at load side matrix. As an example of the generalized procedure, consider the connection and phasor diagram of a delta-grounded wye transformer with a standard thirty-degree connection shown in Figure 1. This diagram is also used as the hierarchical block of a delta-wye transformer connection in PSpice. The utilization of hierarchical blocks allows a subroutine-like (i.e., in library form) procedure to model components in a primary distribution system. Unfortunately, the method is data intensive. According to symmetrical component theory, the equivalent line-to-neutral voltages as a function of sequence line-to-neutral voltages are

$$\begin{bmatrix} VLN_A \\ VLN_B \\ VLN_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a_s^2 & a_s \\ 1 & a_s & a_s^2 \end{bmatrix} \begin{bmatrix} VLN_0 \\ VLN_1 \\ VLN_2 \end{bmatrix}$$

or

$$[VLN_{ABC}] = [A_s][VLN_{012}]$$

where

$$[A_s] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a_s^2 & a_s \\ 1 & a_s & a_s^2 \end{bmatrix} \qquad a_s = 1.0\angle 120^\circ .$$

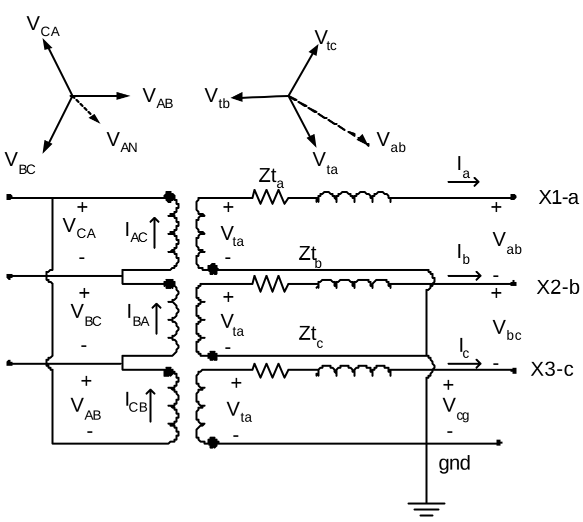

Fig. 1 Delta-grounded wye transformer

The relationship between the line-to-neutral sequence voltages and line-to-line sequence voltages are,

$$\begin{bmatrix} VLN_0 \\ VLN_1 \\ VLN_2 \end{bmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \sqrt{(1/3)}\angle -30^\circ & 0 \\ 0 & 0 & \sqrt{(1/3)}\angle -30^\circ \end{vmatrix} \begin{bmatrix} VLL_0 \\ VLL_1 \\ VLL_2 \end{bmatrix}$$

or in a condensed form as,

$$[VLN_{012}] = [T][VLL_{012}].$$

The line-to-line voltages are transformed to sequence voltages by,

$$\begin{bmatrix} VLL_0 \\ VLL_1 \\ VLL_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a_s^2 & a_s \\ 1 & a_s & a_s^2 \end{bmatrix}^{-1} \begin{bmatrix} VLL_A \\ VLL_B \\ VLL_C \end{bmatrix}$$

or in a condensed form as,

$$[VLL_{012}] = [A_s]^{-1}[VLL_{ABC}].$$

Similar expressions are obtained for all transformer connections and line-line and line-neutral voltages as seen in Table 1.

Table 1 Generalized matrix models for various types of transformers

	Transformer type			
	Delta-grounded wye	Wye-wye	Delta-delta	Ungrounded wye – delta
$[a_t]$	$[W][N_t]$	$[N_t]$	$[W][N_t][D]$	$[N_t][D]$
$[b_t]$	$[W][N_t]\bullet [Zt_{abc}]$	$[N_t]^{-1}\cdot [Zt_{abc}]$	$[W][N_t]\bullet [Zt_{abc}][G]$	$[N_t][N_t][Zt_{abc}][d_t]$
$[d_t]$	$\frac{1}{n_t}[D]$	$[N_t]^{-1}$	$[N_t]^{-1}$	$\frac{1}{3\cdot n_t}\begin{bmatrix} 1 & -1 & 0 \\ 1 & 2 & 0 \\ -2 & -1 & 0 \end{bmatrix}$
$[A_t]$	$\frac{1}{n_t}[DI]$	$[N_t]^{-1}$	$[W][N_t]^{-1}[D]$	$[W][N_t]^{-1}$
$[B_t]$	$[Zt_{abc}]$	$[Zt_{abc}]$	$[W][Zt_{abc}]\bullet [G]$	$[W][N_t]\bullet [Zt_{abc}][d_t]$

where

$$[N_t] = \begin{bmatrix} n_t & 0 & 0 \\ 0 & n_t & 0 \\ 0 & 0 & n_t \end{bmatrix} \qquad [Zt_{abc}] = \begin{bmatrix} Zt_a & 0 & 0 \\ 0 & Zt_a & 0 \\ 0 & 0 & Zt_a \end{bmatrix}$$

$$[W] = \frac{1}{3}\begin{bmatrix} 2 & 1 & 0 \\ 0 & 2 & 1 \\ 1 & 0 & 2 \end{bmatrix} \qquad [D] = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

$$[DI] = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \qquad [d_t] = \frac{1}{3\cdot n_t}\begin{bmatrix} 1 & -1 & 0 \\ 1 & 2 & 0 \\ -2 & -1 & 0 \end{bmatrix}$$

$$[G] = \frac{1}{Zt_{ab} + Zt_{bc} + Zt_{ca}}\begin{bmatrix} Zt_{ca} & -Zt_{bc} & 0 \\ Zt_{ca} & Zt_{ab} + Zt_{ca} & 0 \\ -Zt_{ab} - Zt_{bc} & -Zt_{bc} & 0 \end{bmatrix}.$$

IV. SHORT CIRCUIT CALCULATIONS

One of the main reasons for voltage sags is a fault in the power system. Whenever a circuit breaker clears the fault, voltage sags are alleviated. The symmetrical component method is normally applied in power system fault analysis. The applications of symmetrical component method are well studied. However, the main disadvantage of symmetrical component method is the difficulty in analyzing a system which is inherently unbalanced, such as a system with unequally mutual coupling or a system with unbalanced loads. This section presents another technique, called the "phase frame method," used to analyze faults in unbalanced three-phase distribution feeders [14-15]. The first step in the phase frame method is to model each component in the system, such as system voltage source and their short circuit impedances, distribution lines, transformers, loads, and capacitor banks. For the short circuit calculation, the Thevenin equivalent circuit at the fault point is required. One of the critical points in calculating the Thevenin equivalent circuit is changing the impedance on the primary side of transformer to the impedance on the secondary side of transformers. The impedance of other components can be added arithmetically.

The Thevenin equivalent circuit is used to analyze short circuit faults. The type of faults can be specified by setting parameters, such as V_{ax}, V_{bx}, V_{cx}, and V_{xg}, according to the fault properties. By applying Kirchhoff's voltage law to the Thevenin equivalent circuit,

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} Z_{aa}+Z_f & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb}+Z_f & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc}+Z_f \end{bmatrix} \begin{bmatrix} If_a \\ If_b \\ If_c \end{bmatrix} + \begin{bmatrix} V_{ax} \\ V_{bx} \\ V_{cx} \end{bmatrix} + \begin{bmatrix} V_{xg} \\ V_{xg} \\ V_{xg} \end{bmatrix} \qquad (2)$$

Four additional equations are needed to solve Equation (2). These additional equations can be given from specific type of faults which are presented in Table 2.

Table 2 Current and voltage properties for various types of fault

Type of faults	Voltage properties	Current properties
Three-phase fault	$V_{ax} = V_{bx} = V_{cx} = 0$	$If_a + If_b + If_c = 0$
Three-phase-to-ground fault	$V_{ax} = V_{bx} = V_{cx} = V_{xg} = 0$	
Phase *i*-to-phase *j* fault (*k* is unfaulted phases)	$V_{ix} = V_{jx} = 0$	$If_k = 0$ $If_i + If_j = 0$
Phase *k*-to-ground fault (*i* and *j* are unfaulted phase)	$V_{kx} = V_{xg} = 0$	$If_i = If_j = 0$

V. EXAMPLE OF DISTURBANCE PROPAGATION ANALYSIS

The propagation of the disturbances is investigated by using mathematical and PSpice modeling. Based on information provided by Salt River Project (SRP), a major electric utility company in Arizona, sample distribution feeders serving customers in Tempe and Phoenix, Arizona are chosen as illustrations. All of the parameters, such as line parameters and transformer characteristics for this feeder were calculated in detail from known line and cable geometry [14,16]. Figure 2 shows a substation at which 69 kV / 12.47 kV transformation occurs and Figure 3 shows a representative feeder configuration.

Fig. 2 Substation in Tempe, AZ

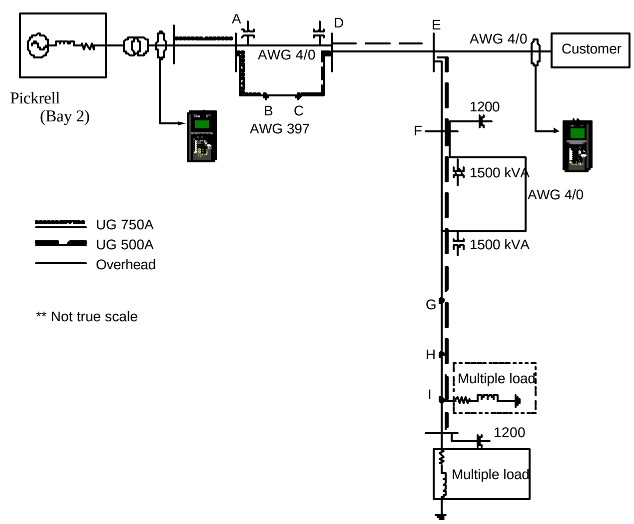

Fig. 3 Single line diagram of a sample system

With the generalized procedure outlined above, the substation and its distribution feeders were simulated in PSpice. The simulation included:

- Ground modeling
- Neutral wire modeling
- Modeling of the 69 kV supply using short circuit data at the substation

- Known load models and estimated constant power models for some unknown loads
- Capacitor banks
- Underground and overhead line models.

Two cases are shown here to illustrate the general procedure and its capabilities. Table 3 shows some descriptors of the two cases. The generalized approach outlined above was used to adjust load models so that measured fault disturbance data matched simulation results. Using the parameters obtained in this way, there is some confidence that the model of the substation plus feeders (plus loads) models the actual physical system in the field. In this way, the PSpice model can be used to examine the results of faults not measured, and various power quality indices and their changes as one moves throughout the system can be studied.

Table 3 Two examples of fault disturbance propagation analysis

Case	Fault Location	Type of fault in 69 kV system	Fault impedance (O)
1	Upstream of 69 kV	Phase C to ground	4 O
2	Upstream of 69 kV	Double phase to ground fault (Phase A and B)	4 O (both phases)

In the cases studied, it was found that for some loads, sags in distribution voltage resulted in increases in load current. Obviously, this is not an expected consequence for fixed impedance loads. The loads in such cases were assumed to be electronic loads, and a constant power (i.e., active power, totaled across the three phases) was assumed. This was implemented in PSpice and the model and measurements were found to agree. As examples, Figures 4 and 5 refer to Case 1, and Figures 6 and 7 refer to Case 2. The agreement of voltages and current should be noted. Also note that disagreement is in high frequency phenomena, and it is believed that the field measured quantities do not show the high frequency effects. This is because the bandwidth of the monitoring instrumentation is limited to about 4 kHz. The PSpice simulations do not have such a limitation.

VI. HOW DISTURBANCES PROPAGATE THROUGH SYSTEM COMPONENTS

The PSpice model described above, tuned to match measurements in several places in the system, was used to assess the voltages and currents at points of instrumentation as well as other points in the system.

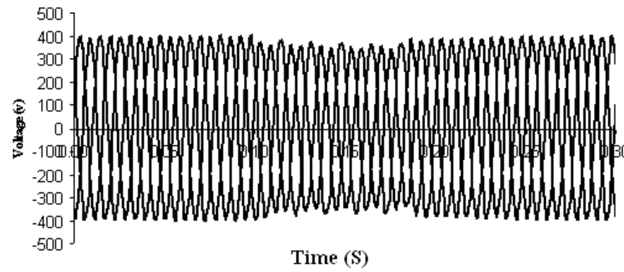

Figure 4 Field measurement results of voltages at the secondary side of a distribution transformer located at customer S for Case 1

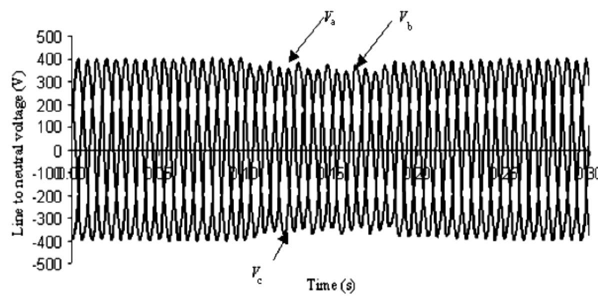

Figure 5 Simulation results for Case 1 at customer S, voltage at secondary distribution, compare with Fig. 4 to compare with field measurements.

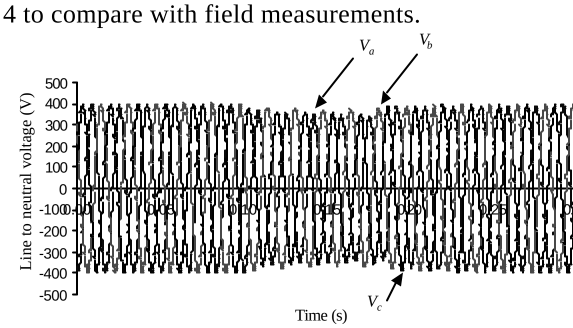

Figure 6 Measurement results of voltages at secondary side of a distribution transformer located at customer M (Case 2)

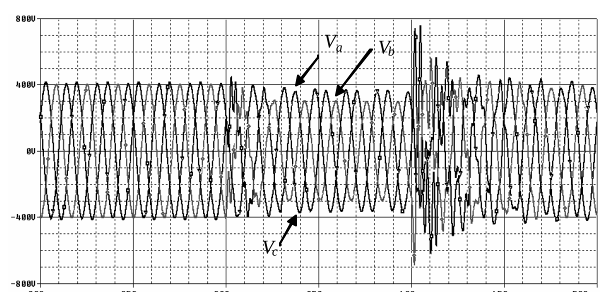

Figure 7 Simulation results of voltages at secondary side of a distribution transformer located at customer M (Case 2).

A large number of tests were run, and the electric utility supplied 13 instrumented events for analysis. Figure 8 shows the primary distribution system studied with three selected power quality indices labeled at several points of interest. Figure 8 shows Case 1 described above. Table 4 shows some numerical results from this case in the vicinity of a delta / wye connected transformer located at a customer ('Customer S') at the lower right of Fig. 8. Tabulations such as Table 4 can be utilized to obtain general remarks on the way power quality disturbances propagate in a primary distribution system. Although no general conclusions can be drawn from one table such as this or one case studied, when a large number of cases are studied, and a large number of components are analyzed, some generalized results appear. Results were found to be consistent up to a (typical) primary distribution feeder length of about 350 m. These results are summarized in Table 5.

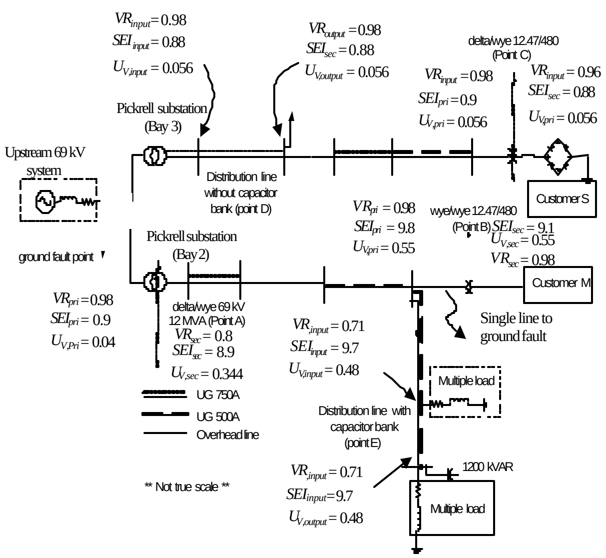

Fig. 8 Voltage regulation, sag energy index and unbalance factor map for Case 1

VII. CONCLUSIONS

The main conclusions of this paper relate to the potential of using simulation for the analysis of power quality disturbance propagation, and using that analysis to determine what components in a primary distribution system cause mitigation of the disturbances. PSpice has been successfully utilized in hierarchical blocks to simulate distribution system components -- but the method is data intensive. It is possible to 'tune' the simulation to match actual measurements of disturbances. The developed model may be used in connection with virtual measurements to assess the impact of system components on the propagation of power quality disturbances. The main distribution system elements that are found to mitigate certain disturbances are:

- Wye / wye and delta / wye connected transformers (for the sag energy index, if the fault is downstream of the measurement point)
- Delta / wye connected transformers (for voltage regulation, when the fault is upstream of the measurement point).

Table 4 Power quality indices for Case 1 for a delta / wye transformer at Customer S

	Primary side of the delta/wye transformer at Customer S		Secondary side of the delta / wye transformer at Customer S	
	pre-fault	during fault	pre-fault	during fault
U_V	0.0415	0.0557	0.0434	0.0561
VR	0.9913	0.9765	0.9785	0.9638
Zero sequence voltage (pu)	0.0000			
Lowest phase voltage (pu)	-	0.9615 Phase C	-	0.95907 Phase C
U_I	0.0761	0.0963	0.8140	0.8090
Zero sequence current (pu)	0.0000			
SEI	0.90		0.88	

Table 5 Relationship between components and performance indices

	Uv	*Io*	*VR*	*Vo*	*SEI*	
Wye / wye transformer	S	S	NC	S	+ DL DF	- DL DF
Delta / wye transformer	- DF	CP	(- FU) (+ FD)	CP	(+ FU) (-FD)	
Short distribution line	S	S	S	S	S	
Distribution line with capacitor bank	S	S	+ DF	S	+ DL	

-	Severity decreases when passing away from fault location through the component	S	Index same upstream and downstream
+	Severity increases when passing away from fault location through the component	DF	Depends heavily on fault types
CP	Cannot pass through delta/wye transformer	DL	Depends on load types
FD	Fault downstream of measurement point	FU	Fault upstream of measurement point
NC	No conclusion		

References

[1] IEEE Standard 1159-1995, "Recommended practice for monitoring electric power quality," IEEE Standards, Piscataway, NJ, November 1995.

[2] L. Zhang, "Characteristic of voltage dips (sags) in power systems," IEEE Transactions on Power Delivery, vol. 15, no. 2, April 2000, pp. 827-832.

[3] L. Tang, J. Lamoree, M. McGranaghan, H. Mehta, "Distribution system voltage sags: interaction with motor and drive loads," Proceedings of the IEEE Power Engineering Society, Transmission and Distribution Conference, April 1994, pp. 1-6.

[4] E. Collins, A. Mansoor, "Effects of voltage sags on AC motor drives," Proceedings of the IEEE Technical Conference on the Textile, Fiber, and Film Industry, May 1997, pp. 9-16.

[5] A. Sannino, M. Miller, M. Bollen, "Overview of voltage sag mitigation," IEEE Power Engineering Society Winter Meeting, vol. 4, January 2000, pp. 2872 - 2878.

[6] R. Gnativ, J. Milanovic, "Voltage sag propagation in systems with embedded generation and induction motors," IEEE Power Engineering Society Summer Meeting, vol. 1, July 2001, pp. 474-479.

[7] E. Collins, F. Zapardiel, "An experiment assessment of AC contactor behavior during voltage sags," Proceedings of the IEEE International Symposium on Industrial Electronics, vol. 2, July 1997, pp. 439-444.

[8] M. J. Bollen, "Voltage sag: effects, mitigation and prediction," Journal of Power Engineering, vol. 10, June 1996, pp. 129-135.

[9] R. S. Thallam, G. T. Heydt, "Power acceptability and voltage sag indices in the three phase sense," IEEE Power Engineering Society Summer Meeting, vol. 2, July 2000, pp. 905-910.

[10] L. Zhang, M. J. Bollen, "A method for characterization of three-phase unbalanced dips (sags) from recorded voltage waveshapes," IEEE Telecommunication Energy Conference, INTELEC'99, June 1999, pp. 9-3.

[11] D. L. Brooks, M. Waclawiak, A. Sundaram, "Indices for assessing utility distribution system rms variation performance," IEEE Transactions on Power Delivery, vol. 13, no. 1, January 1998, pp. 1666-1671.

[12] R. Gnativ, J. Milanovic, "Voltage sag propagation in systems with embedded generation and induction motor," Power Engineering Society Summer Meeting, vol. 1, July 2001, pp. 474-479.

[13] J. Kyei, R. Ayyanar, G. Heydt, R. Thallam, J. Blevins, "The Design of Power Acceptability Curves," IEEE Transactions on Power Delivery, v. 17, No. 3, July 2002, pp. 828 - 833.

[14] W. H. Kersting, "Distribution system modeling and analysis," CRC Press, New York, 2002.

[15]P. M. Anderson, "Analysis of faulted power systems," Iowa State University Press, Ames, Iowa, 1973.

[16] N. Nimpitiwan, "Attenuation of disturbances in power distribution systems," MSEE Thesis, Arizona State University, Tempe, AZ, December, 2002.

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