Assessment of Voltage Sag Events Based on Measurement Studies in an Industrial Facility

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Abstract—**Voltage sag is the most common power quality problem, which has significant consequences for industrial customers. In industrial facilities, microprocessors and semiconductor-based automated equipment is widely used. These devices are extremely vulnerable to deviations in supply voltage. Consequently, the voltage sag performance of industrial facilities needs to be assessed by measurement studies to determine root causes, characteristics and the size of the problem. In consultation with ÅF Consult Turkey, Trakya Electricity Distribution Company conducted an R&D project funded by the Turkish Energy Market Regulatory Authority to characterize and analyze voltage sag events in electrical distribution networks. In this study, power quality measurement with an IEC 61000-4-30 Class A monitoring device was performed in a textile facility in the Thrace region. The event records were evaluated using sag indices according to IEEE Std. 1564-2014 and voltage waveforms were analyzed. Furthermore, the root causes, the cost of voltage sag events and possible mitigation methods were explored.**

Index Terms—**Financial losses, IEEE Std. 1564-2014, industrial facility, power quality measurement, voltage sag.**

I. INTRODUCTION

The phenomenon of power quality is becoming more important with the development of industrialization and equipment technology. The equipment of industrial customers is very sensitive to disturbances since the production process is highly automated. Energy market regulators determine rules to be applied by utilities, suppliers of last resort and end-users regarding power quality. Thus, power quality is required to be measured using IEC 61000-4-30 Class A monitoring devices in Turkish distribution networks [1].

Voltage sag is one of the power quality problems that is more prevalent than other parameters such as harmonics, voltage unbalance, flicker and transient voltages [2]. Voltage sag is defined in the IEEE Std. 1159-2011 [3] as a decrease in RMS voltage value of the supply voltage to between 0.1 pu and 0.9 pu. Event duration is limited from half-cycle to one minute.

Voltage sag events are commonly caused by short-circuit faults, transformer inrush and motor starting currents. The voltage sags have adverse effects on sensitive equipment such as adjustable speed drives (ASD), programmable logic controllers (PLC) and personal computers (PC) that are widely used in industrial facilities. Tripping of this process control equipment causes downtime of the production system and financial loss in industrial facilities. In the literature, several studies can be found [4]-[6] that estimate sag-related costs based on case studies, statistical analyses and probabilistic approaches.

Sensitive equipment has different voltage sag withstand characteristics that are given in IEEE Std. 1346 [7]. Sag performance of statistically sampled units of PLC, motor starter, PC and AC drives are classified in terms of upper and lower limits. In addition, a variety of equipment compatibility curves was created to define the sag tolerances of equipment. In this context, the ITIC Curve (formerly CBEMA) was developed to reflect personal computer tolerance against voltage sag events. Similarly, the SEMI F47 curve was improved for semiconductors. These curves are comprised of two regions including prohibited and no-damage regions. Voltage sags are distributed in one of these regions in the curve according to the depth and duration of events [8].

Voltage sag mitigation methods can be evaluated in three aspects: utility-side methods, mitigation devices at end-user premises, and increasing equipment immunity [2], [9]. The methods on improvement of distribution networks including minimizing the number of short-circuit faults, reducing time delays of protection systems and changing the topology of power systems are summarized in [10]. A simulation study on utility-side mitigation methods and an evaluation of the effects of short-circuit faults on voltage sag events are provided in [11]. Equipment based mitigation methods are explained in IEEE Std. 1250-2011 [12]. Increasing the immunity of the equipment can be achieved by using extra capacitance to the DC bus or sophisticated rectifiers operating in wider input voltage [13].

The Thrace region of Turkey has different industrial facilities that have sensitive production processes. For this reason, Trakya Electricity Distribution Company (TREDAS) conducted the Voltage Sag R&D Project in consultation with ÅF Consult Turkey in order to characterize and enhance the voltage sag performance of the distribution network. The project was financially supported by the Turkish Energy Market Regulatory Authority (EMRA).

A power quality analyzer compliant with IEC 61000-4-30 Class A was used to measure voltage sag events in the medium voltage busbar of a textile facility in Thrace for 11 days. In this paper, the obtained measurements are evaluated regarding IEEE Std. 1564-2014 [14]. Characteristics of voltage sag events and voltage waveforms are analyzed. Possible root causes of production interruptions resulting from sag events are discussed. Furthermore, the cost of voltage sag events is evaluated through facility inspections and sag mitigation methods that can be performed by utility and end-users are summarized.

II. DESCRIPTION OF THE INDUSTRIAL FACILITY

The textile facility produces yarn using fiber as raw material. The production process of yarn is given in Figure 1.

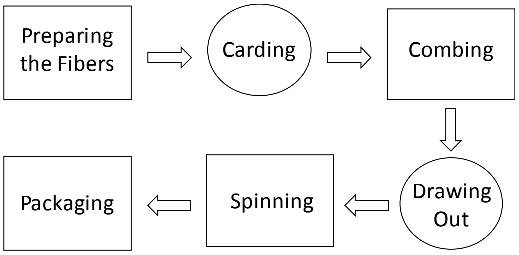

Figure 1. Production process of the textile facility

Manufacturing of the yarn is conducted 24/7 in the textile facility. Products are generally sold on the domestic market.

Preparing the fibers involves cleaning and separating of the raw material for the next step. Carding is the stage where the fibers are forced through numerous wires set in a parallel form. Combing is an essential part of production in order to get smoother and finer yarn. It is the second paralleling process of the yarn. After carding and combing, the raw fiber material is obtained as a sliver. Drawing out consists of rotating rollers where the elongated sliver is fed into large cans. Spinning involves the most sensitive equipment in the production process. Compact spinning machines have several small sized (4 kW) electric motors. In spinning, a sliver of fiber is fed into the spinner by compressed air and yarn is manufactured. The final stage of the production process is packaging, where yarn is covered with stretch film and stored in the warehouse.

The most critical equipment in the production process is the spinning machine that is also vulnerable to voltage sags. Short-time deviations in supply voltage cause interruptions in production activities. The facility has four 2,500 kVA dry-type transformers. Annual electricity consumption of the facility is around 3,423 MWh. A one-line diagram of the industrial customer is presented in Figure 2. The facility is fed through a 283-meter long XLPE cable over an 80/100 MVA power transformer. For the sake of simplicity, only sensitive equipment is indicated in the one-line diagram. The installed power of a spinning machine (SM) is approximately 110 kW. Spinning machine air conditioners (SM - AC), reactive power compensation systems (VAr CS) and the automation system (AS) are also represented in the one-line diagram.

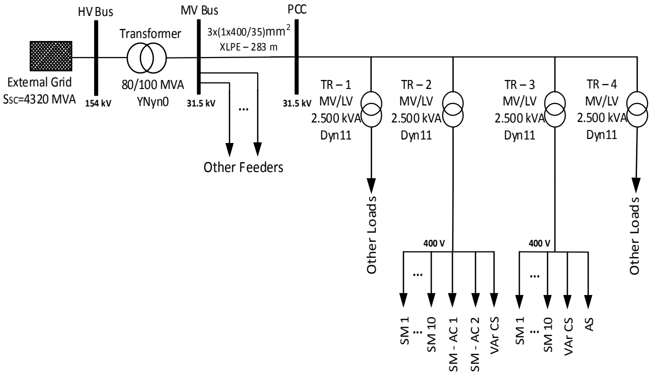

Figure 2. One-line diagram of the textile facility

III. MEASUREMENT STUDIES

The Hioki PW3198 [15] power quality monitoring device compliant with IEC 61000-4-30 Class A standard is used on the MV side of the 31.5/0.4 kV facility transformer to record voltage sag events. Measurement studies were conducted between August 10, 2017 and August 21, 2017.

A. Measurement Results

The results were analyzed using Hioki 9624 PQA software. When the data were examined, it was observed that a total number of 140 short-term voltage variation events were recorded during the measurement. In addition, 72 of 140 events were classified as voltage sag while the rest were detected as voltage swells. Voltage sag events on the ITIC curve are depicted in Fig. 3. Each voltage sag or swell event is represented by a diamond symbol showing the corresponding phase of the circuit.

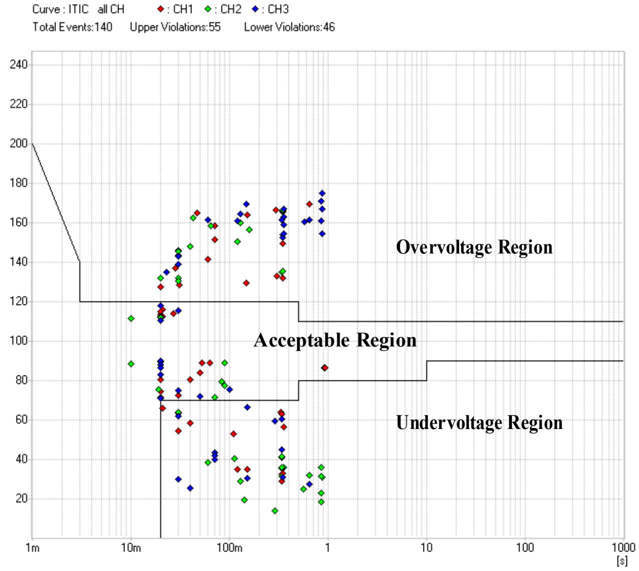

Figure 3. Voltage sag/swell events on the ITIC curve

In case of a multi-phase voltage sag event, the phase encounters the deepest sag marked in the figure. In addition, 46 sag events and 55 swell events are in the prohibited regions of the ITIC curve while the remaining 39 are located in the acceptable region. None of the sag events lasts longer than one second as can be seen in the curve. This can be explained by the protection settings of the relays. In Turkey, the transmission system operator (TEIAS) allows distribution system operators a maximum of one second to clear short-circuit faults. Thus, voltage sags related to short-circuits are not expected to exceed one second. Furthermore, transformer energizing and motor starting phenomena generally cause the type of voltage sags that last longer than one second [16]. Since none of the events recorded had a duration of more than one second, it can be seen that voltage sags related to transformer energizing or motor starting did not take place during the measurement study.

The breakdown of all voltage sag events with respect to retained voltage, number of events and duration is given in Table I. Ranges of retained voltage and duration used in sag distribution tables generally vary, as they are case specific. Consequently, Table I was created by taking IEC 61000-2-8 and UNIPEDE recommended tables into account [14].

TABLE I. DISTRIBUTION OF VOLTAGE SAG EVENTS

Retained Voltage (per unit)	Voltage Sag Duration (seconds)				
	0.01≤t≤0.1	0.1<t≤0.25	0.25<t≤0.6	0.6<t≤1	1<t≤60
0.9-0.8	13	0	0	2	0
0.8-0.7	11	0	0	0	0
0.7-0.6	4	1	3	0	0
0,6-0.5	2	1	2	0	0
0.5-0,4	2	1	3	0	0
0.4-0.3	2	3	8	4	0
0.3-0.2	2	1	2	2	0
0.2-0.1	0	1	1	1	0

Table I indicates that 36 of 72 sag events occurred in the interval of 10 – 100 ms. Practically, circuit breakers used in Turkish distribution networks do not have the capability of interrupting faults of less than 80 milliseconds. Moreover, the tripping time of the protection relay and signal transmission time to the circuit breaker extend the total fault interruption time to over 100 milliseconds [17]. As a result, transmission system faults or intermittent distribution system faults (such as tree contact, galloping etc.), which do not operate the CB, may have led to these 36 sag event durations of less than 100 milliseconds.

B. Voltage Sag Indices

Voltage sag events are classified according to indices defined in IEEE Std. 1564-2014 that include SARFI (System Average RMS Frequency Index), voltage sag severity and energy. SARFI represents the total number of voltage sag events according to specified thresholds (SARFI-X) or compatibility curves (SARFI-Curve). For instance, SARFI-70 gives the total number of sag events that have retained voltage lower than 0.70 pu.

Voltage sag severity depends on both depth and duration of the sag event with reference to the compatibility curve. IEEE Std. 1564-2014 recommends using ITIC or SEMI F47 as reference curves. Voltage sag severity for a single event is calculated as shown in (1) where S is the severity of sag, V is the retained voltage value in pu, d is the duration of the sag event and V_{curve} (d) is the corresponding threshold value on reference curve in pu.

$$S = \frac{1 - V}{1 - V_{curve}(d)} \tag{1}$$

Voltage sag performance of a site or a measurement point can be evaluated using the average sag severity index denoted as $S_{average}$ that is given in (2). N is the total number of sag events and i shows a particular sag event.

$$S_{average} = \left(\sum_{i=1}^{N} S_i \right) \Big/ N \tag{2}$$

Voltage sag energy is described as the duration of an interruption that provides the same energy loss as the sag event that is calculated as in (3) where E_{VS} shows sag energy as a unit of time, V is the lowest RMS voltage value in pu, V_{nom} is the nominal voltage value in pu and T is duration of the sag event in seconds or cycles.

$$E_{VS} = \left[1 - \frac{V}{V_{nom}} \right] . T \tag{3}$$

Average sag energy index (ASEI) is the mean value of all the calculated voltage sag energy values. Equation (4) represents the calculation of ASEI where N is the total number of sag events and i shows a particular sag event.

$$ASEI = \frac{1}{N} \sum_{i=1}^{N} E_{VS_i} \tag{4}$$

Calculated SARFI-X distribution is given in Table II. All SARFI-70 events are located below the ITIC tolerance curve showing that when the retained voltage magnitude drops under the 0.70 pu level, the probability of violating the threshold values greatly enhances.

TABLE II. SARFI-X INDICES OF SAG EVENTS

SARFI – X	**Number of Events**
SARFI – 90	72
SARFI – 80	57
SARFI – 70	46
SARFI – 60	38
SARFI – 50	33
SARFI – 40	27
SARFI – 30	10
SARFI – 20	3

Shallow sags, which are in the interval of 0.9–0.7 pu, make up nearly half of all events. The deep sags are concentrated in the range of 0.4–0.3 pu retained voltage magnitude and the duration of 0.25–0.6 seconds that is shown in Fig. 4.

$S_{average}$ index of the industrial facility is calculated as 1.30 in (2) with reference to the SEMI F47 curve. Since the $S_{average}$ value is greater than one, it can be said that any sag event that occurred in the measurement point has considerable potential to violate the sag tolerance curve.

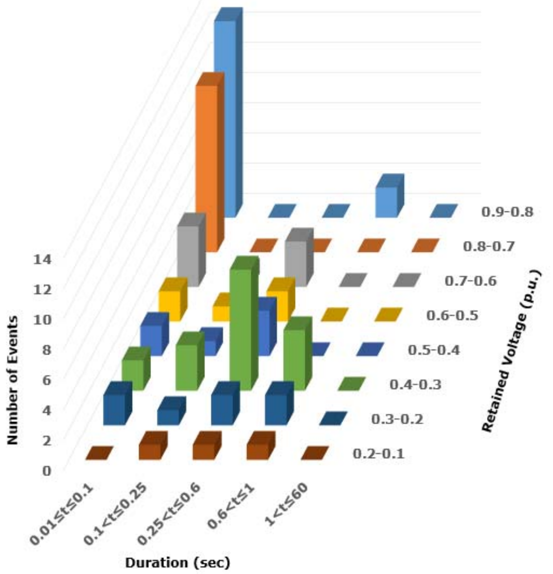

Figure 4. 3D representation of sag events

ASEI index of the total sag events is calculated as 0.17 seconds according to (4). This calculation expresses the interruption equivalent of an average sag event due to the lost energy.

C. Voltage Sag Characteristics

Facility personnel regularly record the events with a time stamp that causes only momentary interruptions in the production process. According to data logs, the yarn production process was interrupted four times in total during the measurement study. As a result, we compared facility staff records with the power quality monitoring records to detect the characteristics of sag events that stopped the manufacturing process. The matching events according to the timestamps are given in Table III.

TABLE III. VOLTAGE SAG EVENTS THAT CAUSED PRODUCTION LOSS

Event No	Day/Month	Time Stamp	Retained Voltage (pu)	Event Duration (s)
1	10/08	20:32:39	0.32	0.641
2	11/08	03:57:47	0.14	0.290
3	18/08	14:49:20	0.87	0.934
4	18/08	15:16:02	0.87	0.913

Although Event 3 and Event 4 are not located in the prohibited region of the ITIC curve, these events interrupted the production process of yarn. This is because the ITIC curve only represents an approach for the sag/swell withstand capability of devices operating at 120 V and 60 Hz ratings [18]. In addition, there are numerous devices having different topological characteristics that can be classified as "sensitive". Consequently, one cannot expect a single curve to project sag ride through the capability of all devices.

Fig. 5 expresses Event 1, which shows a deep voltage sag event occurred at phase B having the minimum value of 0.32 pu. The other two phases experienced a voltage swell simultaneously with the sag event. Generally, this phenomenon is related to a single phase to ground fault at one of the adjacent feeders. When one phase is short-circuited, the voltage magnitude and the phase angle at the star point of the transformer shifts from ideally zero to a specific magnitude with a specific phase angle. Thus, the phase-ground voltages of the other two phases could rise as the star point voltage vector changes.

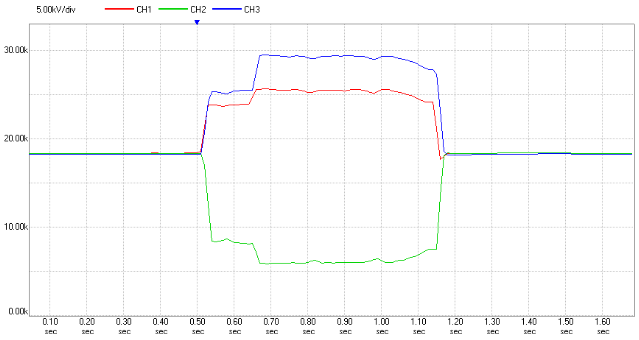

Figure 5. RMS voltage variation at Event 1

Similarly, Fig. 6 shows voltage magnitude deviations of the second event. The retained voltage of the voltage sag is 0.14 pu, which is relatively smaller than the first event, and duration of the event is approximately 0.3 seconds.

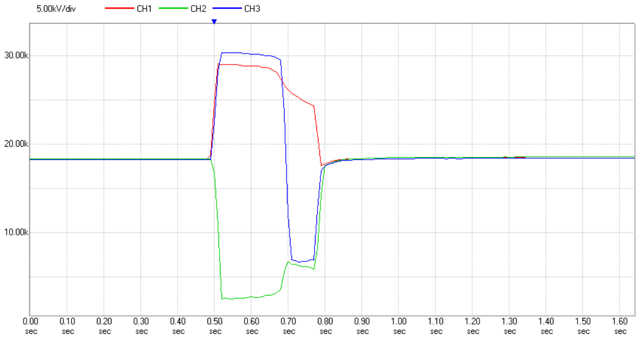

Figure 6. RMS voltage variation at Event 2

Events 3 and 4 represent almost identical sag characteristics in terms of event duration, depth, and phase count as depicted in Fig. 7 and Fig. 8, respectively. The voltage waveform of three phases was exposed to a shallow sag having the value of 0.87 pu for 0.9 seconds. When the current waveform was analyzed, an inrush current was detected that equals about 1.5 times the nominal load current magnitude. Hence, it is concluded that Event 3 and Event 4 were probably related to load side effects unlike the other events that originated from utility-side short-circuits.

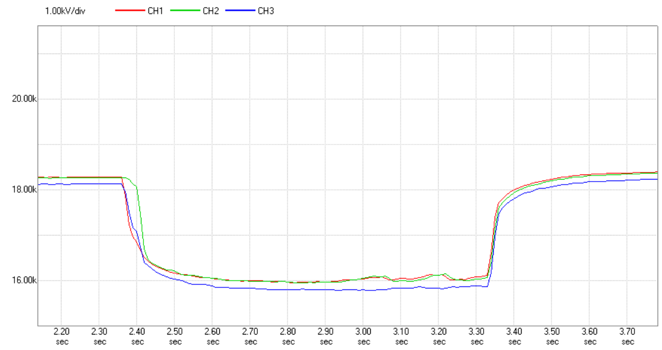

Figure 7. RMS voltage variation at Event 3

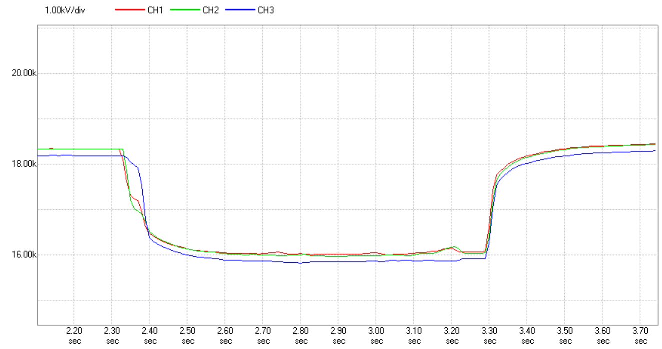

Figure 8. RMS voltage variations at Event 4

D. *Cost of Voltage Sags*

A survey was conducted within the facility to calculate the average annual financial cost of voltage sags. It was identified that a momentary interruption of the production process can only be restored after 45 minutes of waiting time due to the adjustment requirements of the spinning machines. The estimated costs of losses in raw material, idle time and equipment malfunction are listed in Table IV.

TABLE IV. BREAKDOWN OF ESTIMATED COSTS

Cost Parameters	**Financial Losses (US$)**
Raw Material	2,700
Idle Time	2,700
Equipment Malfunction	1,000
Total Cost (per event)	6,400
Number of Interruption (per year)	36
Total Cost (per year)	230,400

It can be inferred from the table that the cost of loss in raw material and workforce is US$2,700 per event. In addition, estimated malfunction cost of the suction motor is US$1,000 per sag event taking into account an average number of damaged devices and failure rates. Therefore, it is calculated that a single voltage sag event costs US$6,400. The yearly number of sag events that cause an interruption in the production process is around 36 according to facility records. Therefore, the financial loss of the textile facility due to sags is approximately US$230,400 per year.

IV. MITIGATION MEASURES

Possible actions to mitigate voltage sags that could be conducted by the operators of distribution networks and facilities are discussed in this section.

A. *Methods in Distribution Networks*

Distribution Network Operators (DNO) can facilitate several mitigation actions listed below to improve the power quality of the network and minimize the sag-related economic loss.

- Finding the root causes of faults helps utilities to take corrective action in problematic areas of the network. This will lead to reductions in the occurrence of faults and fault-related voltage sags simultaneously.
- Activating an instantaneous overcurrent protection function in protection relays could reduce the duration of voltage sags, as this action decreases fault clearing times.
- Proactive maintenance and renovation of old circuit breakers could decrease mechanical trip time and the probability of breaker-failure-originated upstream sympathetic tripping. These actions limit the duration and propagation of voltage sags.
- Supplying industrial customers from express feeders that do not contain branch circuits and other customers may decrease the number and potential effects of sags.
- Replacing conventional reclosers with “Pulseclosers“ provides a limitation in depth, duration and number of sags as it determines fault type (permanent or temporary) with low magnitude test current and prevents reclosing onto permanent faults [19].
- The magnitude of phase to ground faults depends on the grounding type of the power system. The phase to ground faults in solid and low-impedance grounded networks could cause voltage sags in one phase, as these networks rely on high amplitude current detection. On the other hand, resonant grounding schemes like Ground Fault Neutralizer (GFN) reduce phase to ground fault current magnitude almost to zero preventing single-phase voltage sags.
- Using fault current limiting (FCL) technologies such as air-core reactors, superconducting FCL, high-impedance transformers and solid-state FCL decreases the current magnitude of single/multi-phase faults. These applications will increase the retained voltage level of sags in case of a power system fault and lower the detrimental effects of voltage sags.

B. *End-User Mitigation Devices*

Even though the mitigation actions performed in the distribution system can reduce the number and effects of voltage sags, there is no practical way to prevent all short-circuits or to retrofit the whole network. Hence, end-users could integrate mitigation devices to protect sensitive loads against voltage sags if the financial and hidden consequences (loss of reputation, unsatisfied customers, etc.) are critical. Several types of mitigation device could be used to fulfill the different needs of production facilities. Ferroresonant transformers are generally used to protect the loads having a few tens of kVA. It is suggested that the nominal rating of the transformer should be selected as three or four times higher than load size to provide operability. AVC (Active Voltage Conditioner), DVR (Dynamic Voltage Restorer), and DySC (Dynamic Sag Corrector) are inverter-based devices that monitor supply voltage continuously and are used for loads in the range of hundreds of kVA. In case of a voltage sag, these devices inject voltage to restore voltage magnitude and angle at the common coupling point to prevent sensitive load tripping. An STS (Static Transfer Switch) could be placed in the service entrance of a facility that has two alternative sources. UPS (Uninterruptible Power Supply) systems rely on battery packs and fast switching components. The STS and UPS systems also have the capability to mitigate a wide range of power quality problems such as voltage variations, flicker, harmonics and voltage unbalance.

The appropriate mitigation device should be selected according to a cost-benefit analysis and the level of operational efficiency. Prior to commissioning any kind of mitigation device, measurement studies should be performed and voltage sags producing momentary shutdowns should be investigated.

V. CONCLUSIONS

Although voltage sags cause millions of dollars of losses in industry, they remain a hidden power quality issue. Generally, industrial facilities suffer from momentary shutdowns in production processes with resulting economic losses. To quantify and characterize power quality issues, measurement studies using power quality monitoring devices compatible with IEC 61000-4-30 Class A should be performed. In this study, measurement with a Class A monitoring device was carried out in a textile facility in Thrace for 11 days. The detected voltage sag events were classified with respect to the values of duration and retained voltage, and sag indices were calculated regarding IEEE Std. 1564-2014. It was found that all sag events lasted less than one second. Motor starting and transformer energizing may not be responsible for the detected voltage sag events as these phenomena commonly have longer durations. Besides, events with sag durations of less than 80 ms were considered to stem from temporary short-circuit faults since protection systems cannot isolate these faults on time. Only four out of 72 sag events stopped yarn production during the measurement period. The RMS voltage variations of these four sag events were analyzed to investigate possible root-causes. Two of them are considered to originate from phase to ground short-circuits at adjacent feeders while the rest are assessed to be on the load side such as short-term overloading and switching operations. In addition, the estimated cost of these voltage sags is also presented through facility inspections and site surveys.

The mitigation methods that could be applied by DNOs and end-users are explained and discussed in the paper. Although DNOs have a certain degree of capability to reduce fault-related voltage sags, it is impossible to eliminate all the faults due to the nature of power systems. Therefore, the implementation of mitigation devices in the facilities according to measured sag events, sag performance of mitigation equipment and sag withstand level of sensitive loads should be considered. Together with financial analysis, these technical criteria can provide a basis for selection of the optimal technology and method.

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