A novel approach for voltage sag representation in a chemical industry: A case study

Chinmaya Behera | Abhishek Banik | Arup Kumar Goswami

Department of Electrical Engineering, National Institute of Technology Silchar, Silchar, India

Correspondence
Arup Kumar Goswami, Department of Electrical Engineering, National Institute of Technology Silchar, Silchar, Assam 788010, India.
Email: gosarup@gmail.com

Abstract
Voltage sag is a major Power Quality issue which may occur at every possible load point. In the industrial sector, its impact is particularly prominent at it is directly related to financial losses. To eliminate or, at least, mitigate voltage sag, the first, and the most crucial, step is to identify the portions of the network which are vulnerable to voltage sag. Therefore, a novel approach is presented in this article to identify the areas within the network, which are more prone to voltage sag. An impedance matrix-based model followed by Monte Carlo Simulation (MCS) technique is used for the assessment of the voltage sag. This MCS technique is implemented to simulate the number, type, and locations of faults randomly within the system. Then, voltage sag data are collected, and using Bivariate Frequency Distribution, a graphical representation of voltage sag prone buses is developed, which named Voltage Sag Map. The effectiveness of the proposed approach is validated by adopting an industrial distribution system as a case study in this article.

KEYWORDS
impedance modeling, industrial distribution system, MCS, Monte Carlo simulation, power quality, sag map, symmetrical and unsymmetrical faults, voltage sag

1 | INTRODUCTION

Voltage sag has received more attention at the industrial and commercial facilities because of the malfunctioning of various sensitive equipments, which leads to finance-related issues. According to statistical data, the occurrence of voltage sag is more frequent than other power quality (PQ) issues.\(^1\) A sudden reduction in the voltage level ranging from 10% to 90% of its rated Root Mean Square (RMS) value at the power frequency for a duration of 0.5-30 cycles is termed as voltage sag. The voltage sag pivoted mainly around two important parameters, namely, voltage magnitude and duration, which are the essential entities to distinguish (or identify) voltage sag from other PQ issues.\(^2\) The occurrence of voltage sag in a network is due to several reasons, among them the most significant causes being sudden wind gust on conductors and attachments, contacts with trees, cattle, animals, rats, birds, snakes, and so on.\(^1\) The financial impact of voltage sag on the industrial distribution system is analyzed in Reference 3, and how voltage sag has a relationship in generating interruption is given in Reference 4.
An analytical expression is developed for the phase angle jump method to identify different types of voltage sag due to various power system faults. Similarly, the three-phase voltage ellipse parameter helps in the identification of voltage sag as well as swell. There are various types of sensitive equipment connected in industrial facilities, which may trip due to voltage sag. The characteristics of sensitive equipment can be observed in the voltage sag tolerance curve. Therefore, a probabilistic voltage sag severity index (SSI) is developed by considering the voltage sag tolerance curve. The point-on-wave is determined for the three-phase voltage dip due to the influence of sensitive equipment like wind turbine and AC contactors. A single voltage sag event, can turn in to a momentary interruption and sustained interruption if sensitive equipment does not have enough voltage sag ride-through capability. Therefore, low voltage sag ride-through capability of equipment can have different reliability issues in a low voltage power system network. In low voltage distribution networks, there are various PQ-related issues. The copula-based stochastic load model for harmonics analysis, by using copula technique, the computational burden is reduced in Reference 10.

An assessment of voltage sag using monitoring devices data is very tedious and time-consuming work. So the authors in Reference 11 developed a mathematical model so that the stochastic nature of voltage sag can be analyzed using the motoring data of a transmission network. The concept of copula can be used in voltage assessment to reduce the computational burden. The operational voltage of a poly-phase AC circuit is analyzed by using Thevenin’s theorem in Reference 12. The first widespread outline on the voltage sag occurrence is simulated by recognizing several computational tools which envisage the residual voltage, duration, frequency, and economic bearing of voltage sag. The influence of power system faults, its location, and the configuration of generation based upon load demand is taken into account for the evaluation of the voltage sag as well as exposed/affected area for large transmission networks. In a meshed and radial network, residual voltage is evaluated by considering the effects of power transformer as well as faults in Reference 15.

The modeling and simulation guidelines for the prediction of voltage sag using digital simulation is given in Reference 16. Improper selection of protection scheme can help to magnify the impact of a voltage sag event in a power system network. Therefore, the authors in Reference 17 consider different protective device coordination scenarios in the Monte Carlo Simulation (MCS) approach in a time-domain simulation framework to estimate the voltage sag in a distribution network. Due to improper selection and integration of Distributed Generations (DGs) show a negative impact on a power system network. Therefore in Reference 18, a stochastic estimation of voltage sag is studied for a transmission system where solar photovoltaic is connected. Similarly, the probabilistic based fault rates are considered for the estimation of voltage sag when a 2 MW Doubly Fed Induction Generator is connected to a power system network. The time-varying fault rate along with the influence of generator scheduling is considered for yearly Predictable Sag Occurrences at sensitive load buses.

A stochastic model is developed by considering the uniform fault rate and power system faults for the estimation of voltage sag annually. There are different types of indices (ie, reliability, PQ, cost, and so on) that determine the performance analysis of a power system network. The authors in Reference 17 have developed a voltage sag index considering the average number and duration of interruptions in a year for a distribution network. In Reference 22, SSI is used to recognize the weak areas within a network for the calculations of voltage sag. In Reference 23, authors have utilized voltage sag data for accurate identification of the fault location and classification voltage sag. A methodology for prophesying the number of equipment outages per year due to voltage sag is developed.

In all the studies mentioned above, it is found that the researchers have developed various techniques and tools for assessment, quantification of equipment trip, and the financial impact of voltage sag at the load end. Very few studies were found, which identify the vulnerable or affected area due to voltage sag. The identification of the affected area helps in reducing the impact of voltage sag in a power system network. The work in this article is motivated by a visit to a chemical plant. In the chemical plant, it is observed that every year, a substantial amount of financial loss is incurred due to the PQ issues. After interviewing the plant authority, it is found that the financial losses occurred due to maloperation of sensitive equipment triggered mainly by voltage sag. However, the area exposed to voltage sag could not be identified properly.

In this article to address this issue, faults are simulated within an industrial distribution system (ie, underground distribution network) to obtain a voltage sag scenario indicating different sag levels which can be used to assess whether a particular sensitive equipment will trip or not. Representation of voltage sag indicating different levels (which is essential to assess probable tripping of a sensitive equipment) has never been addressed before to the best of the authors’ knowledge. A concept of Bivariate Frequency Distribution (BFD) is used to develop a graphical representation named as Voltage Sag Map (VSM) to identify the voltage sag affected area and represent the number of sags for different voltage levels. Furthermore, to analyze the impact of voltage sag, two different power system networks are considered, which offers insightful
information on how voltage sag is propagating when faults occur. This method is particularly useful when an appropriate voltage sag scenario of a distribution network is required, and it can be easily applied to assist in the development of mitigation strategies. The two crucial information that should be taken into consideration while developing a VSM are that (1) the number of voltage sag events per year and (2) different ranges of voltage sag at each load bus. This VSM helps the industrial operators to understand the behavior of the sensitive equipment connected across the load end. The applicability of VSM can be understood with the help of voltage sag tolerance curve given by the Information Technology Industry Council (ITIC) and Computer Business Equipment Manufacturers Association (CBEMA). Different sensitive equipment have their individual characteristics towards voltage sag. As voltage magnitude and duration are the parameters for defining voltage sag, therefore equipment sensitivity is usually expressed in terms of voltage sag magnitude and duration, and the ITIC curve is shown in Figure 1.

During any disturbance, the duration and magnitude of voltage sag may lie outside the tolerable zone of a particular sensitive equipment which can potentially damage the equipment. And the region bounded by the red line shown in Figure 1 is considered to be the region which is sensitive towards voltage sag for a particular disturbance. Therefore for a given voltage sag duration, the voltage threshold for different sensitive equipment is decided from the ITIC curve. For an example, let us consider a Programmable Logic Controller (PLC) which is a key equipment for automating industrial activities which necessarily means that many industrial processes (involving other sensitive equipment) are dependent on its functionality. And when a PLC malfunctions during a disturbance which results in voltage magnitude lying outside its ride through capability region (0.3-0.9 pu), it forces other equipment to stop operation which results in a considerable loss of revenue. With the help of this study, an industrial operator can adopt precautionary measures to avoid tripping of a sensitive equipment connected at a vulnerable load point which is identified by using VSM. The overall objective of this work is presented in the form of a block diagram shown in Figure 2. The rest of the article is organized as follows; the concept of MCS-based fault positioning method for the assessment of voltage sag is given in Section 2. In Section 3, the Type-2 fuzzy fault rate (FFR) is used for the evaluation of voltage sag per year. The procedure for developing VSM for an industrial distribution system is given in Section 4. The results obtained by using the proposed VSM concept is given and discussed in Section 5 before concluding in Section 6.

![Figure 1](image1.png)  
**Figure 1** Sensitive equipment acceptability curve

![Figure 2](image2.png)  
**Figure 2** Block diagram for the overall objective
2 | MCS-BASED FAULT POSITIONING METHOD FOR THE VOLTAGE SAG ASSESSMENT

This section focuses on voltage sag evaluation using fault positioning method considering symmetrical and unsymmetrical faults. A stochastic approach is considered to evaluate the voltage sag magnitude. There are mainly two stochastic methods for evaluation of voltage sag magnitude, namely (i) the Critical distance method and (ii) the Fault positioning method. In this work, voltage sag is evaluated by using the fault positioning method. As fault are random, it can lie anywhere in-between the connected buses so, a parameter \( \xi \) (denoting fault position in-between a line) is considered, based on which the residual sag is evaluated. The MCS technique is used to simulate the fault type, location, and number per year. The probability of occurrence of fault varies from point to point based on conductor material specification, voltage level, and length of the power network. In Table 1 probability of occurrences for different types of faults in different power network is given, which is used to evaluate the number of voltage sag per year. Where \( P_{L-L-L} \) is a symmetrical fault and \( P_{L-L-G}, P_{L-G}, \) and \( P_{L-L} \) are the unsymmetrical faults. The mathematical formulation for faults occurring at the buses and in-between the lines are given in the following subsection.

2.1 Evaluation of voltage sag when fault occurs at a bus

Let us consider that a fault has occurred at bus \( n \) shown in Figure 3. Now the voltage magnitude at load bus \( m \) in the post-fault scenario can be evaluated using the impedance matrix.

\[
\begin{align*}
U_m^{(0)} &= 0 - [Z_m] I_n^{(0)} \\
U_m^{(+)} &= U_m^{(+ \text{prf}} - [Z_m] I_n^{(+)} \\
U_m^{(-)} &= 0 - [Z_m] I_n^{(-)} \\
\end{align*}
\]

where \( U_m^{(0),(+),(-)} \) is zero, positive and negative sequence voltages respectively at bus \( m \), \( U_m^{(+ \text{prf}} \) are the prefault voltages at bus \( m \) and \( I_n^{(0),(+),(-)} \) are the sequence fault currents at the faulted bus \( n \). \( Z_m^{(0),(+),(-)} \) is the transfer matrix.

| Fault number | Type of faults | Overhead system | Underground system |
|--------------|----------------|----------------|-------------------|
| 1            | \( P_{L-L-L} \) | 5\%            | 4\%               |
| 2            | \( P_{L-L-G} \) | 10\%           | 17\%              |
| 3            | \( P_{L-G} \)   | 70\%           | 73\%              |
| 4            | \( P_{L-L} \)   | 15\%           | 6\%               |

**TABLE 1** Probability of different types of faults

**FIGURE 3** Power system network of a faulted \( n \)-bus system
impedance matrix between load bus $m$ and bus $n$, $Z_{m,n}^{(0)}$, $Z_{m,n}^{(+)}$, and $Z_{m,n}^{(-)}$ are the zero, positive, and negative sequence transfer impedance values in the $Z$-bus matrix. Equation (2) is used to evaluate the voltage magnitude when a fault occurs at a particular bus. The pre-fault current magnitude is neglected as it is very small with respect to fault current magnitude.

### 2.2 Evaluation of voltage sag when fault occurs in a line

When a fault occurs anywhere in a line of a power system network, the fault position method is used to evaluate voltage sag magnitude. The accuracy of this method depends upon the fault position and the number of simulated faults, so MCS technique is used to simulate random faults in a line of a power system. In this subsection evaluation of voltage sag magnitude for the faults given in Table 1 are discussed. Let fault has occurred in the line connecting bus $i$ and bus $j$ shown in Figure 3 (at point $f$), the position at which the fault has occurred is denoted by $\xi$ and its value lies between 0 and 1, as seen from Equation (3).

$$\xi = \frac{D_{ij}}{D_{ij}}$$

(3)

where $D_{ij}$ is the distance between bus $i$ and the fault point $f$ and $D_{ij}$ is the distance between bus $i$ and bus $j$. The driving point impedance (at point $f$) and transfer impedance (between bus $m$ and the fault point $f$) can be expressed in terms of zero, positive, negative sequence impedances and $\xi$. The sequence transfer impedances between the load bus $m$ and fault point $f$ can be expressed as

$$Z_{m,f}^{(0)} = (1 - \xi)[Z_{m,f}^{(0)} + \xi z_{m,f}^{(0)}]$$

$$Z_{m,f}^{(+)} = (1 - \xi)[Z_{m,f}^{(+)} + \xi z_{m,f}^{(+)}]$$

$$Z_{m,f}^{(-)} = (1 - \xi)[Z_{m,f}^{(-)} + \xi z_{m,f}^{(-)}]$$

(4)

where $z_{m,f}^{(0,+,−)}$ are the sequence transfer impedances corresponding to buses $i$ and $m$, $Z_{m,f}^{(0,+,−)}$ is the sequence transfer impedance corresponding to bus $m$ and $j$. Now the sequence driving point impedance at fault position $f$ can be expressed as

$$\begin{bmatrix}
Z_{i,f}^{(0)} \\
Z_{i,f}^{(+)} \\
Z_{i,f}^{(-)}
\end{bmatrix} = \begin{bmatrix}
(1 - 2\xi + \xi^2) & 2(\xi - \xi^2) & \xi - \xi^2 \\
(1 - 2\xi + \xi^2) & 2(\xi - \xi^2) & \xi - \xi^2 \\
(1 - 2\xi + \xi^2) & 2(\xi - \xi^2) & \xi - \xi^2
\end{bmatrix} \times \begin{bmatrix}
Z_{i}^{(0)} & Z_{i}^{(+)} & Z_{i}^{(-)} \\
Z_{j}^{(0)} & Z_{j}^{(+)} & Z_{j}^{(-)} \\
Z_{j}^{(0)} & Z_{j}^{(+)} & Z_{j}^{(-)}
\end{bmatrix}$$

(5)

$Z_{i}^{(0,+,−)}$, $Z_{j}^{(0,+,−)}$, and $Z_{j}^{(0,+,−)}$ are the sequence driving point impedances at bus $i$, $j$, and $f$ respectively, $Z_{i}^{(0,+,−)}$ are the sequence line impedance of the line connecting bus $i$ and bus $j$.

The prefault voltage at $f$ is expressed as follows

$$U_{p}^{prf} = U_{p}^{prf} + (U_{p}^{prf} - U_{p}^{prf})\xi$$

(6)

where $U_{p}^{prf}$ and $U_{p}^{prf}$ are the pre-fault voltages at bus $i$ and bus $j$. When a fault occurs at a point on the line connecting two buses $i$ and $j$, the voltage sag magnitude at the load bus $m$ can be evaluated by using Equation (6) and sequence impedances which are discussed before. The evaluation of voltage sag magnitude at the load bus $m$ due to symmetrical and unsymmetrical faults at point $f$ is discussed below.

- **Symmetrical three-phase fault (L-L-L):** The positive sequence network is used for the evaluation of voltage sag magnitude due to L-L-L fault which is expressed as

$$U_{m}^{pf} = U_{m}^{prf} - \frac{Z_{m,f}^{(0,+,−)}}{Z_{f}^{(0,+,−)}} U_{p}^{prf}$$

(7)
where $U_{pfa,m}^f$ is the post-fault voltage sag magnitude at bus $m$.

- **Unsymmetrical Double line to ground faults (L-L):** When L-L fault occurred between phase $b$ and $c$, the voltage sag magnitude is expressed as

$$
U_{pfa,m}^f = U_{pfb,m}^f - \frac{Z_{mf}^{(+)} - Z_{mf}^{(-)}}{Z_{ff}^{(+)} + Z_{ff}^{(-)}} U_{prf}^f
$$

$$
U_{pfb,m}^f = a^2 U_{pfa,m}^f - \frac{a^2 Z_{mf}^{(+)} - a Z_{mf}^{(-)}}{Z_{ff}^{(+)} + Z_{ff}^{(-)}} U_{prf}^f
$$

$$
U_{pfc,m}^f = a U_{pfa,m}^f - \frac{a Z_{mf}^{(+)} - a^2 Z_{mf}^{(-)}}{Z_{ff}^{(+)} + Z_{ff}^{(+)}} U_{prf}^f
$$

(8)

where, $U_{pfa,m}^f$, $U_{pfb,m}^f$, and $U_{pfc,m}^f$ are the post-fault voltage magnitudes of phase $a$, $b$, and $c$ respectively at the load bus $m$. $a$ is the phase shift operator having a magnitude of the unity of a phase of 120°. Similarly, for other types of faults, the voltage sag magnitudes can be evaluated. Now MCS technique is applied for selecting the fault type ($F_{typ}$), number and location of fault ($FL$) randomly. This technique is based on iterative process, and the maximum number of iterations is 8760. Fault type is simulated in the system by using the following equations.

**FIGURE 4** Flow chart of the MCS technique used for the assessment of voltage sag
\[ F_{\text{typ}} = \begin{cases} 
 1 & \text{if } P_f \leq P_{L-L-L} \\
 2 & \text{if } P_{L-L-L} < P_f \leq (P_{L-L-L} + P_{L-L-G}) \\
 3 & \text{if } (P_{L-L-L} + P_{L-L-G}) < P_f \leq (P_{L-L-L} + P_{L-L-G} + P_{L-L}) \\
 4 & \text{if } (P_{L-L-L} + P_{L-L-G} + P_{L-L}) < P_f 
\end{cases} \] (9)

\( P_f \) is the probability of different types of faults, which is a uniformly distributed random number varying between 0 and 1. Probability for different types of faults for transmission and distribution systems is given in Table 1. To simulate the fault location through MCS, a PDF should be used to represent fault location. If a line fault occurred near a bus then fault is considered on the bus itself. The generalized formulae for determining fault location is given in Equation (10).

\[ F_L = [B \times \xi] + 1 \] (10)

where \( F_L \) is the fault location, \( B \) is the number of branches, \( \xi \) is the fault location parameter and its value varies from 0 to 1. A flowchart is given in Figure 4 depicting the implementation of MCS technique to evaluate the voltage sag.

### 3 | CALCULATION OF FAULT RATE

In this article, different types of faults are considered for the evaluation of voltage sag. The fault rate depends on the intensity and probability of occurrence of faults in a power system. Type-2 fuzzy\textsuperscript{26} system is used for the evaluation of the fault rate. Causes for different types of fault are mentioned in Table 2. It is observed from the table that equipment failure and tree touching are having a maximum impact on the transmission system. For the case of an underground system, equipment failure and dig-in are the most severe causes of fault in an industrial distribution system. The input variables for the type-2 fuzzy technique are the causes and intensity of faults, which are mentioned in Table 2. Fault rate values for transmission/distribution and underground distribution systems are different, which is shown in Section 5. Pictorial representation for the evaluation of the fault rate is shown in Figure 5. The output is the defuzzified values, which give the fault rate of each line.

### 3.1 | Estimation of voltage sag frequency (EVSF)

The combination of fault positioning method and FFR are used to evaluate EVSF, which provides the total number of voltage sag per year. This EVSF is evaluated for both the balanced and unbalanced type of faults. For a given load connected across a load bus, EVSF can be evaluated according to Equation (11).

\[ \text{EVSF} = \text{NVSFBF} + \text{NVSFLF} \] (11)

where NVSFBF and NVSFLF is the number of voltage sag frequency due to bus faults and line faults respectively which can be evaluated using Equations (12) and (13).

### TABLE 2 | Different types of faults and their impact on the transmission system\textsuperscript{26}

| Causes             | Transmission system | Underground distribution system |
|--------------------|---------------------|--------------------------------|
|                    | Probability of occurrences | Impact of causes | Fault probability | Probability of occurrences | Impact of causes | Fault probability |
| Equipment failure  | 0.4                 | 0.7               | 0.46             | 0.4                 | 0.7               | 0.46             |
| Trees              | 0.3                 | 0.5               | 0.51             | 0.1                 | 0.2               | 0.21             |
| Lightning          | 0.18                | 0.4               | 0.37             | 0.18                | 0.3               | 0.28             |
| Animals/birds      | 0.08                | 0.3               | 0.20             | 0.08                | 0.3               | 0.20             |
| Over loading       | 0.02                | 0.2               | —                | 0.02                | 0.2               | —                |
| Accident           | 0.01                | 0.2               | 0.25             | 0.01                | 0.2               | 0.35             |
| Vandalism and dig-in | 0.005              | 0.1               | 0.21             | 0.21                | 0.6               | —                |
FIGURE 5  Flow chart for the evaluation of fault rate^{26}.

\[
\text{NVSFBF} = \sum_{m=1}^{4} \sum_{n=1}^{3} \sum_{o=1}^{B_N} \text{FFR} 
\]

where \( m \) is the type of fault selected during the evaluation of EVSF (ie, LLL, LG, LL, and LLG), \( n \) is the phase number (ie, Ph A, Ph B, and Ph C), and \( o \) is the bus number varying from 1 to \( B_N \).

\[
\text{NVSFLF} = \sum_{m=1}^{4} \sum_{n=1}^{3} \sum_{p=1}^{L_N} \xi_p \times \text{FFR} 
\]

\[
(13)
\]

where \( p \) is the line number varying from 1 to \( L_N \), \( \xi_p \) is the fault location at the \( p \)th line varying from 0 to 1 and \( l_p \) is the length of the \( p \)th line.

4  VOLTAGE SAG MAP (VSM)

There are different ways of representing voltage sag: (1) scatter diagram, (2) voltage-dip table, (3) SARFI indices, and 4) single-index event. All these methods need huge data and rigorous analysis to achieve acceptable results. And at the same time, these methods are inefficient to determine weak networks or critical processes which involve sensitive equipment. In this section, an effective graphical representation of number of voltage sag for different voltage range is proposed which is termed as VSM.

4.1 Concept and development of VSM methodology

1 According to Transmission and Distribution Power Quality (TPQ-DPQ III) reports and IEEE standards, it is found that the incompatibility and low voltage sag ride-through capability of the sensitive equipment in the industrial plant leads to a significant amount of production losses. Therefore the knowledge of voltage sag propagation is a crucial task for industrial operators. So, that it can help the industrial personnel to identify critical or weak buses in a power system network where the sensitive equipment is connected.

2 VSM is developed for each phase individually, and it is because, during a fault, each phase has a different range of voltage sag magnitudes. In general, the faulted phase shows a dip in voltage, whereas, in the non-faulted phase, it
may show a rise or dip or unchanged voltage level. The dip in voltage for the non-faulted phases is due to transformer winding connections.

So after assessment of voltage sag its presentation plays a very vital role to understand the effect and propagation of voltage sag in a power system network. The VSM is developed by using the concept of BFD table for which, the voltage sag magnitude along with the corresponding number of voltage sag in the system is considered as the two variables. The steps which are followed to develop the VSM is given below:

Step 1: Read system data.
Step 2: Simulate the voltage sag according to the methodology described in Section 2 using the system data.
Step 3: The voltage sag data is stored (preferably in pu) from the simulated results. The data can be collected from real-time monitoring systems as well.
Step 4: Two variables are defined, namely the voltage sag magnitude and the corresponding number of voltage sag. Both of these variables are divided into intervals. The voltage sag magnitude is quantized into the desired number of intervals in the range 0-0.95. Similarly, the no. of voltage sag is divided into intervals depending on the voltage sag data.
Step 5: The BFD table is made with the voltage sag magnitude as the columns and the corresponding number of voltage sag as the row. The bus numbers are put in the table in corresponding positions, and if there is no sag for a particular range of voltage sag magnitude and number, “NS” is put in that place meaning no sag.
Step 6: Finally, the VSM is developed in accordance with Table 3.

From Table 3 it can be seen that buses are chosen according to the voltage magnitude and the number of voltage sag range, for an example let us consider the number of voltage sag within the range 4-5 and the voltage magnitude between 0.9 and 0.95 the buses are 5 and 6. This means that buses 5 and 6 have experienced 4-5 sags in the range of 0.9-0.95 pu in a year.

5 | RESULTS AND DISCUSSION

In this section, the concept of VSM is implemented and analyzed by considering a realistic underground distribution system of a chemical manufacturing facility. This section commences with the description of underground distribution network along with the transmission network with which it is connected. Then VSMs are developed to represent the voltage sag scenario at the load buses along with the voltage sag propagation in the network.

5.1 | System description

The case study considered in this study is a chemical industry which is located in Uttarakhand, India, and the power to the industry is fed from the 132 kV Thakurdwara Sub-Station (SS) (ie, bus no. 28) of Power Transmission Corporation of Uttarakhand Limited (PTCUL). The Single Line Diagram (SLD) of the transmission network through which the chemical industry’s power is fed is shown in Figure 6.

| TABLE 3 | A sample BFD for generating VSM |
|----------|----------------------------------|
| Voltage magnitude (pu) | 0-0.1 | 0.1-0.2 | 0.2-0.3 | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.7 | 0.7-0.8 | 0.8-0.9 | 0.9-0.95 |
| Sag range | NS | NS | NS | 2.45 | NS | 4.32 | NS | NS | NS | 2.5 |
| 2-3 | 2.5 | 2 | NS | NS | NS | NS | NS | NS | 3 | 33 |
| 4-5 | 33.45 | NS | NS | NS | NS | NS | 55.6 | NS | NS | 5,6 |
| 6-7 | NS | 2.9,11 | NS | 2.5 | NS | 55.6 | NS | 55.6 | NS | NS |
| 8-9 | NS | NS | NS | 5.8 | NS | NS | NS | NS | NS | 5,32 |
| 10-11 | 55.6 | NS | NS | NS | 55.6 | NS | 2.5,8 | NS | NS | 2.8 |
| >11 | NS | NS | 55.6 | 15 | NS | NS | NS | NS | NS | NS |
The length of the transmission network is around 2073 km and having 36 buses that transmit power in three different voltage levels that is, 400 kV, 220 kV, and 132 kV. In Figure 6 the chemical plant is located at the bus no. 29. This chemical industry is the world’s first and only company to produce ethylene oxide (one of the green chemicals), its derivatives, and glycols from agricultural wastes (like molasses or sugar cane). The industry is meant to operate round the clock and is under continuous supervision by a Distributed Control System (DCS), which is very sensitive to voltage sag. The high sensitivity of DCS towards voltage sag may malfunction some critical load resulting in a huge production loss. This production loss translated to approximately 13 lakhs INR revenue loss for the financial year 2017-2018. This financial loss can only be minimized by adopting proper and strategic mitigation planning, which can be done only after assessing and identifying the weak or vulnerable load points in the network. The upper and lower voltage tolerance limits of different sensitive equipment connected across the industrial load buses are given in Table 4. The $U_{\text{max}}$ and $U_{\text{min}}$ are the upper and lower voltage tolerance limits of the sensitive equipment, respectively. It means whenever a sensitive equipment encounters a voltage sag event, the equipment may or may not trip depending upon its voltage tolerance limit. The schematic diagram of the industry is shown in Figure 7 and fed through a 20/25 MVA transformer at 6.6 kV. In the chemical plant, protective devices are connected to the bus-bar of rating 6.6 kV, 300 MVA, 2500 A.

![Schematic diagram of Uttarakhand transmission system](image)

**FIGURE 6** Single line diagram of Uttarakhand transmission system

| Sl.no | Sensitive equipment                        | $U_{\text{max}}$ (pu) | $U_{\text{min}}$ (pu) |
|-------|-------------------------------------------|------------------------|-----------------------|
| 1     | Personal computer (PC)                    | 0.63                   | 0.46                  |
| 2     | Programmable logic controller (PLC)       | 0.9                    | 0.3                   |
| 3     | Adjustable speed drive (ASD)              | 0.71                   | 0.59                  |
| 4     | 5 hp AC drive                              | 0.8                    | 0.6                   |
| 5     | Motor stator (MS)                          | 0.6                    | 0.4                   |

**TABLE 4** Voltage tolerance limit of Sensitive equipment

---

1. **BEHERA ET AL.**
2. **FIGURE 6** Single line diagram of Uttarakhand transmission system
3. **TABLE 4** Voltage tolerance limit of Sensitive equipment
The plant has three Points of Common Coupling (PCC) where loads are connected, and at each PCC, three SS (i.e., SS1, SS2, and SS3) are connected. The bus-bar rating of the first PCC is 6.6 kV, 300 MVA, and 1200 A and the equipment connected to this PCC consists of alternator panel, relay panel, AVR panel, AVR cum excitation panel, control and relay panel, Diesel Generator (DG) panel, generator and metering panel, current and potential transformer panel, and so on. All these control panels are used to protect the loads. Bus-bar ratings of the second and third PCCs are 6.6 kV, 300 MVA and 1600 A, and it consists of loads such as air compressor (275 kW), cooling water pump (550/275/330 kW), boiler (255 kW), oxygen compressor (475 kW), chiller (330 kW), and so on. A simplified SLD of the chemical industry’s underground distribution system is shown in Figure 8. The base values considered for the chemical plant’s distribution system are 25 MVA and 6.6 kV, and the length of the whole network is 5.3 km, which is small as compared to typical transmission and distribution networks.

5.2 Case study

The type-2 FFR values for the transmission and the underground industrial distribution systems are shown in Figures 9 and 10. With this fault rate values, symmetrical and unsymmetrical faults are simulated using the proposed method to evaluate the number of voltage sag for the industrial distribution system, which is shown in Figure 11. Similarly, faults are simulated for the transmission system, and the result is contrasted with the industrial distribution system, as shown in Figure 12.

A total of 1361 voltage sag per year occurred in the chemical plant considering symmetrical and unsymmetrical types of faults, most of them being capable of tripping the equipment. A total of 1341 voltage sag occurred in the transmission system in a year. The occurrence of voltage sag in the range of 0.7-0.95 pu. never shows an adverse effect on the transmission system because of its higher voltage level and the line parameter values, which assists the line to re-energies automatically depending upon the duration of voltage sag. In addition to that, the transmission systems have generator buses that add to the system inertia resulting in faster voltage recovery as compared to distribution systems that do not have any generation of its own.
FIGURE 8  Single line diagram of the chemical plant’s underground distribution system

FIGURE 9  Fault rate for the Uttarakhand transmission system

FIGURE 10  Fault rate for industrial distribution system
FIGURE 11  Voltage sag due to different types of faults occur at the chemical plant

FIGURE 12  Comparison of two different systems based on a number of sags per year

TABLE 5  Correlation of different sensitive equipment with industrial loads

| Types of industrial loads/equipment | Ratings                      | Sensitive equipments |
|------------------------------------|------------------------------|---------------------|
|                                     |                              | ASD     | PLC | PC  | MS  | 5 hp AC drives |
| Chiller                            | 33 kW                        | Y       | Y   | Y   | Y   | Y              |
| Boiler                             | 225 kW, 255 kW               | N       | Y   | Y   | N   | Y              |
| Cooling water pump motor           | 333 kW, 550 kW, 275 kW       | Y       | Y   | Y   | Y   | Y              |
| Oxygen compressor                  | 450 kW                       | Y       | Y   | Y   | Y   | Y              |
| Air compressor                     | 330 kW, 850 kW               | Y       | Y   | Y   | Y   | Y              |
| Capacitor bank                     | 750 kVAR, 2500 kVAR          | N       | N   | Y   | N   | N              |
| Circuit breaker (6.6 kV, 300 MVA)  | 600 A, 1800 A, 3000 A        | Y       | Y   | N   | Y   | Y              |

On the other hand, in industrial distribution systems, there are a large number of lagging loads, the majority of them being motors that take high starting currents resulting in frequent voltage sag. The majority of the loads connected in this chemical plant is run with the help of various sensitive equipment mentioned in Table 4. In Table 5 shows the list of major loads and their rating along with the sensitive equipment involved to serve the particular load/process. In Table 5 “Y” stands for the equipment is serving the particular load/process and “N” stands for the equipment is not serving the particular load/process.

A VSM is developed for the industrial underground distribution system, and it could have been developed for the transmission system as well. The VSM described in Section 4 helps in a better understanding of voltage sag profile at all the 69 load points of the chemical plant’s distribution system. This map can serve as the blueprint for developing the protection scheme and mitigation strategy to immune the sensitive and important loads from the voltage sag. For example, the VSM is developed according to the proposed method for the chemical plant considering L-G fault as it occurs most frequently as par Table 1. The voltage sag data is obtained by simulating LG fault randomly using MCS aided fault positioning method in the chemical plant’s underground distribution network. And then a BFD is developed as shown in Table 6, which is further used for generating VSM.

Now, let us begin the analysis by considering a 5 HP AC drive and a PLC which are connected at bus no. 5 of the chemical plant’s distribution network. As seen from Table 4, the upper and lower limits of voltage magnitude for 5 HP AC drive and PLC are 0.8-0.6 pu and 0.9-0.3 pu. So, the VSMs ranging from 0.9 to 0.3 pu are developed and shown in Figures 13-18. For the 5 HP AC drive, it can be seen from Figure 14 that bus no. 5 is enclosed by black dotted line...
TABLE 6  BFD for generating VSM for LG fault

| Sag range | Voltage magnitude (pu) | 0.1-0.2 | 0.2-0.3 | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.7 | 0.7-0.8 | 0.8-0.9 | 0.9-0.94 |
|-----------|------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0-1       |                        | 10, 15, 16, 22, 28, 29, & 31 | 5, 21, 22, & 60 | 11, 17, & 21 | 5, 10, 11, 13, 16, 21, 22, 28, 29, 31, 33, 41, 57, & 60 | 2, 41, 42, & 65 | 2, 5, 10, 11, 14, 15, 16, 19, 20, 21, 39, 46, 47, 57, & 59 | 2 & 23 | 1 & 34 | 1, 5, 10, 11, 17, 18, 20, 21, 29, 30, 39, 41, 58, & 60 |
| 2-3       |                        | 21, 41, & 47 | 8, 28, 29, & 65 | 28, 29, 31, 33, 51, & 65 | NS | 5, 21, 22, 28, 29, 31, 41, 58, & 60 | 28, 29, & 33 | 5, 6, 10, 11, 13, 14, 16, & 17 | 5, 8, 13, 14, 16, 17, 21, 57, & 61 | 34 to 40, 42, 45, 48 to 50, 52, 56, 59, 64, & 65 |
| 4-5       |                        | 7, 8, & 18 | 41 | 5 | NS | 8 & 34 | NS | 81, 46, & 47 | 12, 18, 19, 42, 45, 46, 48, & 49 | 7, 9, 15, 44, & 47 |
| 6-7       |                        | NS | NS | 18 | 13 | 10, 11, 13, & 14 | NS | 28, 29, 31, 33, & 65 | 1, 58, & 59 | 27, 31, 54, 55, & 56 |
| 8-9       |                        | NS | NS | 8, 22, 41, & 47 | NS | 16 & 17 | NS | 22 & 58 to 60 | 11, 22, & 41 | 62 & 63 |
| 10-11     |                        | NS | NS | 58, 59, & 60 | NS | NS | NS | NS | 21 | 24 to 26, 28, 35, 36, 38, 51, 64, 65, & 67 | 68 & 69 |
| 12-13     |                        | NS | NS | NS | NS | NS | NS | NS | NS | 5 & 32 | NS |
| 14-15     |                        | NS | NS | NS | NS | NS | NS | NS | NS | 4 & 39 | NS |
| 16-17     |                        | NS | NS | NS | NS | NS | NS | NS | NS | 3 | NS |
**Figure 13** VSM in the range of 0.8-0.9

**Figure 14** VSM in the range of 0.7-0.8

**Figure 15** VSM in the range of 0.6-0.7
**Figure 16**  VSM in the range of 0.5-0.6

**Figure 17**  VSM in the range of 0.4-0.5

**Figure 18**  VSM in the range of 0.3-0.4
which means it will experience 2-3 sags in a year. Similarly if we consider the situation of bus no. 5 in Figure 15, it can be found to be enclosed by red dotted line which means that it will experience 0-1 sags in a year. Therefore, cumulatively it can said that bus no. 5 may experience 2-4 sags per year. And similarly this analysis is done for the PLC connected at bus no. 5 using the VSMs shown in Figures 13-18, and it is found that it may experience 11-17 sags in a year.

Similarly, the VSM for all other types of faults can be developed as well by using the BFDs shown in Tables A1-A3 given in the Appendix section. It can be observed from the VSM that bus no. 2 experienced voltage sag in the range of 0.5-0.95 pu. As power is fed to the plant from a 132 kV (HV) SS to the 6.6 kV (LV) SS of the chemical plant through a 25 MVA transformer. The combined $X/R$ ratio of the transformer and the 6.6 kV LV bus-bar helps the line to reenergize itself (after a fault) and never allows the voltage at the bus no. 2 to drop below 0.5 pu. From the VSM, it is quite easy to understand that most of the buses in the plant’s distribution system experience a voltage sag in the range of 0.8-0.95 pu. From this, it can be inferred that the protection scheme, voltage sag mitigation strategy should be kept at par along with the proper $X/R$ ratio to add voltage sag ride-through capability to the system. The bus numbers 5, 10, 11, 21, 22, 28, 29, 31, 58, 59, and 60 are considered as the weak/vulnerable links in the system because these buses experience voltage sag of all possible ranges (ie, from 0.1 to 0.95 pu). Hence it is very much necessary for the plant authority to protect the loads or sensitive equipment with necessary mitigation strategy, recheck all the electrical connections, ensure proper distribution of the loads at all these buses, and so on.

A VSM is a convenient way for every industry (not only for the chemical industry) to understand the impact of different PQ issues so that precautionary measures can be adopted accordingly. After identifying weak/vulnerable load points by using VSM, the voltage sag indices can be evaluated accurately. One of the voltage sag indices for the identified weak buses is shown in Figure 19. The sag score and lost of energy index shown in Figure 19 are for the identified weak buses (ie, bus no. 5, 10, 11, 21, 22, 28, 29, 31, 58, 59, and 60) are more as compared to other buses.

### 6 CONCLUSION

In this article, the impedance matrix-based model is used to evaluate the voltage sag at the faulted buses. Faults in different systems results in different patterns of voltage sag because of the difference in line parameters. As the line susceptance for underground cable is higher than that of the overhead distribution system, fault intensity is higher for the underground distribution system. The fault positioning method is used to evaluate the number of voltage sag due to both balance and unbalanced faults. For the random simulation of different fault types, numbers, and locations, the MCS technique is used. The main disadvantage of the MCS technique lies in the fact that its simulation time is highly dependent on the number of faults to be simulated. So, as the number of faults increases, simulation time increases accordingly. In this
article, the analysis of voltage sag is done considering transmission and underground distribution systems. From the study, it has been observed that the transmission system is less affected as compared to the underground distribution system, mainly owing to its higher voltage level and inertia of the system. The VSM is developed and verified to help in understanding the behavior of different sensitive equipment based on the ITIC sensitivity curve, and its propagation in a chemical plant’s distribution system. The VSM provides two important information, first the voltage sag propagation at different magnitude levels and second the number of voltage sags experienced by different sensitive equipment at different voltage level per year. The concept of Voltage Sag Map (VSM) can also serve the purpose of identifying the optimal strategy for placing mitigating devices. In other words, this VSM data can be used for any algorithm which determines the optimal location of mitigating devices. Using the concept of VSM, maps for other PQ issues like harmonics, interruptions, power factor, voltage swell, and so on can also be developed in a similar way, which can offer great applications in the analysis of different types of electrical systems.

**PEER REVIEW INFORMATION**

*Engineering Reports* thanks Iman Niazazari and other anonymous reviewers for their contribution to the peer review of this work.

**CONFLICT OF INTEREST**

The authors declare no potential conflict of interest

**AUTHOR CONTRIBUTIONS**

Chinmaya Behera contributed to the conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, validation, visualization, and writing the original draft. Abhishek Banik contributed to the conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, validation, visualization, and writing the original draft. Arup Goswami contributed to the conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, supervision, visualization, writing the original draft, review, and editing.

**REFERENCES**

1. Transmission – Distribution power quality report (TPQ-DPQ III). Report no: 00000003002003905, 2014 Program 1 Power Quality.
2. IEEE recommended practice for monitoring electric power quality. *IEEE Std 1159-2019 (Revision of IEEE Std 1159-2009)*. IEEE; 2019:1-98
doi:10.1109/IEEESTD.2019.8796486. https://ieeexplore.ieee.org/document/8796486.
3. Behera C, Banik A, Nandi J, Reddy GH, Chakrapani P, Goswami AK. A probabilistic approach for assessment of financial loss due to equipment outage caused by voltage sag using cost matrix. *Int Trans Electr Energy Syst*. 2020;30:e12202. https://doi.org/10.1002/2050-7038.12202.
4. Arias-Guzmán S, Ruiz-Guzmán OA, Garcia-Arias LF, et al. Analysis of voltage sag severity case study in an industrial circuit. *IEEE Trans Indus Appl*. 2017;53(1):15-21.
5. Begum MTA, Alam MR, Muttaqi KM. Analytical expressions for characterising voltage dips and phase-angle jumps in electricity networks. *IET Gener Trans Distrib*. 2019;13(1):116-126.
6. Alam MR, Muttaqi KM, Bouzerdoum A. Characterizing voltage sags and swells using three-phase voltage ellipse parameters. *IEEE Trans Indus Appl*. 2015;51(4):2780-2790.
7. Liao H, Abdelrahman S, Guo Y, Milanović J. Identification of weak areas of power network based on exposure to voltage sags—Part I: Development of sag severity index for single-event characterization. *IEEE Trans Power Deliv*. 2015;30(6):2392-2400. https://doi.org/10.1109/TPWRD.2014.2362965.
8. Wang Ying, Deng Ling-feng, Bollen Math, Xiao Xianyong. Calculation of the Point-on-Wave for Voltage Dips in Three-Phase Systems. *IEEE Transactions on Power Delivery*. 2019;1–1. http://dx.doi.org/10.1109/tpwrd.2019.2960524.
9. Gautam Prajwal, Piya Prasanna, Karki Rajesh. Development and Integration of Momentary Event Models in Active Distribution System Reliability Assessment. *IEEE Transactions on Power Systems*. 2019;1–1. http://dx.doi.org/10.1109/tpwrs.2019.2962177.
10. Lennerhag Oscar, Bollen Math HJ. A Stochastic Aggregate Harmonic Load Model. *IEEE Transactions on Power Delivery*. 2019;1–1. http://dx.doi.org/10.1109/tpwrd.2019.2961790.
11. Santos AD, Rosa T, de Barros MTC. Stochastic characterization of voltage sag occurrence based on field data. *IEEE Trans Power Deliv*. 2019;34(2):496-504.
12. Heydt GT. Thévenin’s theorem applied to the analysis of polyphase transmission circuits. *IEEE Trans Power Deliv*. 2017;32(1):72-77.
13. Conrad L, Little K, Grigg C. Predicting and preventing problems associated with remote fault-clearing voltage dips. *IEEE Trans Indus Appl*. 1991;27(1):167-171. https://doi.org/10.1109/ICPS.1989.37237.
14. Moschakis MN, Hatzigeryiou ND. Analytical calculation and stochastic assessment of voltage sags. *IEEE Trans Power Deliv*. 2006;21(3):1727-1734. https://doi.org/10.1109/TPWRD.2006.874108.
APPENDIX A. LISTS OF BFD TABLE FOR DIFFERENT TYPES FAULTS FOR GENERATING VSM

| TABLE A1  | BFD for generating VSM for LLL fault |
|-----------|--------------------------------------|
| **Voltage magnitude (pu)** | 0.1-0.2 | 0.2-0.3 | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.7 | 0.7-0.8 | 0.8-0.9 | 0.9-0.94 |
| **Sag range** | 0-1 | 2-69 2-69 2-69 NS | 24-38, 51-63 NS | 2-69 2-69 2-69 |
|           | 2-3 | NS NS NS 20-38, 51-63 NS | NS 2-69 2-69 2-69 |
|           | 4-5 | NS NS NS NS NS | NS NS NS NS |
|           | 6-7 | NS NS NS NS NS | 3-18, 41-49 NS NS NS |
|           | 8-9 | NS NS NS NS NS | NS NS NS NS |
|           | 10-11 | NS NS NS NS NS | NS NS NS NS |
|           | 12-13 | NS NS NS NS NS | NS NS NS NS |
|           | 14-15 | NS NS NS NS NS | NS NS NS NS |
|           | 16-17 | NS NS NS NS NS | NS NS NS NS |
| Sag Range | Voltage Magnitude (pu) | 0.1-0.2 | 0.2-0.3 | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.7 | 0.7-0.8 | 0.8-0.9 | 0.9-0.94 |
|-----------|------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0-1       | NS                     | 2-7, 19-21, 24-26, 39, 40, 43, 53, 54, 56, 57, 58, 60, 64, 65, 67, 68, & 69 | NS     | 2-7, 14, 19-21, 39, 40, & 43 | 24, 25, 53, 54, 58, 60, 64, 65, & 67-69 | NS     | NS     | 27-29, 31, 35, & 37 | 2-69    |
| 2-3       | NS                     | NS     | 8, 9, 27-29, 31, 32, 36-38, 41, 50, 51, & 63 | 21, 28, 29, 31, 44-47 & 49 | 3-7, 10-12, 14-16, 18, 19, 20, 26, 27, 30, 32, 33, 35-40, 43, 50, 51, 55, 56, 57, & 63 | NS     | NS     | 8-11, 14, 15 | 13, 17, 22, 41, 42, 28, 52, 59, & 61 |
| 4-5       | NS                     | NS     | 10-16, 18, 24-26, 30, 33, 35, 44, 46, 47, 54-58, 60, 64, 65, 67, 68, & 69 | NS     | 2, 8, & 9 | NS     | NS     | 4-8, 12, 19, 20, & 24 | 23 & 66 |
| 6-7       | NS                     | NS     | NS     | NS     | NS     | NS     | NS     | 32, 33, 39, 40 | 34      |
| 8-9       | NS                     | NS     | NS     | NS     | NS     | NS     | NS     | 13, 17, 22, 41, 42, 48, 52, & 59 | 62      |
| 10-11     | NS                     | NS     | NS     | NS     | 3-8, 19-24, 55, 67, & 69 | NS     | NS     | NS     | NS      |
| 12-13     | NS                     | NS     | NS     | NS     | NS     | NS     | NS     | NS     | NS      |
| 14-15     | NS                     | NS     | NS     | NS     | NS     | NS     | NS     | NS     | NS      |
| 16-17     | NS                     | NS     | NS     | NS     | NS     | NS     | NS     | NS     | NS      |
| Sag range | Voltage magnitude (pu) | 0.1-0.2 | 0.2-0.3 | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.7 | 0.7-0.8 | 0.8-0.9 | 0.9-0.94 |
|-----------|------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0-1       |                        | 2,8-11, 14, 16, 18, 21, 27, 28, 29, 31, 36, 37, 38, 50, 51, 55, 62, & 63 | 2, 8, 9, 21, 27, 28, 29, 31, 44-47, 50, 51, 55, & 62 | 29, 31, 44-47, 62, & 63 | 2-16, 18-24, 55-40, 49-52, 60 & 62-69 | 2, 8-12, 14, 15, 16, 18, 21, 27, 28, 31, 36, 37, 38 44-45, 46, 50, 51, 55, & 61, 62-63 | 2, 8-11, 13-16, 18, & 21 | 2-69 |
| 2-3       | NS                     | 8, 9, 27, 28, 29, 31, 32, 36, 37, 38, 41, 50, 51, & 63 | 21, 28, 29, 31, 44-47, & 49 | 2, 8-11, 14-16, 18, 21, 28, 36, 38, 50, 51, & 55 | NS | 44, 45, 46, 50, 51, 55, & 61-63 | 27-29, 31, 36-38, 44-47, 50, 51, 55, 62, & 63 | NS |
| 4-5       | NS                     | 10, 11, 14-16, 18, 24, 25, 26, 30, 33, 35, 44, 46, 47, 54-58, 60, 64, 65, & 67-69 | NS | NS | NS | 3-7, 19, 20, 24-26, 30, 32, 33, 35, 39, 40, 43, 48, 49, 52-60, 62, & 64-69 | NS | NS |
| 6-7       | NS                     | NS | NS | NS | NS | NS | 49, 52, 53, 54, 56-60, 62 & 64-69 | NS | NS |
| 8-9       | NS                     | NS | NS | NS | NS | NS | NS | NS | NS |
| 10-11     | NS                     | 36, 37, 38 | 10, 11, 14-16, 18, 24, 25, 26, 30, 33, 35, 44 46, 47, 54, 55-58, 60, 64, 65, & 67-69 | NS | 3, 50, 51, & 55 | NS | NS | NS|
| 12-13     | NS                     | NS | NS | NS | NS | NS | 3-7, 19, 20, 24, 25, 26, 30, 32, 33, 35, 39, 40, 43, 48, 49, 52-60, 62, & 64-69 | 24, 26, 30, 32, 33, 34, 39, 40, 43, 48, 49, 52-54, 56-60, & 64-69 | NS |
| 14-15     | NS                     | NS | NS | NS | NS | NS | NS | NS | NS |
| 16-17     | NS                     | NS | NS | NS | NS | NS | 39, 40, 43, 48, 49, 52-54, 56-60, 62, & 64-69 | NS | NS |