Simulation of Voltage Sag Events in Distribution Networks and Utility-Side Mitigation Methods

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Abstract

As industrialization and automation processes continue to expand, power quality parameters and voltage sags in particular become more important. Sensitive equipment trips due to voltage sags cause enormous financial loss in the industrial sector. Consequently, in consultation with ÅF Turkey, Trakya Electricity Distribution Company (TREDAS) began an R&D project on voltage sags funded by the Turkish Energy Market Regulatory Authority (EMRA). The project aims to characterize voltage sags and perform research into sag mitigation methods. In this paper, the results of the simulation studies of a feeder located in the Thrace region are presented. The effects of short circuit faults on the development of voltage sag events and utility-side mitigation methods are analyzed through computer simulations using EMTP-RV software. Furthermore, definitions of voltage sag indices according to IEEE Std. 1564 – 2014 are given and the methods used to minimize the effects of voltage sags are explained.

1. Introduction

Power quality issues have been recognized as a problem since the 1980s with the proliferation of microprocessor and semiconductor-based equipment. Although the term “power quality” can be defined in many ways, nearly all of the definitions include a relationship between equipment characteristics and power waveforms [1, 2]. Thus the concept itself expresses the degree of change in equipment performance because of non-ideal voltage, current and frequency waveforms.

Efficiency, reliability and competitiveness issues force industrial facilities to integrate more sophisticated automation equipment such as adjustable speed drives (ASD), programmable logic controllers (PLCs) etc. These sensitive devices that control and manage production processes boost the need for high power quality because minor deviations occurring on the supply-side cause critical equipment to cease functioning or lead to abnormal operations. Any failures emerging in sensitive equipment generally interrupt the manufacturing process and companies are subject to losses in raw material, labor and electrical energy. A survey [3] conducted in 25 EU countries revealed that losses from poor power quality are estimated to be $151 billion per annum and the industrial sector represents approximately 90% of the total loss. It is also reported that 24% of the total financial loss is directly related to voltage sags [3]. Another study [4] showed that 70% of all power quality problems originated from the customer side while the rest were related to the utility side.

Voltage sags are generally described as the reduction in voltage magnitude for a very short duration. The standards by which the voltage sags are defined differ from each other on the limitation of threshold values. IEEE Std. 1159-2009 [5] uses intervals of 10% and 90% for the voltage magnitude and 0.5 cycle to one minute for the event duration, whereas EN 50160-2010 [6] determines the lower limit of voltage magnitude as 5% instead of 10%.

Typical root causes of sag phenomena are utility-side short circuit faults, transformer inrush currents, and starting currents of electric motors [7]. However, it is considered that motor starting and inrush currents of transformers have less effect on voltage waveforms than faults on networks [8]. So, faults on distribution or transmission networks are more likely to create sensitive equipment malfunctions.

Reducing the numbers and effects of voltage sag events using utility-side methods and commissioning end-user equipment at industrial facilities have been investigated in various studies. Utility-side mitigation methods such as reducing the number of faults, shortening of fault duration and system design are summarized in [9]. Also, studies that use network reconfigurations and optimized switching action methods to minimize the sag depth can also be found in [10, 11]. Apart from those, IEEE Std. 1250-2011 [12] provides guidance on equipment based solutions that typically include Dynamic Voltage Restorers (DVR), Active Voltage Conditioners (AVC), Dynamic Sag Correctors (DySC), Constant Voltage Transformers (CVT), Uninterruptible Power Supplies (UPS) and Static Transfer Switches (STS).

To examine sag characteristics, a study [13] conducted in a network mainly comprised of overhead lines indicated that 31% of all sags originated from faults in the transmission system and the rest were related to the distribution network. In addition, two years of EPRI research showed that single phase voltage sags are the most frequent sag type in terms of phase count with a 68% share [14], which resembles the breakdown of short circuit faults.

The adverse effects of voltage sags are mostly seen in regions with heavy industry sectors where these facilities are fed by power lines with high fault statistics like long rural overhead lines. The Thrace region of Turkey has these characteristics and the service supplier company TREDAS began the Voltage Sag R&D Project in consultation with ÅF Turkey and financially supported by the Turkish Energy Market Regulatory Authority (EMRA). The main objectives of the project are listed below:

- Characterizing voltage sag events in the TREDAS region
- Evaluating voltage sag records taken from IEC 61000-4-30 Class A [15] monitoring devices
- Research on both end-user and utility side mitigation methods and carrying out pilot field applications

In this paper, characteristics of voltage sags are defined, sag indices are given, and sag mitigation methods that can be performed by distribution companies are listed and explained. Furthermore, a feeder located in the TREDAS region is modeled with EMTP-RV software and utility-based solutions to minimize the effects of voltage sags are simulated and discussed.

2. Voltage Sag

According to the IEEE Std. 1159-2011, voltage sag is defined as a decrease in RMS voltage value to between 0.1 pu and 0.9 pu. Event duration is limited from half-cycle to one minute. Voltage sag events are classified by retained voltage and duration. Retained voltage shows the remaining voltage RMS value after a disturbance has occurred [5]. On the other hand, voltage depth is used in order to express the severity of the voltage sag event. The value of voltage depth indicates the difference between retained (residual) and reference (threshold) voltage values. Both definitions are commonly expressed in percentage of the nominal voltage value.

In the standard, voltage sag events are divided into three subclasses in terms of time durations:

- Instantaneous voltage sag: 0.5 to 30 cycles
- Momentary voltage sag: 30 cycles to 3 seconds
- Temporary voltage sag: > 3 to 60 seconds

2.1. Voltage Sag Indices

The voltage sag indices are formed to quantify the performance of an entire power system or a single measurement point in terms of sag events. In the IEEE Std. 1564-2014 [16], the definitions of the following indices are provided:

- SARFI (System Average RMS Variation Frequency Index) Indices
- Voltage Sag Tables
- Voltage Sag Severity
- Voltage Sag Energy

SARFI index is divided into two subgroups as follows:

- SARFI – X
- SARFI – Curve

SARFI – X index gives the number of voltage sag events regarding specified threshold values. For example, SARFI – 70 indicates the number of events where retained voltage is below 70% of the reference voltage value.

SARFI – Curves provide equipment compatibility limits for voltage disturbances. The most considered curves are CBEMA, ITIC and SEMI F47. These curves demonstrate the compatibility of sensitive equipment such as PLC, ASD and PC in terms of retained voltages and durations [17].

Voltage sag tables present a count of sag events by means of retained voltages and durations in a table format. The rows represent ranges of retained voltage while the columns of the tables represent ranges of voltage sag duration. There are several tables suggested, including UNIPEDE, IEC 61000-4-11 and IEC 61000-2-8.

Voltage sag severity is calculated using retained voltage and sag duration by comparing the reference curves such as ITIC and SEMI F47 for each single event. The index is greater than one if the sag event is longer or deeper than the allowed reference value.

Voltage sag energy is described as the duration of an interruption that provides the same energy loss as the sag event.

The voltage divider model given in Fig. 1 can be used to calculate voltage sag magnitude in a radial network. It is a simple and adequate model to characterize a sag event. In Fig. 1, E is the pre-fault voltage value, Z_s is impedance of the source at the point of common coupling (PCC), and Z_f is the total impedance between the PCC and the fault location [13].

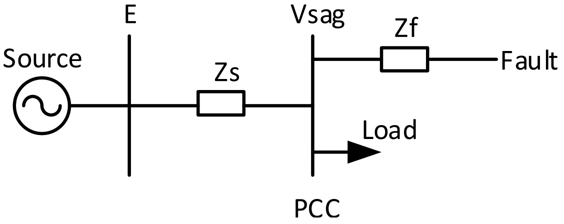

Fig. 1. Voltage divider model for voltage sag event

During a fault at an adjacent feeder, the voltage at the PCC can be calculated using Equation (1).

$$V_{sag} = \frac{Z_f}{Z_S + Z_f} E \tag{1}$$

2.2. Mitigation Methods

Voltage sag events have adverse effects on equipment that is sensitive to short duration supply voltage variations. In the textile and plastic industries in particular, sensitive equipment may malfunction or trip resulting in significant financial loss due to voltage sag.

There are several mitigation methods to minimize the negative impacts of voltage sag events for both utility and end-user sides.

In this paper, we examined utility side mitigation methods. On the other hand, end-users can implement mitigation equipment such as AVC, DVR, CVT, STS and UPS against voltage sag events to keep the production process running [18]. In addition, D-STATCOM and Distribution Static VAR Compensator (D-SVC) can be used by utilities and large industrial consumers [19].

Utility side mitigation methods can be applied in three ways as follows [7]:

- Reducing the number of faults due to short circuits
- Lowering the fault clearing time
- Changing the power system design

2.2.1. Reducing the Number of Faults Due to Short Circuits

Short circuit faults occur for various reasons and cannot be avoided completely in electrical power systems. Moreover, faults in the adjacent feeders generally cause voltage sags. Hence, minimizing the number of short circuit faults will reduce the number of voltage sag events. In this context, the following actions can be considered by utilities:

- Tree trimming is one of the most efficient methods to prevent short circuit faults by tree contact with overhead lines. Utilities can reduce short circuit faults by scheduling periodical tree trimming activities.
- The time interval of periodical inspection and maintenance processes can be tightened. Incipient faults may be detected before they develop into solid

faults that cause outage or equipment failure at the fault location.
- Faults caused by lightning and switching can also be decreased. Surge arresters can be used where overhead lines are most likely to be struck by lightning.
- Overvoltage and aging of insulation materials can be a source of short circuit faults. Increasing the insulation levels enables the equipment to improve its capability to withstand overvoltage.
- Bird-related outages are some of the most critical issues in distribution networks. IEEE has conducted a survey among 114 utility companies and 86% of respondents stated “birds” as the primary source of animal-intrusion outages. Using bird related outage mitigation products on overhead lines and utility poles can reduce the number of short circuit faults [20].

2.2.2. Lowering Fault Clearing Time

Designing an electrical power system that never encounters a fault or failure is not practical. Thus, protection systems have been developed to provide continuity of service and to protect network equipment.

The time delay concept is commonly used in protection equipment to achieve selective protection coordination. The Coordination Time Interval (CTI) is recommended as 300 ms in the IEEE Buff Book [21].

Decreasing fault clearing time is one of the most important parameters in voltage sag events. As mentioned above, voltage sag is characterized by retained voltage and duration. By lowering fault clearing time the duration of voltage sag events can be reduced. As a result, the possible negative impacts of sag events on sensitive equipment can be avoided.

The definite time short circuit protection function can be combined with inverse-time overcurrent protection. In this manner, short circuit faults can be isolated quickly and loads on the parallel feeders will be less exposed to voltage sags. Furthermore, the coordination time interval between protection relays should be configured as low as possible.

Another important factor in protection systems is switching equipment like circuit breaker (CB). Lowering fault-clearing times mainly requires faster breaker operations. Any delay in CB operation results in more time to remove the fault from the power system resulting in more severe voltage sags. Hence, periodical inspections and control activities of CBs are suggested to provide a more secure and reliable power system.

2.2.3. Changing the Power System Design

It is possible to change the design and structure of the power system to minimize the adverse effects of voltage sag events. The possible methods are listed below:

- Installing a distributed generation (DG) source close to the sensitive loads can help to increase retained voltage. As a result, some of the sensitive equipment may not be tripped due to short circuit faults on parallel feeders.
- Splitting bus is another method for industrial customers that have sensitive production processes. If they are connected to a feeder that has a high frequency of short circuit faults, bus splitting and supplying the facility via express feeder is an essential method. In this manner, voltage sags originating from parallel feeder faults can be reduced at the PCC of the industrial customer.
- Using series reactors at strategic points in the distribution network can increase the retained voltage at the point of interest or measurement. That increases the electrical distance from the PCC of the industrial customer to the fault location by adding in series impedance. However, installing series reactors will increase steady state power losses.

3. Modeling and Simulation

The MV/LV electrical network of the textile factory and the MV network feeding this industrial facility are modeled with EMTP-RV software to analyze the effects of power system faults on the supply voltage waveform. Fault locations are indicated on the one-line diagram of the modeled system that is given in Fig. 2.

Also, these sag mitigation techniques are evaluated on the scenarios created in the software model: 1) using series reactors at strategic points of the network, 2) integrating generators near the sensitive loads, 3) feeding the facility through an express feeder

Conductor size and length of the overhead lines located in the feeder are listed in Table 1.

Table 1. Line data

Line No.	Conductor Type	Length (km)
1	2 x 3/0 AWG	12
2	3/0 AWG	0.36
3	1/0 AWG	1.8
4	1/0 AWG	1.7
5	954 MCM	100
6	3/0 AWG	5
7	3 AWG	1
8	3/0 AWG	0.36
9	3/0 AWG	0.36

Eight out of nine lines are operated at the 31.5 kV level. Line 5 is a transmission line operated at 154 kV that is modeled to analyze the effects of transmission faults on end-users connected to the distribution system. Transformer data used in modeling studies are given in Table 2.

Table 2. Transformer data

Transformer	Voltage (kV)	Vector Group	S (MVA)	%uk	Neutral Resistance
TR 1	154 / 31.5	YNyn0	100	11.98	20 Ω
TR 2	31.5 / 0.4	Dyn11	1.6	6.36	Direct

In simulation studies, a three-phase short circuit fault is applied at fault locations in order to obtain the worst retained voltage value. Duration of the fault is chosen as 80 ms. Fault locations and their descriptions are given in Table 3.

Table 3. Fault locations

Fault Location	Description
Fault 1	954 MCM transmission line 100th km – Line 5
Fault 2	End of the 3/0 AWG parallel feeder – Line 9
Fault 3	Another branch on the same feeder – Line 7

Fault 1 aims to show the impact of a transmission level short circuit fault on a distribution level connected customer. Fault 2 is created to investigate the parallel feeder’s effect and Fault 3 is used to study the effect of a fault occurring at a point physically closest to the industrial customer. Duration of each fault is the same and equals 80 ms.

It is assumed that the industrial customer has 400 V phase to phase and 230 V phase to neutral voltage in steady state operation.

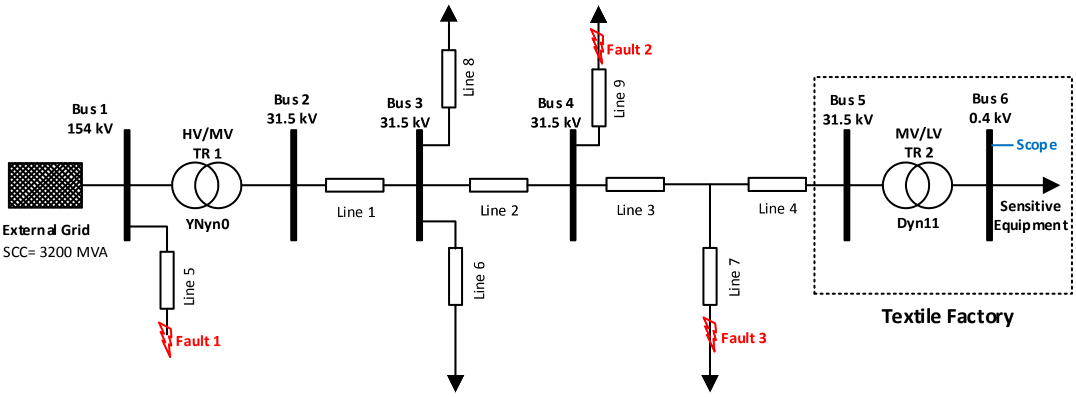

Fig. 2. One-line diagram of the modeled system

3.1. Simulation Studies for Base Cases

Base cases are constructed to evaluate voltage sag performance of the existing distribution network subjected to three-phase short circuits. Related simulation results are given in Table 4. Calculation of voltage sag severity is performed using SEMI F47 compatibility curve and sag energy is obtained with reference to IEEE Std. 1564 – 2014.

Table 4. Base case results – retained voltage

Fault Location	Retained Voltage		Sag Severity	Sag Energy (ms)
	RMS (V)	Per Unit		
Fault 1	192	0.83	0.34	25
Fault 2	7	0.03	1.94	80
Fault 3	34	0.14	1.72	78

According to Table 4, a fault at the transmission line (Fault 1) caused voltage sag at the point of interest even though the fault location is 100 km away. The three phase short circuit fault at Fault 1 caused shallow voltage sag with 0.83 pu retained voltage value. In addition, it can be inferred that smaller retained voltage values cause higher sag severity and energy. For instance, Fault 3 created a voltage sag having the values of 1.72 sag severity, which exceeds the SEMI F47 curve reference value defined as 1 (one). Sag energy, which corresponds to the interruption time of voltage sag, is equal to energy lost by the event. Therefore, shallow sag events such as Fault 1 produce less sag energy that equals 25 ms.

3.2. Simulation Studies with Mitigation Methods

As previously mentioned, utility-side mitigation methods against voltage sag are modeled and simulated using the same parameters. Also, the efficiency of utility-side mitigation methods is investigated.

First of all, a synchronous generator with 0.5 MVA rated power output is directly connected to Bus 6. It is assumed that the synchronous generator remains connected to the distribution network during the fault. Simulation results are given in Table 5.

Table 5. Synch. gen. at Bus 6 – retained voltage

Fault Location	Retained Voltage		Sag Severity	Sag Energy (ms)
	RMS (V)	Per Unit		
Fault 1	220	0.96	0.08	6
Fault 2	132	0.57	0.86	54
Fault 3	111	0.48	1.04	61

Retained voltage values in each scenario increase with the help of the generator compared to base cases in Table 4.

Secondly, installing series reactors at strategic points is simulated. The series reactor is the additional impedance that increases total impedance from supply to the faulted point. For this case, 31.5 kV/5 mH series reactor is implemented to Line 9 and Line 7, which is close to Fault 2 and Fault 3, respectively.

The disadvantage of installing a series reactor is that it increases the power losses in steady-state operation. Simulation results for implementing series reactors are given in Table 6.

Table 6. Series reactor application – retained voltage

Fault Location	Retained Voltage		Sag Severity	Sag Energy (ms)
	RMS (V)	Per Unit		
Fault 1	194	0.84	0.32	23
Fault 2	52	0.23	1.54	76
Fault 3	56	0.24	1.52	75

Lastly, an industrial customer that has sensitive equipment in production activities can be fed by an express feeder. In this context, the textile facility is fed through a 15 km long, 3/0 AWG conductor overhead line that is the outgoing feeder of Bus 2 in Fig. 2. Obtained results are given in Table 7.

Table 7. Express feeder – retained voltage

Fault Location	Retained Voltage		Sag Severity	Sag Energy (ms)
	RMS (V)	Per Unit		
Fault 1	199	0.87	0.26	19
Fault 2	142	0.62	0.76	49
Fault 3	170	0.74	0.52	36

3.3. Comparison of Simulation Results

According to the simulation results, all of the three-phase short circuit faults caused voltage sag at the point of measurement. Transmission level faults that are distant (~100 km) from the textile facility may lead to interruptions in the production process of the company. Faults in the parallel feeder cause voltage interruptions at the textile facility (Bus 6) since the fault location is electrically closest to the measurement point. Similarly, Fault 3 caused deep voltage sag that probably lead to service interruption in production activities of the facility.

Voltage sag severity and energy are highly correlated with retained voltage value and duration of the sag. As the sag duration is assumed to be constant in the analysis, retained voltage value is the only parameter that affects severity and energy. Hence, sag severity and energy values change with the reciprocal of the retained voltage magnitude. So, mitigation methods decrease sag severity and energy simultaneously. It is concluded that the express feeder method reduces sag severity below the value of 1 for all fault locations. Similarly, total sag energy loss in express feeder applications is relatively lower than other mitigation methods.

The fault caused retained voltage values in the base case and mitigation methods are illustrated in Fig. 3.

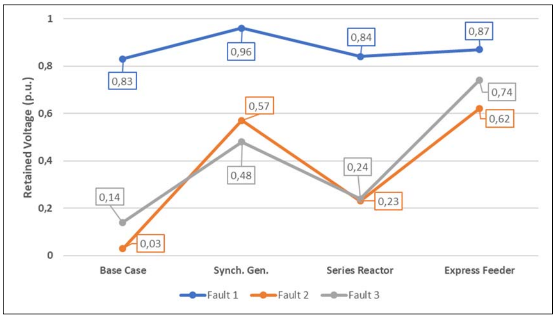

Fig. 3. Retained voltages in all scenarios

As can be seen in Fig. 3, all mitigation methods against voltage sag events have positive impacts in terms of retained voltage. Installing a synchronous generator helped to increase retained voltage during short circuit faults. Distributed generation systems with fault ride through (FRT) capability can be installed on the industrial customer busbar to prevent the tripping of sensitive equipment from short duration voltage variations. Using a series reactor in the network also increased retained voltage but the obtained increment was relatively smaller than generator integration. On the other hand, using a series reactor leads to additional technical loss in return. Last but not least, feeding the industrial customer over an express feeder is the most effective method from the technical point of view although it might be the most expensive method to implement. Decreasing the number of customers connected to the same feeder decreases the number and impact of voltage sag events.

4. Conclusion

In this paper, voltage sag definitions are given according to IEEE Std. 1159 – 2011 and voltage sag indices are reviewed according to IEEE Std. 1564 – 2014. Utility-based voltage sag mitigation methods such as reducing the number of faults due to short circuits, lowering fault clearing time and changing the power system design are discussed. A feeder of an industrial customer supplied in the TREDAS distribution network is modeled using EMTP/RV simulation software. In the model, three-phase short circuit faults are applied in order to get the worst-case retained voltage RMS values of voltage sag events. Simulation results for base case and utility-based mitigation methods are compared in terms of sag depths, sag severity and sag energy.

When the simulation results were analyzed, it was concluded that using an express feeder for industrial customers with sensitive equipment in the production process can dramatically increase (from 0.03 pu to 0.74 pu) the retained voltage. Although installing a generator has a positive effect on retained voltage levels, this action has to be performed near the load bus to enhance the efficiency of this approach. Even if a series reactor can increase retained voltage values, it leads to operational and financial problems such as prolonged voltage drops and steady state energy losses.

Although the mitigation methods mentioned above are beneficial, these methods are impractical for implementation throughout the network due to financial and operational constraints. Therefore, reducing the number of faults and the fault duration as a proactive approach is the key solution in a wider perspective.

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