Technical and economical assessment of the effect of voltage sags on adjustable speed drives

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Abstract. This paper describes a method for the evaluation of the economical losses caused by voltage sags in an industrial facility in which the presence of adjustable speed drives (ASD´s) is significant. The nature of the data that must be provided in order to have practical information about system reliability at the point of common coupling (PCC) is analysed in detail. Then, the adequate methodology for considering the technical and economical consequences of voltage sags on the production is described for the case of critical drives.

The analysis that is carried out in this work is also useful for making critical evaluations on the interest that the different solutions (ride-through alternatives) oriented to the improvement of performance of these apparatus can have in a particular case.

Key words.

ASD’s, sags, ride-through capability.

1. Power system quality required data for the estimation of the number of failures

The mechanism through which a voltage sag can caused a failure in an ASD is not always the same. The presence of an overcurrent in the moment of the recovery of the voltage is one of this mechanisms and it should be considered if a good performance is required. Motor deceleration during the sag, can lead the production process to fail, even if the electrical parts of the machine can ride-through it. Nevertheless, the most usual cause of failure consists on the actuation of a low voltage protection relay. This relay is usually placed on the DC bus and it monitors this DC voltage ordering the disconnection of the drive in the case of undesirable low voltage levels in order to protect the apparatus both in the control and power stages.

At the present time no clear standards exist on the format in which voltage sag information of a particular location must be presented. In fact this matter is nowadays a great concern and several groups such us the IEEE PES & IAS Task Force (P1564) are working hardly on it. The most known curves such us CBEMA or ITIC have severe limitations on showing sag information as they only take into account its duration and depth. Other information such us phase angle jump or point on wave of sag initiation can be of importance for certain loads (e.g. relays). Fortunately, this voltage sag characteristics do not have significant importance in the case of ASD’s. The same can not be said in relation with the three-phase character of voltage sags, crucial aspect that is neglected by the above-mentioned representations.

Due to the three-phase nature of the loads considered in this paper, the thee-phase nature of the voltage sags should also be taken into account. The voltage sags classification presented in [1] will be adopted, as it is one of the most important references that are being taken into account in the elaboration of standards. This classification leads us to consider that every voltage sag event affecting an ASD can be classified among types A, C or D. Making this distinction, a duration/depth representation of the sag is then possible. The performance of the ASD will be completely different depending on this classification, so whatever serious consideration of this phenomenon should have it into account.

There are two main different ways of collecting the required data related to the presence of voltage sags in the PCC of the installation under study. On one side, a monitoring program, with the correct extension (this is not an easy matter [2]), can lead to reasonable accurate estimations of the electrical environment. On the other side, the possibility of making probabilistic studies should not be discarded. In this case, starting from a good knowledge of the configuration of the electric system and its protections together with the lightning density levels of the area, a good estimation can also be achieved.

Whatever the source of this information will be, we must determined first, what are the minimum data that will be necessary in order to achieve the objective proposed in the introduction of this paper. According to what we have remarked above, a representation of the type of the CBEMA curve will be adopted in order to show the duration/depth characteristics of the different events. Nevertheless, a different curve will be necessary for every voltage sag type due to its different effect in the

https://doi.org/10.24084/repqj02.314

ASD's. Then we can make a distinction between 3 sources of data according to the voltage sag types A, C, and D, which are the only ones of interest in this kind of loads. For every one of these types of voltage sags we will consider its duration (with a conservative criterion the largest duration of the three phases will be consider), and its depth (in the same way the phase of lower voltage during the sag will be taken into account). Figures 1, 2 and 3 shows an example of every voltage sag type, by the representation of the evolution of the line voltages during the event.

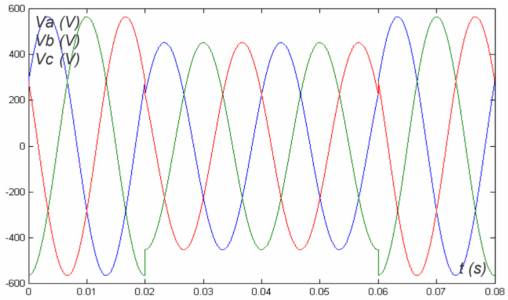

Fig. 1. Voltage sag type A. Duration 40ms. Depth 80%.

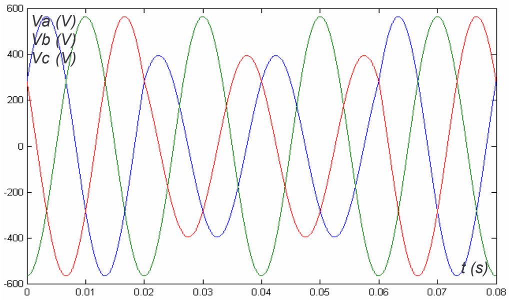

Fig. 2. Voltage sag type C. Duration 40ms. Depth 70%.

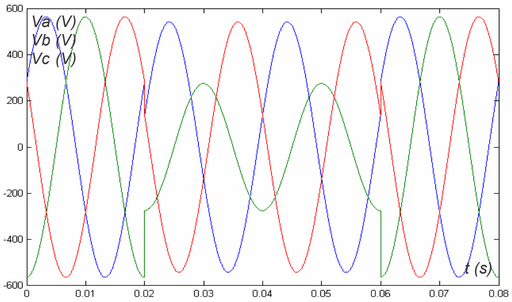

Fig. 3. Voltage sag type D. Duration 40ms. Depth 40%.

As one can noticed, the procedure of register of the information is quite simple and can be carried out by near any commercial power quality monitor. To classify a particular sag on types A, C or D, it is enough to consider if the lower voltage line value occurs simultaneously in 3, 2 or 1 phases.

In the most favourable case, the data will be offered to the engineering staff as probability density functions of occurrence of voltage sag events. Figure 4 shows an example of these functions. As one can see, they are defined in the range that concerns to voltage sags events, that is depths from 0 to 90% and durations from a half period to a minute. The integration of these functions on the whole interval gives the number of events of a certain type expected in the PCC during a year. Voltage sags of type A, are the less common ones, as they are caused by symmetrical three-phase short-circuits. On the other hand they are the most damaging ones, as they have the biggest probability of causing the trip of the machine. Voltage sags experienced by ASD's of types C and D are caused by single-phase and phase-to-phase faults and its transformations in the power system to lower voltage levels due to transformers connections.

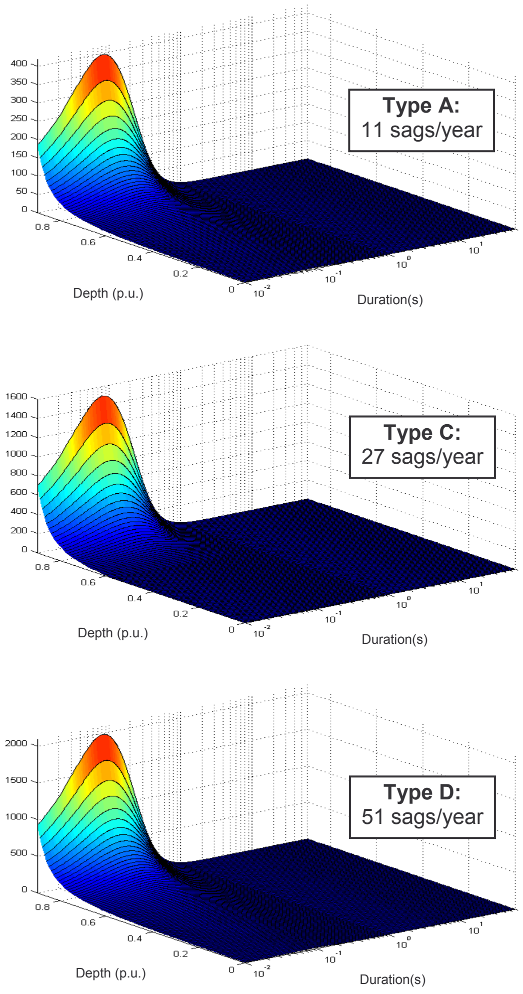

Fig. 4. Probability density functions of A,C and D voltage sag types

2. Assessment of ASD's tolerance to voltage sags

It is possible to determine if any point on a duration/depth voltage sag representation will produce failure or not in a particular machine, according to the above-mentioned classification. This allows us to evaluate the coordination between the electric environment and the electric equipment. Let us make a brief description of the internal parameters that have a major influence in the ride-through capability of an ASD.

DC-bus capacitance (C)

It is well known that adding an amount of DC-bus capacitance to an ASD, enlarges its tolerance to voltage

https://doi.org/10.24084/repqj02.314

sags. The reason is quite simple; a larger capacitance implies a larger reserve of energy, and then a better capacity of working without supply for a larger time. Capacitance levels between 75-360 μF/kW are usual in modern ASD's [3].

Threshold level of the minimum voltage relay (V_{DCmin})

During the operation of the ASD in the presence of a voltage sag, the voltage on the DC-bus decreases progressively. If the operation of the apparatus (both in the control and power stages) can be carried out at lower DC voltages, then the setting of the protection relay will be lower too. This aspect contributes decisively to an improvement of the ride-through capability of the device.

Operating power (P)

The level of the power demand of the ASD determines the maximum duration of every voltage sag type that it can put up with. The reason is that this parameter together with the DC-bus capacitance determine de decreasing rate of the DC-bus voltage.

The influence of the abovementioned parameters can be easily understood for the case of a voltage sag that isolates the apparatus from the supply network. The discharging process that takes place in the capacitor is ruled then by equation 1. This equation shows the maximum time (t_{max}) that the machine can stand in operating mode before tripping.

$$t_{max} = \frac{C\left(V_{DCo}^{\ 2} - V_{DCmin}^{\ 2}\right)}{2P} \tag{1}$$

In this equation V_{DCo} is the DC-bus voltage at sag initiation.

Figure 5 shows the value of t_{max} as a function of V_{DCmin} for different common values of the rate C/P for an ASD with a rated voltage of 400V, assuming an ideal V_{DCo} value.

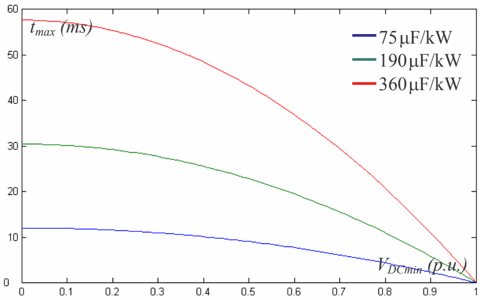

Fig. 5. Maximum tolerable voltage sag duration for an ASD as a function of V_{DCmin} and the ratio *C/P*

Series line input reactors (L)

These AC-side inductances are frequently used in this type of drives with the aim of reducing the harmonic contents on the supply and the diode peak currents. Furthermore they reduce nuisance tripping of ASD's due to capacitor switching transients and voltage unbalance. An addition of 2-5% of line reactors is usually suggested [4].

These AC side reactors do not have a remarkable influence in the behaviour of the apparatus when facing voltage sags of type A, because the ASD operates practically isolated from the supply in this case. (Nevertheless the reduction caused by these reactors on the pre-sag DC-side voltage can be important). On the other hand their influence in type C voltage sags is significant. In this case the bridge enters in a single-phase operating mode, and the filtering AC level can cause important reductions on the DC-bus voltage that could result in the actuation of the relay [4].

As a general rule it is widely accepted that voltage sags of type A are the most damaging ones for ASD's. As one can see in figure 5, if the depth of the sag is enough to reach a value below V_{DCmin}, the usual levels of capacitances used nowadays do not allow the ASD to operate during the sag for more than a few periods before tripping (at least in the case of working at rated power).

Voltage sags of type C can hardly cause the failure of a drive. In this type of sags, the value of one of the line voltages remains unchanged and this make that the decay of normal DC-bus voltage is very small. As a consequence the operating values remains very close to those on the pre-sag situation. Only an abnormally small capacitance or an excessive AC inductive filtering together with an operation at full load can lead to a trip in this case.

When a voltage sag of type D occurs, the three line voltages go down. Nevertheless two of them have always a moderate drop (ideally these two voltages can not be lower than 86% of its pre-sag values). As a consequence, considering reasonable levels of capacitance on de DC-bus, this sort of trips could be avoided if the apparatus is designed to operate with a DC-bus voltage close to 60% of its rated value. Unfortunately this is not a usual practice in commercial ASD's.

Simulation tools based in the time domain are a useful method when trying to evaluate the effect of a voltage sag on a particular drive. This solution has been adopted by the authors of this paper. Nevertheless, other analytic procedures, which theoretical bases have been outlined above, can lead to very accurate estimations, if some simplifications are considered.

3. Estimation of economical losses caused by voltage sags

If we consider a particular drive (with its characteristic parameters of capacitance, AC line reactors, and minimum DC-bus voltage) operating at a certain load level, it is possible to determine in the most general case three compatibility curves to voltage sags, corresponding to types A, C and D. As it was stated in the previous section, it is usual that one or even two of these curves do not actually exist, as for example type C sags are expected to cause failure in no case. An example of this curves are shown in figure 6. One can notice in this figure that the curve corresponding to type C starts from a minimum supply line voltage of 57% because lower levels are not defined for this type of sag.

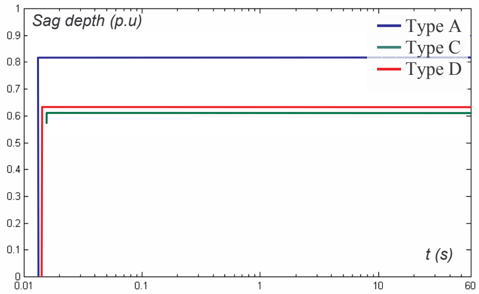

Fig. 6. Compatibility curves of an ASD for the different voltage sag types

Taking these curves into account and considering the probability density functions of every voltage sag type, is now quite simple to make an evaluation of the number of failures per year expected in the machine. The application of equation 2 will help us in facing up to this task.

$$N = \sum_{tp\in[A,C,D]} \left(\iint\limits_{\substack{0.01\le t\le 60 \\ 0\le d\le 0.9}} f_{tp}(t,d)\cdot s_{tp}(t,d)dtdl \right) \tag{2}$$

In this equation, N is the total number of failures expected per year, f_{tp} is the probability density failure function associated to voltage sags of type tp, and s_{tp} is a surface associated to each compatibility curve that has a unity value in the internal points of the curve and has a null value in the rest of the interval. The variables t and d stands for the duration and the depth of the sag respectively.

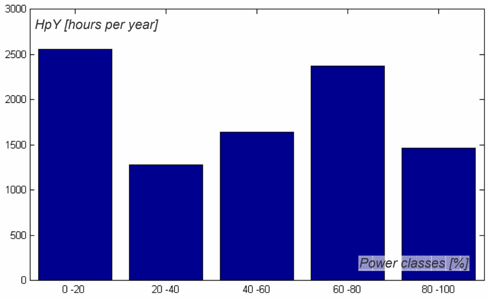

Fig. 7. Annual distribution function of the power demand of the ASD

If we pretend to take into account that an ASD rarely operates always at the same load level, the above equation needs to be more general. Let us consider then a certain distribution function of the power demand of the machine during the year as the one showed in figure 7 (HpY stands for the number of hours per year at a certain load level). An approximation to this distribution will be obtained considering either the diary, weekly o seasonal operating mode according to the particular application.

In this new situation the influence of the value of the load level in each interval on each compatibility curve must be considered, as the immunity area goes larger as the power demand decreases. The new formulation that should be used for this case is shown in equation 3.

$$N = \sum_{i\in R} \frac{HpY_i}{8750} \left(\sum_{tp\in[A,C,D]} \left(\iint\limits_{\substack{0.01\le t\le 60 \\ 0\le d\le 0.9}} f_{tp}(t,d)\cdot s_{tpi}(t,d)dtdl \right) \right) \tag{3}$$

In this equation R stands for the set of different power classes and s_{tpi} stands for the compatibility surface assigned to each voltage sag type on each power class.

Let us considerer now as an example a situation close to reality in which voltage sags of types C can be neglected for the abovementioned reasons. The data that will be taken into account concerning the rated values, internal configuration and AC filtering level of the machine are shown in table I.

TABLE I. – ASD data

Rated Voltage (V_N)	400V
Rated Frequency (f_N)	50Hz
Rated Power (P_N)	11kW
DC bus capacitor (C)	1,0mF
AC line filter (L)	2%
Min. voltage trigger level (V_{DCmin})	420V

If we take into account the probability density failure functions showed in section 2, and we consider the device operating at rated power continuously, the application of equation 2 demonstrate that 11.76 failures per year are expected. Now, considering the discrete distribution of power demand showed in figure 7, and using equation 3, this number of failures is limited to 6.98. This result is a good evidence of the importance of the working cycle of the machine on these estimations. A more detailed description of these results is presented in table II, where F100 stands for the total number of failures per year with full time operation at rated power and FAWC stands for the number of failures considering the actual working cycle of the drive.

TABLE II. – Number of failures per year caused by sags

	TOTAL	F100	FAWC
Type A	10.21	5.43	5.13
Type D	51.03	6.33	1.85
All types	61.24	11.76	6.98

To illustrate the calculation process, one of the addends considered in equation 3 is showed in figure 8 by means of the volume under the represented surface. Specifically this addend correspond to the one associated to the interval 40-60% of the demand power for type A voltage sags.

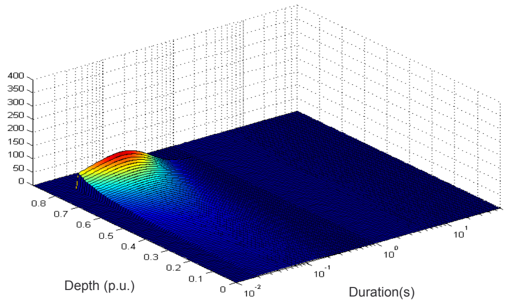

Fig. 8. Addend on the calculation process carried out to evaluate the number of failures at each power interval

Starting from the total number of failures per year, and considering an economic study carried out by means of the data obtained from the production department, the estimation of the financial losses that can be attributed to the presence of voltage sags in the factory is now immediate.

This is in its own a crucial information when trying to make a serious study of the economical feasibility of applying solutions oriented to the improvement of the susceptibility of the plant to voltage sags. Moreover, this methodology can be a valuable tool to help the company to update contracts in the current liberalization energy market.

4. Evaluation of ride-through alternatives to improve performance

There are different solutions that a factory can adopt when trying to mitigate the negative influence of voltage sags in the production due to the tripping of ASD´s. Some of these solutions are of global nature (at plant level). Among these are the well known DSTATCOM (Distribution Static Synchronous Compensator), the DVR (Dynamic Voltage Regulator) or the most complete UPQC (Unified Power Quality Conditioner). All of them lead to enormous investments, and nowadays its use is only interesting for very specific sectors of the industry with a special concern on these problems (e.g. semiconductor production plants). Other types of solutions are of local nature, and can be implemented directly on the problematic ASD. These will be the ones considered in this section.

There are methods of improving the susceptibility of the apparatus as simple as enlarging the capacity used in the DC-bus. The methodology described in this paper allows a quick economical evaluation of the convenience of adopting such a solution. Other solutions can also be evaluated, such as enlarging the inertia of the drive [5] or making a design oriented to a low speed or low load operating point.

Figure 9 shows the evolution of the estimated economical losses caused by voltage sags in a facility due to a critical ASD for different values of the installed capacitance in the DC-bus. As a simple approximation the losses caused by each nuisance tripping has been evaluated here in 2000€.

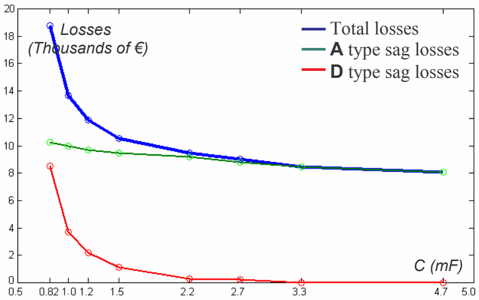

Fig. 9. Economic looses caused by voltage sags as a function of DC-bus capacitance

The actuation that should be undertaken has to be determined by a comparison between the estimated annual losses and the costs that will imply the corrective system. Nevertheless not only the direct costs must be considered (ex: cost of the additional capacity), but also other ones that the new configuration will caused (ex: redesign of the protection system).

5. Conclusion

The economical impact of voltage sags on factories with an intensive use of ASD´s is nowadays a matter of great concern. A serious estimation of the consequences is nevertheless not simple.

The task is even harder due to the lack of a standard that fix the format in which the information on voltage sag events in a particular PCC should be presented.

The authors have then selected the information that result more relevant in the task of estimating the number of failures per year in a particular machine or factory. The simple consideration of the well known CBEMA curve will lead to an unacceptable overestimation of the number of tripping events, making the study very poor from the economical point of view.

From the selected data, a deep knowledge of the internal performance of the drive, allows to make a very accurate estimation of the behaviour of the apparatus when faced to every voltage sag event. A simple compilation of user accessible internal parameters of the ASD will permit the application of this methodology.

The effect of the actual working cycle of the drive has been remarked, as it can deeply determinate the final results. Every analysis that considers the ASD`s operating always at rated values will highly overestimate the final results.

The methodology developed in this paper allows making an economical evaluation of the most common solutions used to achieve an improvement on the ride-through capability of this type of apparatus.

Acknowledgement

The works that have lead to the publication of this paper have been financed by the Spanish Science and Technology Ministry through the National Plan of Scientific Research, Development and Technological Innovation (I+D+I) by means of the project with reference DPI2002-04416-C04-03.

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