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Voltage sags in the automotive industry: Analysis and solutions

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A B S T R A C T

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