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Voltage sags in the automotive industry: Analysis and solutions

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ABSTRACT

The objective of this paper is to present the actual solutions used to solve process-interruption problems caused by voltage sags in a large automotive industry. A brief description of the industrial process is presented to focus attention on only the production units that are most vulnerable to voltage sags. Then, the industry's experience with interrupted production is reported and analyzed. A two-step procedure is proposed to evaluate the equipment that should be targeted for the application of compensating solutions. In applying this procedure, a criteria based on the Kaizen approach is used to select both the areas for intervention and the types of compensating solutions. The results consist of adequate compensating devices, characterized by very low costs in comparison to the costs associated with lost production, due to the negative effects of voltage sags. The effectiveness of the proposed solutions was proven by an ex-post analysis that lasted for one year after the intervention. The main conclusion of the study provides evidence that supports the real possibility of solving extensive voltage sag problems in large industries using economical devices. The practical implications of the method were demonstrated by extending it successfully to additional production units in the same factory.

1. Introduction

The relevance of the problems in industrial systems caused by poor power quality has been addressed extensively in the literature [1–5]. For example, voltage sags can cause huge problems that are significant technically and economically [6,7]. These problems are more important for industries that are highly automated due to the inevitable vulnerability of the equipment to power quality issues, such as voltage sags.

The main detrimental effects of voltage sags are that protective devices are tripped and the equipment is shut down, stopping the manufacturing process. The economic value of such process interruptions represents costs incurred by the factory as a direct result of voltage sags. These costs depend on many factors that are linked to the type of manufacturing activity and to the extent of the affected area. The main cost components are related to lost work, lost production, damaged equipment, and recovery work. In addition, the so-called 'hidden costs' must be added to account for any second level effects that reflect on the performance of the business, such as retaining customers, satisfying customers, and protecting the company's reputation [8–10].

A compatibility analysis is generally required to evaluate the effects of voltage sags in terms of process interruptions due to the electrical tripping of the equipment [8,9]. In the compatibility analysis, the performance of the supply system feeding the factory in terms of voltage sags is compared to the susceptibility of the factory's equipment to such sags. The voltage sag performance of the supply system is represented as a scatter plot in which each point corresponds to the amplitude, and the duration of the voltage sag that is registered at the busbar of the supply system. The sag susceptibility curve of the equipment is represented as a curve that provides the minimum magnitude that the equipment can withstand for a given sag duration. Standard susceptibility curves are available as the well-known Computer Business Equipment Manufacturers Association (CBEMA), Information Technology Industry Council (ITIC), and Semiconductor Equipment and Materials International groups (SEMI) curves [3,8,10]. Any sag that is inside the susceptibility curve will trip the equipment.

Most literary contributions have performed this analysis as an *estimation of compatibility*. This means that the process interruptions that occur are evaluated by estimating the voltage-sag performance of the power supply and/or the susceptibility curves of the equipment.

The estimation of the voltage sag performance of the power supply can be obtained by conducting proper simulations of faults to provide the expected characteristics of voltage sags at the busbar that feeds the factory (i.e., number of sags, voltage amplitude, and

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duration); both critical distance method and fault position method can be used [11–14]. A different approach was used in [15] to estimate the sag performance at the busbar that feeds a factory by using reliability data of similar electric networks. A few papers have reported voltage-sag characteristics measured at the specific busbar that was being analyzed, and very good contributions were provided by [16,17].

The estimation of the susceptibility curves of a given piece of equipment may be the most difficult task that must be performed when analyzing voltage sag concerns. Usually, the aforementioned standard curves, i.e., CBEMA, ITIC, and SEMI, as well as some typical curves for categorized equipment [15,18] are used. A few contributions have referred to the specific equipment that was actually present in the industrial process that was being considered. For example, in [16], a voltage sag generator was used to derive the sag response of a set of representative machine tools, after which a plant sag threshold was established.

The evaluation of the costs associated with process interruptions due to voltage sags is crucial because it is used to guide decisions concerning mitigating solutions that increase the compatibility between the power supply and the industrial equipment. The capital and operating costs of alternative solutions must be compared to the savings the solutions generate. So, some of the savings provided by the solutions would result from avoiding some of the costs associated with voltage sags, such as the downtime of machines and lost production. The viable solution, among those that are applicable, corresponds to savings that exceed the total costs. Several financial methods can be used, such as the net present value, the pay back time, the break even analysis, the cost-benefit analysis [8,10,19].

This paper illustrates the solutions used to solve the process interruption problems due to voltage sags in a portion of a large automotive manufacturing industry. Given the dimensions of such a large industry, it was mandatory to select a specific, reasonable area in which to implement voltage sag compensation measures. The characteristics of the voltage sags that occurred were measured at a 150/20-kV substation that feeds the plant for approximately one year. The actual tripping of the main machines of the plant, which were measured in the same time period of the voltage sags, were available from internal reports, so a compatibility analysis was not essential. To distinguish between the solutions that were able to mitigate the voltage sag problems, a procedure based on the Kaizen method [20] is proposed, and a very simple, cost-benefit analysis was used to choose the appropriate solution from a reduced set of solutions that seemed feasible and applicable.

In the following section, the main characteristics of the manufacturing process are described. Then, voltage sags that have occurred are analyzed, and the procedure used to evaluate the process interruptions is described. Finally, the solutions that were implemented are presented, and their benefits are illustrated by an ex-post analysis.

2. Main features of the automotive manufacturing process

Automobile manufacturing is a very interesting industrial sector in which scientific techniques designed to solve specific problems can be tested and validated. In addition, techniques that are proven to be effective in this sector have significant potential for general use in other applications, as was indicated in [21–23].

The area of the plant that was considered in our study consisted of approximately 300,000 m^2 of warehouses with more than 3500 workers. The process is subdivided according to the specific units involved, including the press shop, body shop, paint shop, assembly area, and finishing area. These units are located in separate buildings that are connected by aerial tunnels that are used to move the car on two-rail conveyors.

The manufacturing process ends in the assembly unit in which all of the mechanical parts, i.e., engine, braking system, windows and windshields, wheels, and shock absorbers, are attached to the body of the car. Most of the work in the assembly unit involves human labor, even if there is a complex, synchronized system for moving the parts. In the specific case of this factory, assembly is conducted in two buildings, i.e., B2 and B7. Fig. 1 shows a simplified work-flow diagram of the assembly process. It shows that the various parts are assembled as the cars are moved along the line into B2 and B7. After assembly, the cars are sent to the finishing unit, where they are tested to determine that accurate assembly was achieved.

The assembly is a classic example of a progressive-type manufacturing process in that the various parts of the cars are assembled in a consecutive manner in order to realize finished products faster than could be done by the use of handcraft-type methods. The sequential organization of workers, tools, machines, and parts presents several advantages, including:

- low cost for moving the parts;
- low cost of unskilled labor;
- simplification of the production control process.

Conversely, such sequential organization strongly influences both the time and the way that the products are advanced, resulting in some disadvantages, including:

- lack of flexibility;
- repeatability of operations;
- strong interdependence between operations;
- high costs for specialized facilities.

The characteristics of the process that were mentioned above provide evidence of the high vulnerability of the entire assembly process to power quality issues, and this is the reason the analysis is focused on voltage sags affecting this area of the plant. The assembly stations, which are called elementary technological units (ETUs), have to complete their operations in a specific amount of time. Any variations in timing or any malfunctions of the equipment create problems that affect all of the ETUs, including those that are downstream and upstream of the malfunctioning ETU.

3. Analysis of occurred voltage sags

The study was initiated with the approval of the management of the factory after several process interruptions had occurred in the first few months of 2011.

The monitoring system, which already had been installed at the 150/20 kV substation, provided the phase voltages that were measured and found to be out of the specified range for a period of six months. The analyzer was installed at the 20-kV bus that feeds the plant, and the information recorded for each event refers to each phase and includes the date, time, duration, and retained phase voltage.

The raw output data were processed to represent the voltage sag performance of the supply system as a scatter plot, as shown in Fig. 2. From the figure, the inferior performance of the supply system is evident, with 54 sags in only six months.

The scatter plot in Fig. 2 requires proper phase and time aggregation. The phase aggregation takes into account that the measured voltage sags are three-phase voltage sags, so they must be counted as a single sag; the time aggregation allowed us to count sags that occurred in strict succession as one sag. This is the typical approach

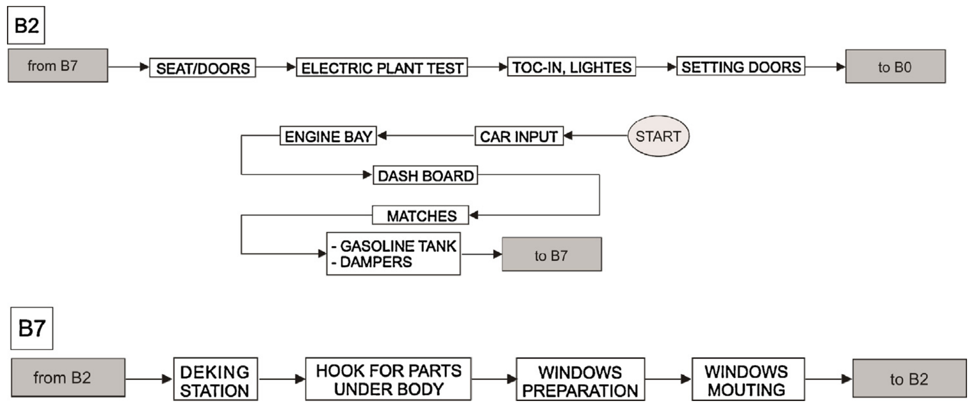

Fig. 1. Simplified work flow diagram of the assembly unit, buildings B2 and B7.

that is used to assess voltage sags in an industrial process; in fact, the first sag is the only critical sag, because the process has already been interrupted when the successive sags occur. Fig. 3 shows the scatter plot that resulted from phase and time aggregation. To better analyze the performance of the supply system, three zones were identified in Fig. 3, i.e., a "soft" zone (green) that includes sags that are characterized by amplitudes ranging from 70% to 90% and by durations less than 500 ms; a "severe" zone (red) that includes sags that have amplitudes less than 70% and durations greater than 500 ms; and a "border" zone (yellow) that includes all the sags in

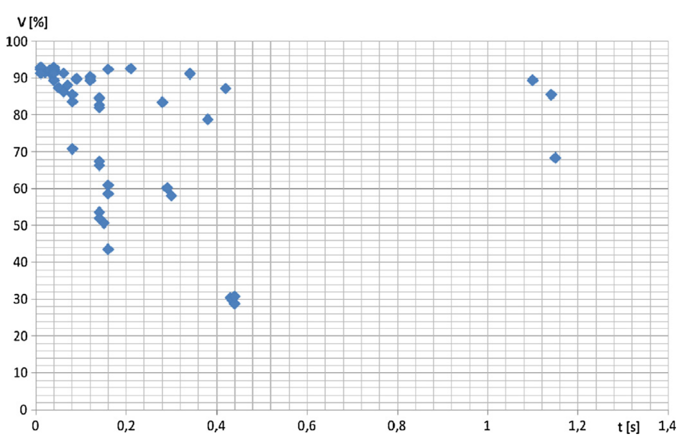

Fig. 2. Scatter plot of the measured voltage sags.

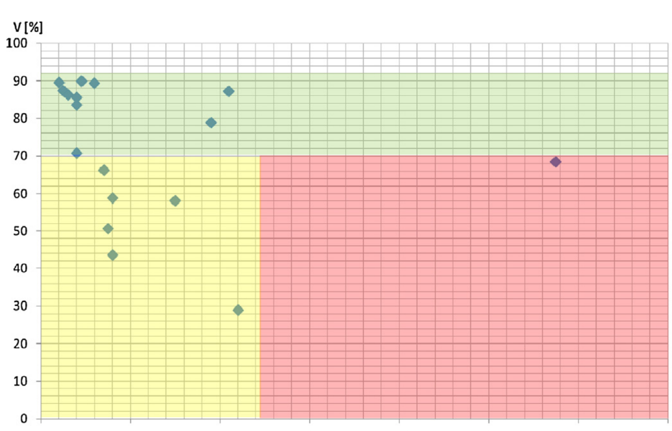

Fig. 3. Scatter plot of measured voltage sags after phase and time aggregation. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

the remaining area. Fig. 3 confirms that the performance of the supply system was not acceptable during this time period, even though most of the events were in the "soft" zone, whereas only one sag fell in the "severe" zone, and the remaining events were in the "border" zone.

4. Analysis of process interruptions

The analysis of process interruptions is fundamentally important for use in guiding interventions designed to mitigate the effects of the voltage sags on a very complex industrial process for which it is unrealistic to expect to solve all the problems at once. To this aim, we proposed a procedure to distinguish between the alternative mitigating solutions. The procedure involves the evaluation of the effects of the voltage sags on the industrial process and the selection of the equipment to which mitigating solutions will be applied. The procedure proposed in this paper respects the framework depicted in [9]. To effectively support these analyses with quantitative measures, proper metrics were introduced, as explained below.

When voltage sags occur in the assembly unit, one or more pieces of equipment shut down, which causes the entire process to stop. Information regarding equipment shutdowns and process interruptions was obtained from reports provided by the manager of the production unit, and this information was integrated with what we learned by interviewing personnel who work in the unit. In fact, as also discussed in [9], the analysis of the process stops must involve electrical-plant specialists and people with other technical skills, such as the personnel who work in the unit.

The equipment interruptions were measured by introducing a suitable metric, which we called 'lost unit' (LU). For a given piece of equipment, one LU represents one quantity of lost production associated with the interruption of the operation of the equipment. Fig. 4 shows the total LU of each piece of equipment in the assembly unit, and this LU is referenced to the specified time period of six months. Fig. 5 shows the number of interruptions of the operation of each piece of equipment in the assembly unit during the same period. Associating the number of sags to the number of equipment interruptions and comparing the results in Figs. 4 and 5, the mean values of LU for sag related to each piece of equipment in the assembly unit were evaluated. Fig. 6 shows the mean values of LU for sag, providing evidence that one sag can cause different values of LU for different pieces of equipment.

To analyze the effects of the voltage sag on the basis of LU values, different aspects must be accounted for.

After several meetings with the personnel and many inspections of the production lines, it was clear that the most important aspect to account for was the time it took to restart the equipment. If two equipment interruptions occurred due to the same voltage

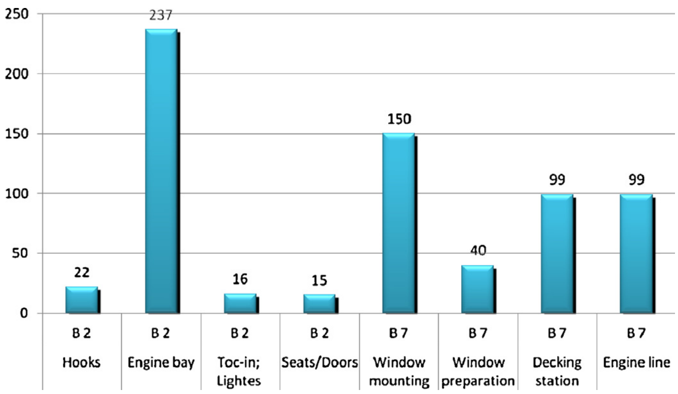

Fig. 4. Value of LU of each piece of equipment that was interrupted in the assembly unit.

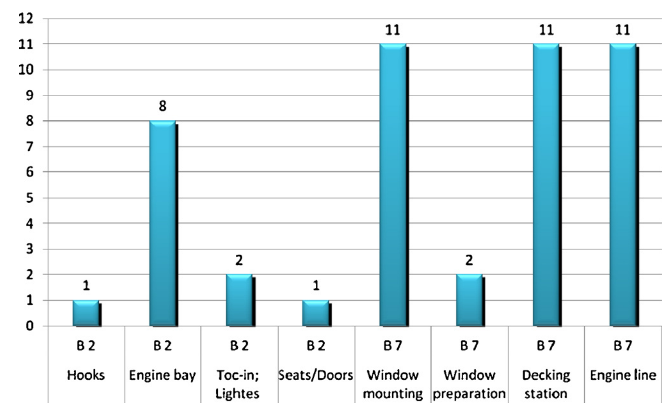

Fig. 5. Number of interruptions in the operation of each piece of equipment in the assembly unit.

sag, the equipment with the higher LU value will require more time to restart. In general, the time required to restart is linked to the complexity of the procedure for resetting and programming the equipment. Consequently, the mean time between failure (MTBF) is the most significant reliability index concerning the susceptibility of a piece of equipment in a manufacturing process to voltage sag. In fact, the MTBF takes into account both the mean time to failure (MTTF) and the mean time to repair (MTTR) [24].

One more factor is crucial, i.e., who is present on the production line when an interruption occurs; this is very important because not all workers have the same level of skill for dealing with such a situation. This consideration represents a clear example of human reliability that can affect the performance of an industrial process

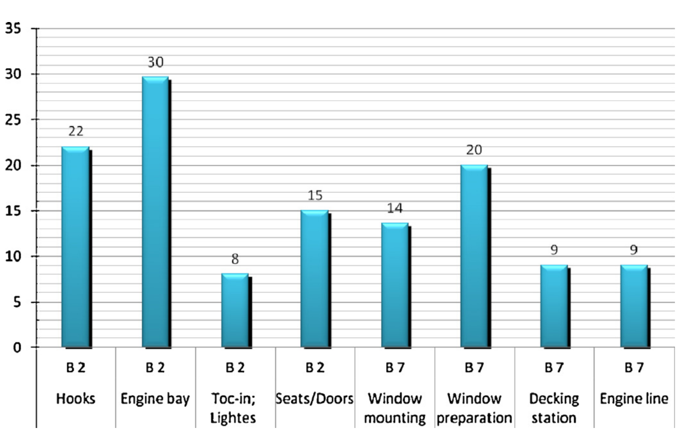

Fig. 6. Average value of LU for sag of each piece of equipment in the assembly unit.

in a decisive manner when equipment interruptions occur due to voltage sags [25].

Further important aspects refer to the position of the equipment in the manufacturing line. The most critical pieces of equipment are those that are located at the end of the production line. In fact, a voltage sag that interrupts a piece of equipment at the beginning of the manufacturing line does not stop the process, because the downstream equipment can continue to operate until the material that had accumulated before the interruption is used up. However, a piece of equipment at the end of the production line can operate as a bottleneck for the entire production line and cause a total shutdown of the line.

To select the equipment to which compensating solutions will be applied, the total costs and the degree of complexity of the intervention must be evaluated before the final choices can be made. These two features can be estimated by conducting proper inspections of the process lines. In fact, the more sophisticated and complex the processes are, the greater the costs and the difficulty of installing compensating devices will be.

To quantify the effects of voltage sags on a piece of equipment and the viability of the compensating solution, a valuable index is proposed, i.e., Macflu, which is defined as:

$$\text{Macflu} = \text{Magnitude} \times \text{Costs} \times \text{Fluency}, \quad (1)$$

where 'Magnitude' refers to the extent of the effects of the voltage sags on the selected equipment; 'Costs' refers to the economic value of the compensating devices; and 'Fluency' measures the ease with which the compensating intervention can be implemented. The value of Macflu is evaluated by assuming that each term in Eq. (1) ranges from 1 to 5 with the following rules:

- heavy effects of voltage sags correspond to the minimum value of Magnitude;
- low costs of compensating devices corresponds to the maximum value of Costs;
- the greatest ease with which the compensating intervention can be implemented corresponds to maximum value of Fluency.

In this paper, the value of Magnitude was established as a function of the aforementioned LU metric, but, in general, it can be evaluated by using other metrics that account for the severity of the effects of the voltage sag. The values of both Costs and Fluency were estimated on the basis of preliminary information that was derived from inspections of the process lines and interviews with operators. Fig. 7 shows the values of the Macflu index for the various pieces of equipment in the assembly unit; for each value of Macflu, the computed values of Magnitude, Costs, and Fluency also are reported. It is worthwhile to precisely indicate that the values of MacFlu in Fig. 7 are useful for selecting the equipment to which the compensating solutions will be applied.

The equipment to which compensating solutions should be applied can be selected based on the Macflu values by using different criteria that are based on the Kayrio and Kaizen methodologies [20]. According to the Kayrio methodology, the decision maker must decide the best way to compensate for the severe effects of voltage sags while taking into account the high costs and the complexity of the solutions. According to the Kaizen methodology, interventions that require lower costs and less complexity are preferred, even if all of the effects of the voltage sags cannot be compensated. Consequently, while the Kayrio methodology leads to the selection of equipment that is characterized by low values of Macflu, the Kaizen methodology favors equipment that is characterized by high values of Macflu.

In this study, the Kaizen method was used. It is the most valuable for achieving the goal of obtaining continuous, small improvements in the compatibility between the power supply and the industrial

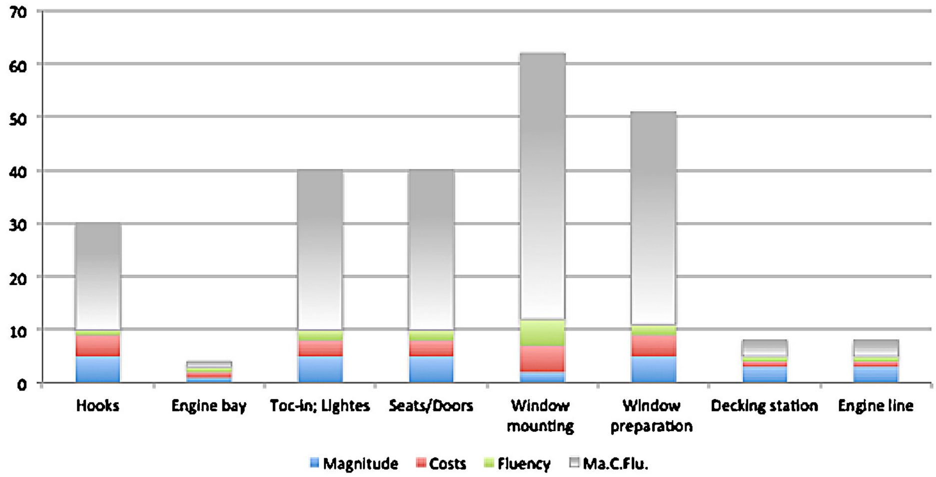

Fig. 7. Macflu index for the various pieces of equipment in the assembly unit.

equipment. In fact, this method allows the gap between the current level of performance and the desired/optimal level to be closed gradually. Fig. 7 shows the window-mounting equipment in the assembly unit had the maximum value of Macflu. This equipment consists of two robots that take the window glass and locate it on the windshield and on the rear window of the car and then spread the gasket. So, the window-mounting machine is relatively simple, but it is one of the most critical machines of the assembly unit in terms of LU, as shown in Figs. 6 and 7.

5. Compensating solutions

After the window-mounting machine was selected as the equipment on which to start compensating solutions, the scatter plot of Fig. 3 was manipulated to highlight the voltage sags that stopped the robots. The red circles in Fig. 8 shows the results.

With the exception of one voltage sag placed in the red zone, none of the other sags that caused the robots to stop was particularly severe in terms of amplitude and duration. These types of sags often result in negative effects on the electronic and/or control sections of complex equipment. This consideration indicated the need to analyze the structure of the two robots and to perform a fault-tree analysis. As are most automatic industrial machines, the robots are composed of four main parts, i.e., the power section, the control section, the measuring and transducers, and the communication. Fig. 9 shows the fault tree of the robot with the top event being the equipment interruption due to voltage sags. Matching Fig. 8 with Fig. 9, it could be argued that most of the interruptions of the robots were the result of interruptions of units other than the power section.

To establish which compensating solution is really feasible, a deep and extensive analysis of the electric circuit that supplies the robots of the window-mounting was conducted. The complete survey of lines, switchboards, and protections allows the determination of the real connections among the parts of the robots and the related installed electric power equipment. For each robot, the estimated power for both the control section and the measuring and transducers was about 2 kVA, whereas it was about 60 kVA for the power section.

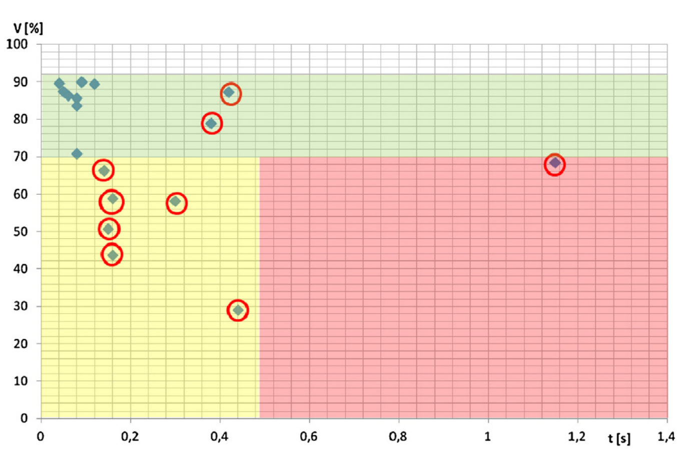

Fig. 8. Voltage sags stopped the robots of the window-mounting. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

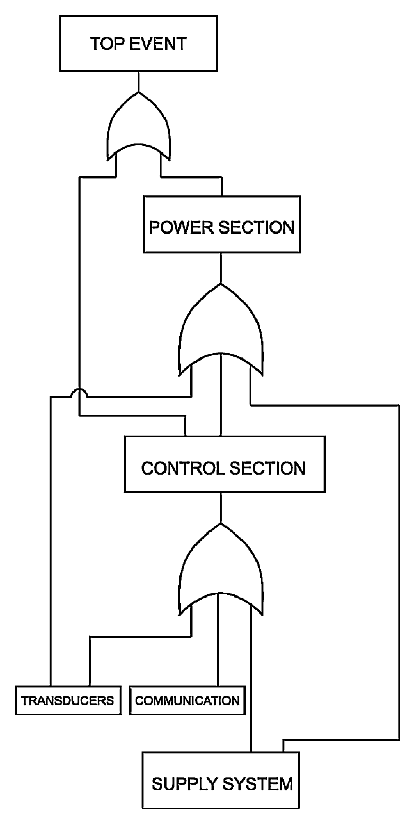

Fig. 9. Fault-tree of the robots of the window-mounting.

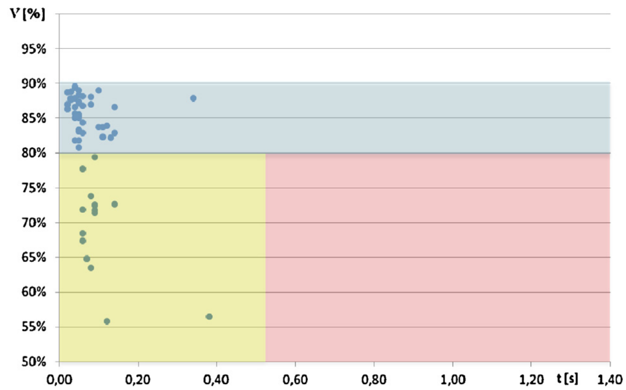

Fig. 10. Scatter plot of the measured voltage sags after the installation of the compensating devices.

Among the devices that compensate for voltage sags in industrial systems [15,17,18], some are discarded immediately. Embedded solutions are not practical because the contract with the robotics company expressly forbids any intervention inside the equipment. In agreement with the Kaizen approach, the flywheel motor-generator sets and the superconducting storage devices are not considered, because it is not necessary to compensate for all of the interruptions. The dynamic voltage restorers were discarded for different reasons. First, their use is not justified for the low electric power that is involved in the control, measurement, and transducing sections. Then, for the power section, the industry managers prefer more commercial solutions that are available from a wide range of suppliers.

To solve the problems of voltage sags in the automotive industry, two different solutions are envisaged:

(i) installing an uninterruptible power supply (UPS) on the control section and on the measuring and transducing units;
(ii) solution (i) plus the addition of a UPS on the power section.

In particular, the first solution requires the installation of three, single-phase UPS of the voltage frequency independent (VFI) type with a size up to about 3 kVA, while the second solution requires, in addition, two, three-phase UPS-VFI up to about 60 kVA. Again, according to the Kaizen approach, the first solution was implemented, which covers only the control and the measuring and transducing units. In fact, a very simple cost-benefit analysis showed that the costs of the proposed solutions were lower than their benefits by three orders of magnitude. Once the three UPS-VFI were sized and rated, they began operation after one month.

The effectiveness of the proposed solution was proven by an ex-post analysis that was performed by assessing the measurements that were collected by the monitoring system installed at the 150/20 kV substation. Fig. 10 shows the scatter plot of the measured voltage sags for one year after the compensating devices were installed. It is evident that several sags occurred in that period; however, there were no interruptions of the assembly process due to the shutdowns of the window-mounting equipment.

6. Conclusions

The impact of voltage sags on a very vulnerable automotive industry was reduced by low-cost compensating solutions. Effective methods for analyzing the measured voltage sags and the registered equipment interruptions were used to attain this very important objective. In particular, using Kaizen criteria, a step-by-step procedure was proposed to select a specific manufacturing unit inside the extensive production area, after which the specific equipment were chosen for the implementation of compensating solutions. A new index was proposed that we refer to as 'Macflu,' which was used as a valuable metric to guide the selection of equipment for the application of compensating solutions. The compensating solutions that were implemented were successful as demonstrated by the ex-post analysis, which lasted for one year after the intervention. At the present time, we are planning to implement the proposed method on additional production units inside the same factory.

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