Effects of Voltage Sags on Industrial Processes: Case Study

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Abstract

A voltage dip (or sag) is a sudden reduction in the supply voltage on one or more phases to a value between 90% and 1% of the reference voltage followed by a voltage recovery shortly afterward. In recent years, interruptions, or failures in manufacturing processes due to the poor quality of energy supplied have attracted the interest of industrial consumers, mainly because these events represent significant financial losses to the industrial sector. The failure of some equipment can lead to a partial or total shutdown of the production chain. In this context, this paper shows a study of the case of a supervisory system that can estimate the process immunity time (PIT) of a machine. The estimation process considers PIT values of each equipment that participates in the operational control of the machine, their supportability curves to voltage sags, and their respective connections (serial, parallel, etc.). The results show that the supervisory system is a useful tool to assist planners during decision-making to reduce operating costs.

Keywords

Voltage sags, Industrial Processes, Industry 4.0.

1. Introduction

Currently, electric energy brings convenience, comfort, and safety for users (residential, commercial, industrial customers). However, interruptions of power supply or when it is supplied with a poor power quality can lead to interruption of manufacturing processes (Cunha & Silva 2003; Hu et al. 2020).

Voltage sag has received more attention at the industrial and commercial facilities because of the malfunctioning of various sensitive equipment, which leads to finance-related issues. According to statistical data, the occurrence of voltage sag is more frequent than other power quality issues (Arias-Guzman et al. 2015; Behera, Banik, & Goswami 2020; Polat, Selim, Yumak, Gul, & Unal 2018). This an important aspect that must be considered so that the industrial sector feels more confident to invest in Industry 4.0.

According to Bollen (2000), electric disturbances are characterized according to their intensities and durations. For example, short-duration voltage variations are defined as a precarious voltage level (sag or swell) during a short period of time (milliseconds). These types of events can cause unintentional failures in electronic devices (also called equipment disruptions or equipment trips) that control industrial processes. In this way, voltage sags and power interruptions are usually the result of faults in the network and switching actions to isolate the faulted sections. In IEEE (1995), voltage sags are defined as a reduction in RMS voltage magnitude between 10% and 90% of nominal voltage during 0.5 cycles up to 1 min caused by faults (short circuits) on the power system or starting of large loads (e.g., motors). Momentary power interruptions cause a complete loss of voltage for a period less than 1 min. They are caused by protective devices (reclosers) in response to faults as attempts to clear non-permanent faults, first opening and then reclosing after a short time delay. A permanent power interruption, in turn, is defined as the decrease in the voltage supply magnitude to zero for more than 1 min. They are generally caused by trees striking lines or poles, storms, or miscoordination of protection devices.

Based on the phases affected during the sag, the voltage sag has been classified into three types: (i) single-phase sags: frequently occurring voltage sags single-phase in events that are basically due to a phase to a ground fault occurring somewhere on the system. On other feeders from the same substation, this phase to ground fault appears as a single-phase voltage sag. Typical causes are lightning strikes, tree branches, and animal contact. (ii) Phase to phase sags: where the two-phase or phase to phase sags are caused by tree branches, adverse weather, animals, or vehicle collision with utility poles. These types of sags typically appear on other feeders from the same substation. (iii) Three-phase sags: these sags are caused by switching or tripping of a 3 phase circuit breaker, switch, or recloser which will create a three-phase voltage sag on other lines fed from the same substation. Symmetrical 3 phase sags arise from starting large motors and they account for less than 20% of all sag events (Kabir & Rahman 2017).

Voltage sags can have different effects on sensitive equipment, such as Adjustable Speed Drives - ASD's, programmable logic controllers - PLC and personal computers - PC, which are widely used in industrial installations (Cruz, Lavega, & Orillaza 2015; Cunha & Silva 2003; Engineering & June 1996). The failure of any of this equipment, can cause a production interruption leading as consequence financial losses in industrial installations.

The loss of industrial users mainly comes from unplanned shutdown caused by accidents. The key to reduce the consequences of voltage sag of industrial users is to maintain process parameters as far as possible and avoid process interruption (Zhuang et al. 2020).

Two aspects related to industrial customers must be considered to assess financial losses with respect to electric disturbances. The first one is related to equipment (for example, PLCs, ASDs, etc.) and the second one is related to production processes which are controlled by their respective equipment. In case of equipment, it is important to understand its behavior when exposed to electric disturbances as voltage sags. The definition of "voltage-tolerance curve" or "supportability curve" is commonly used for this purpose. As reported in EN 50160:2010 and Polat (2018), this curve shows which combinations of magnitude and duration, as two most prominent voltage sag characteristics, can affect the normal functioning of customers' equipment. However, such as pointed out by Milanovic (2006), Honrubia-Escribano (2012) and Yasir (2012), since equipment is from diverse manufacturers and bear different behaviors, it is almost impossible to represent equipment through a single voltage sensitive curve. Thus, a better representation uses a "voltage sensitivity range" with an uncertainty region between an upper and a lower voltage sensitivity curve.

For the estimation of process behavior with respect to voltage sags, the industrial machine under analysis is segregated into equipment that participates in each functionality. Therefore, each equipment is associated with its respective supportability curve. This curve features two parameters: the residual voltage (Vsag) and the equipment failure time (Tsag) during a voltage sag. Thus, supportability curve for the industrial machine under analysis can be assessed according to the equipment connection (series, parallel and mixed). A serial connection of 6 devices is shown in Figure 1.



Figure 1: Structure of the serial process.

This case represents an industrial process of a conveyor belt consisting mainly of: a power supply, a PLC, a Human Machine - HMI interface, a frequency inverter, a sensor and a power contactor. The calculation of the probability of process stop or failure (U_{nPT}) is defined by the equation:

$Un_{PT} = 1 - (1 - P_{device1}) * (1 - P_{device2}) * (1 - P_{device3}) * (1 - P_{device4}) * (1 - P_{device5}) * (1 - P_{device6})$

The P_{device} values represent the probability of failure of each equipment, depending on the values of Vsag and Tsag and PIT. To identify the PIT value of the entire industrial process, it is essential to identify the most critical device, that is, with the lowest PIT. Each device is related to the most important process parameter (Pp) to analyze its impact. Thus, each Pp controlled by a device has a curve that determines its behavior in the face of a voltage dip as shown in Figure 2.



Figure 2: Behavior curve of a process parameter in the face of a voltage dip.

Where:

Pnom: Process Parameter nominal value

Pmin: Minimum value at which the process can operate

T: Start of the deviation from the nominal value. Failure of the device that controls the process

TPUP: Time when the process cannot be maintained, needs to be stopped or restarted

 $T + \Delta t$: Start of steady fall

The failure of some of this equipment can lead to the imminent partial or total shutdown of the production system, which represents significant financial losses in industrial installations. Thus, this paper proposes a supervisory system capable of estimating the PIT of a machine, based on the PIT values of each equipment (PLC, contactor, adjustable speed drive - ASD, etc.) that participates in the operational control of the industrial process and their respective connections.

2. Case study

In this paper, a conveyor belt process is used as example to illustrate the proposed methodology, this one is formed mainly by: a source, a PLC, an HMI, a Frequency Inverter, a sensor and a power contactor. The PLC is responsible for the programming logic of the belt operation; the HMI is responsible for visualizing the process, inserting which devices will be needed for the process, as the ASD has the purpose of controlling the speed of the conveyor belt, the sensor has the purpose of identifying the presence of product on the belt and sending an electrical signal for the PLC. In Totally Integrated Automation Portal (IAT Portal), Siemens Step7 CPU-314C-2PN / DP PLC programming software, connected by profinet communication cable to a model HMI: Simatic Panel Siemens Touch KTP600 Color.

In the "Main Screen", the following texts are created:

• 8 textfield's: "Choose process devices", "Device 1", "Device 2", "Device 3", "Device 4", "Device 5", "Device 6", "Total Time";

• 6 Symbolic I / O field's - Mode Input. The Vector is a method is to store several values in which a variable can assume. Each Instance with 6 vectors:

➢ Vector 0: CLP;

- ➢ Vector 1: HMI;
- Vector 2: Contactor;
- Vector 3: Sensor;
- Vector 4: Inverter;
- Vector 5: Source;

• 1 Symbolic I / O field's - Mode Output: It displays the calculated time;

• 1 Button - Mode Text: Command button to perform the calculation

The "Time Screen" is displayed when pressing the F6 key of the HMI and it was created in it:

• 7 textfield's: "Enter the support time for each device", "CLP", "HMI", "ASD", "CONTACTOR", "SOURCE" and "SENSOR";

• 6 Symbolic I / O field's - Mode Input: Where the support times for each device are inserted.

The programming is developed in the IAT- Portal software of the PLC. In the programming block of the software, a FUNCTION programming page [FC1] is created, named ENERGIA SINK. Briefly, each line of programming is named Network. From Network 1 to 7, the global variable is linked to the local variable. The global variable receives the value entered in the HMI and through a MOVE block, the value is moved to the local variable. This procedure is performed for each device in the process.

The "Main Screen" has 6 I / O field's, and within each I / O field, 6 devices can be chosen according to the need. Programming is carried out for each possible combination within each device. Each device in the process received a vector number, i.e., CLP = 0, HMI = 1, CONTACTOR = 2, SENSOR = 3, ASD = 4, SOURCE = 5. When the vector is selected, the program links the chosen variable to a memory that is used to perform the sum of the timing. The programming for the link of each device is written as follows:

In the main screen, a "Calculate" button performs the operation mathematic operation (PIT) that is performed through a function block called ADD, which was created through the Struction List, as shown below.

| A(| | | \ first condition AND | | |
|-----------------|------------------------|--|--|--|--|
| A | \ second condition AND | | | | |
| A | \third condition AND | | | | |
| А | (| | \ fourth condition AND | | |
| А | "CALCULAR" %M50.0 | \ the calculation of the PIT is done by activating Bit M50.0 | | | |
| ٦L | IB Label_36 | | | | |
| L | "DEVICE 1 CARREGADO" | %MW14 | \carries "Pdevice1" value in memory word MW14 | | |
| L | "DEVICE 2 CARREGADO" | %MW16 | \ carries "Pdevice2" value in memory word MW16 | | |
| +1 | | | | | |
| Т | #"SOMA 1 E 2" | | $\ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ $ | | |
| А | N OV | | | | |
| SA | AVE | | | | |
| C | _R | | \ set clear value | | |
| Label_36 : A BR | | | | | |
|) | | | | | |
| ٦L | IB Label_37 | | | | |
| L | #"SOMA 1 E 2" | | \ load the sum of "Pdevice1" and "Pdevice2" | | |
| L | "DEVICE 3 CARREGADO" | %MW18 | \ carries "Pdevice3" value in memory word MW18 | | |
| | | | | | |

T #"SOMA 1 2 E 3" \performs the sum of "Pdevice1", "Pdevice2", and "Pdevice3" AN OV SAVE CLR \ set clear value Label 37: A BR) JNB Label_38 #"SOMA 1 2 E 3" \load the sum of "Pdevice1", "Pdevice2", and "Pdevice3" L "DEVICE 4 CARREGADO" %MW20 \ carries "Pdevice4" value in memory word MW20 L +I T #"SOMA 1 2 3 E 4" \ performs the sum of "Pdevice1", "Pdevice2", "Pdevice3", and \"Pdevice4" AN OV SAVE CLR \ set clear value Label_38 : A BR) JNB Label 39 L #"SOMA 1 2 3 E 4" \load the sum of "Pdevice1", "Pdevice2", "Pdevice3", \and "Pdevice4" \ carries "Pdevice5" value in memory word MW22 "DEVICE 5 CARREGADO" %MW22 L +1 "SOMA 1 2 3 4 E 5" %MW40 \performs the sum of "Pdevice1", "Pdevice2", "Pdevice3", \"Pdevice4", Т and "Pdevice5" AN OV SAVE CLR \ set clear value Label 39: A BR) JNB Label_40 "SOMA 1 2 3 4 E 5" %MW40 \ load the sum of "Pdevice1", "Pdevice2", "Pdevice3", 1 \"Pdevice4", and "Pdevice5"

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| L | "DEVICE 6 CARREGADO" | %MW38 | \ carries "Pdevice6" value in memory word MW38 |
|----|----------------------|-------|--|
| +I | | | |
| Т | "TEMPO SERIE" %MW10 | | \ performs the sum of "Pdevice1", "Pdevice2", "Pdevice3", \"Pdevice4", "Pdevice5", and "Pdevice6" |

Label_40 : NOP 0

3. Results

The supervisory system is applied to conveyor formed by a CLP, a HMI, an Inverter, and a Contactor. This system has two screens: "Main Screen" and "Time Screen" for insertion of the process devices and the values of the support times of each device, respectively, as shown in Figure 3 (ab).



Figure 3: Supervisory screen developed.

Once the support time for each device has been inserted, they are stored in memory so that the immunity time to the process is automatically calculated. The system allows you to enter values for the supportability time of each device, once the values are included, the system automatically calculates the probability of process stop or failure (Un_{PT}) and the immunity time of the entire process (PIT). The devices for the operation of a conveyor belt were selected according to Figure 4.

Determining the values of the sensitivity levels of the devices is a difficult and complex task, since we should consider the installation of measuring equipment connected directly to the machine. Some levels of sensitivity were determined from case studies conducted by EPRI (Electric Power Research Institute), ANSI (American National Standards Institute) and IEEE (Institute of Electrical and Electronics Engineers) of the SIDAQEE Project:

a) Ambient conditioning equipment

These have a very high sensitivity to sinking, when they reach levels around 80% of the nominal, disregarding the duration period.

b) Activation in direct current and electronic power

Used on a large scale in industrial processes. It is important to maintain quality in the supply of energy for these loads. Based on preliminary monitoring results, it is sensitive when the voltage is reduced to close to 88% of the nominal, that is, it has a high level of sensitivity.

c) PLCs - Programmable Logic Controllers

Older programmable logic controllers are less sensitive and allow zero voltage for up to 15 cycles. However, the most modern ones, equipped with more sophisticated electronics, begin to present problems in the range of 50% to 60% of the nominal voltage.

d) Robotics equipment

Robots generally require a strictly constant voltage to ensure proper and safe operation. Therefore, these machines are often set to go out of operation or disconnected from the distribution system when the voltage reaches levels of 90% of the nominal.

e) Computers

Computers are the main source of concern when it comes to sinking, since the data stored in memory can be totally lost under undesirable undervoltage conditions. Thus, tolerance limits for computers related to disturbances in the electrical system were established by ANSI / IEEE.



Figure 4: Example of a conveyor belt with the command-and-control elements.

To define the PIT of the case study, values of PIT of CLP, HMI, Inverter, and Contactor are compared. The lower values among them are 500 ms regarding to frequency inverter. Thus, considering the sensitivity curve and the sensitivity region of the device that presented the PIT of 500 ms and random data (Tsag = 650 ms; Vsag = 0.5 pu; PIT = 500 ms). The probability of machine failure is obtained from PIT data and equipment sensitivity data. The probability of failure is 80% when submitted to the scenario as shown in Figure 5.



Figure 5: Machine failure probability value.

Once the time values of the sensitivity to the sinking voltage of each device in the production process are known, we generate a database collected from equipment analysis and data issued by equipment manufacturers. By entering the values, it is possible to obtain the PIT values constantly without the need for a measuring device.

4. Conclusion

The development of a program capable of generating the total time of support to the voltage sags, coming from the electricity distribution network, is essential to keep the productive process efficient, without stoppings and, consequently, without repeated sets up.

The immunity of an industrial process allows to analyse its operational continuity during a voltage sag. Different processes or similar processes may have different characteristics, thus, to identify the immunity of a process, it is necessary to identify the most critical equipment within a process. The process immunity time - PIT defines the operational inertia of the production process with respect voltage sags. PIT is quantified after the failure of the equipment that controls the process. Process immunity is directly proportional to the PIT value.

In this way, the development of this programming allows the visualization of the total time of support of the process, being able to assist corrective and preventive actions to reduce financial losses with respect to unexpected production stoppings caused by voltage sags.

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7. Biographies

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