DETERMINATION OF MAXIMUM TIME NEEDED FOR MOTORS TO RESTART AFTER A PERTURBATION

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ABSTRACT

Voltage sags and short interruptions represent more than 85% of industrialist complaints to utilities, for the huge economic losses they suffer due to such perturbations. In order to protect production lines, industrialists normally determine the immunity curve of the whole production process. The complex immunity curve is obtained by combining the curves of all sensitive equipment involved in the production process. Process controllers, measuring devices, switches, and all equipment of low-power consumption, are usually considered sensitive equipment. Given the sensitive equipment dropout characteristics, mitigation measures can be planned to keep the production line control. A simplified analytical methodology is presented, that allows industrialists to determine the maximum duration that their production-line sensitive equipment must be kept in-condition for a successful process to restart. The methodology can include both the system hot-load pickup and the shedding scheme data. The interaction between immunity, shedding, and load pickup can be easily assessed by applying the proposed technique.

INTRODUCTION

Voltage sags and short interruptions are the two most important transient power quality events that represent more than 85 % of industrialist complaints to utilities for production disruptions. Published studies have shown that nearly 50 % of such events are originated inside the customers´ circuits. Each production halt generates economic losses of $10,000 on average [1].

Due to high production losses, industrialists conduct studies to determine immunity curve of the whole production process, which is obtained by combining the curves of all sensitive equipment involved in the process. The immunity curve is a graph of voltage magnitude versus dropout-time. The most widespread used and standardized one is the CBEMA or ITIC graph. The most sensitive equipment is identified and mitigation measures adopted, as shown in Figure 1 which illustrates three immunity curves and the number of events associated with each.

The first steps of the progressive mitigation can be easily done through the use of interfaces (or backup devices) such as UPSs whose technical characteristics depend on the load represented by the sensitive equipment and the corresponding backup time. The best economical and technical behavior and recovering possibility of the

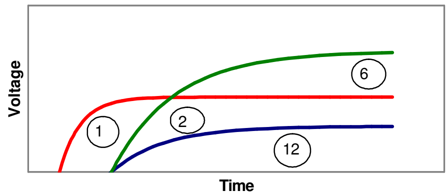

Figure 1 Individual and combined immunity curves.

production lines are obtained by keeping motors connected during this type of perturbation [2]. The solution has raised concern of motor and equipment manufacturers who claim that damaging torques and currents are generated when contactors are kept closed during the perturbation [3]. The question that arises when applying this policy is: for how long the sensitive equipment must be kept under operating conditions or on standby? The answer is simply "while the production line is in a situation of obtaining a post-perturbation successful restart." The duration depends mainly on the behavior and operating state of the high-inertia components (motors and propelled machinery) of the production line during and after the perturbation, in conjunction with the supply system characteristics. The thermal effect of the restart process must be also considered because if it is too long, the windings high temperature can damage the motor. Depending on the mechanical load of the production line characteristics and on the phenomenon under study, there are limiting conditions which if surpassed the process should be stopped due to the impossibility of getting back into the steady-state mode. The speed drop of the most critical component is the most commonly used limiting condition.

One aspect that needs careful analysis is the perturbation probability of occurrence, from both voltage magnitude and duration viewpoints. Several surveys have been published, where the most probable values can be assessed. For instance, voltage sag amplitude between 50 % and 80 % and durations from 5 to 20 cycles, and occurrence frequency of 20 – 25 events per year are typical values [4, 5].

TRANSIENT BEHAVIOR OF MECHANICAL LOADS

The transients that must be studied in order to determine the mechanical load restart ability are: behavior during voltage sag, behavior during short interruptions, and behavior when the full voltage magnitude is recovered (after voltage sags or short interruptions).

Behavior during voltage sags:

For the present analysis it is considered that during the perturbation the motor contactor is kept closed by an auxiliary device. When the voltage sag starts, the supply voltage-drop generates a torque reduction proportional to the square of the voltage. Therefore, the speed decreases by an amount that is a function of the voltage magnitude and motor mechanical load until a new equilibrium is reached, if any – otherwise, the motor will stall as a result. Generally it is assumed that voltage sag is of constant magnitude (rectangular perturbation), consequently the induction motor is transformed into an induction generator, hence smoothing – initially and finally – the voltage variation, as shown for the experimental results given in Figure 2 [6, 7].

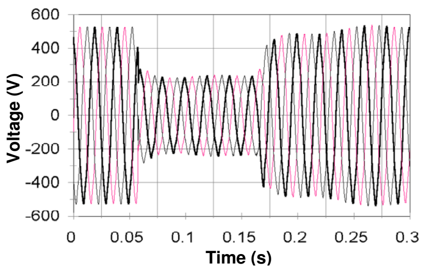

Figure 2 Motor terminal voltages during voltage sag.

This effect is done by initially supplying current to the perturbation origin, because its back emf is temporarily higher than the supply voltage. At the end of the voltage sag duration, energy is absorbed from the supply to recover the pre-fault conditions. The energy used for this extra supply and demand is extracted from the unbalance between the pre-perturbation, on-perturbation, and after-perturbation kinetic and magnetic energies involved.

The induction motor operating as induction generator, depending on the location of perturbation origin, could supply significant currents to the cause (fault or overcurrent). The current share would be high for nearby faults (closed circuit), being practically an open circuit for far faults, as shown in Figure 3 which was experimentally obtained for bolted faults. Therefore, as shown in Figures 2 and 3, voltage and current variations approximately follow exponential curves.

The main cause of voltage sag are short-circuit faults that are mostly of single-phase type, thus unbalanced perturbations are more the rule than the exception. Also, a speed drop follows an exponential curve with small oscillations, which can be approximated to an exponential curve. Conversely voltage drops follow an exponential process having two time constants or one combined time constant, corresponding to both electromagnetic and mechanical phenomena. For studies of voltage sags with very low magnitude, the relatively low value of the electromagnetic time constant – in comparison with the mechanical time constant – can be ignored without

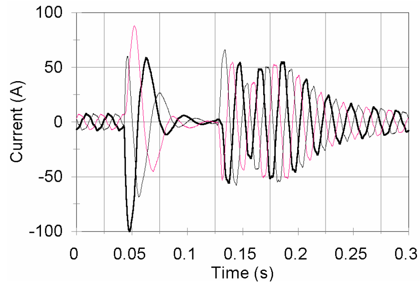

Figure 3 Motor current during voltage sag.

introducing significant error. Therefore, apart from the electromagnetic variation, the speed drop is given by [8]:

$$\omega(t) = \omega_s e^{-\tau_1 t} + A (1 - e^{-\tau_1 t})$$

where A is a function given by:

$$A = (V^2 - \omega_s R_2 T_L) / (J \omega_s R_2)$$

ω_s = synchronic speed
V = supply voltage
τ_1 = mechanical time constant
R_2 = rotor circuit resistance
T_L = resultant torque
J = moment of inertia.

Analytically, the process of speed change is considered as a combination of two phenomena. First, the speed drop without supply up to standstill exclusively ruled by the kinetic stored energy and a time constant given by the rotating elements losses. Second, the speed recovery up to the value determined by the point of intersection of the electromagnetic-torque and resistant-torque curves [9]. Figure 4 shows the total speed variation and its two components.

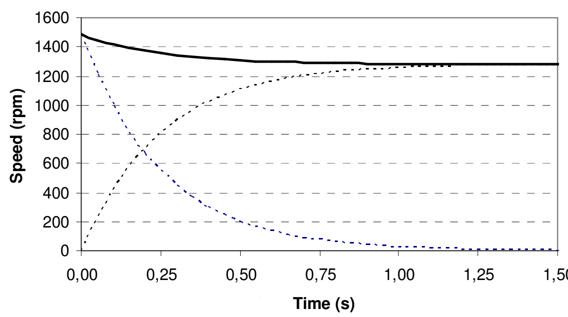

Figure 4 Speed drop during a voltage sag.

The speed reached is a function of the perturbation magnitude and duration. Figure 5 shows the slip increase as function of voltage-sag magnitude and duration presented elsewhere [10], for slips of 1%, 5% and 10 %, respectively. Both methodologies can be used for the determination of the voltage sag final speed and possible equipment recovery as a function of voltage sag magnitude and duration. The thermal effect of on-sag current must be verified especially for deep and long perturbations. In general, this overcurrent is not a limiting factor for the subsequent restart [6].

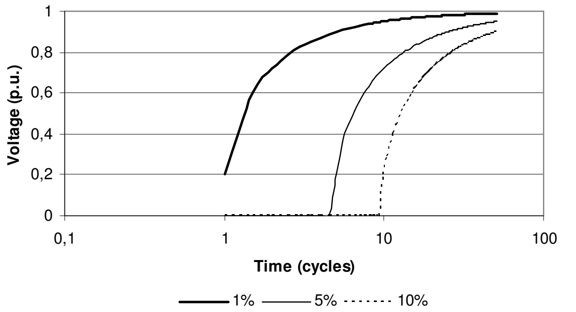

Figure 5 Voltage magnitude vs. duration for slip increase of 1, 5 and 10%.

Behavior during short-interruptions:

This case has been studied by several researchers, especially for assisted motor starts, using circuit breakers programmed with reclosing schemes, and transfer-switch applications [11]. Most of the published studies consider that short interruptions happen without current flowing through motor winding, which is true only when the circuit opening is located at – or close to – the motor terminals. With open terminals (and no winding current) during short interruptions, the motor and connected load will *coast*, reducing the back emf and speed. Voltage drop will depend on both electromagnetic and mechanical time constants, but speed drop will be determined only by the mechanical load, thus in this case only one time constant need to be considered. Figure 6 shows the voltage drop (rectified waveform) as time function, where the initial sudden drop in the back emf – and the following smooth exponential drop – can be seen. Since the motor is under no-load condition, speed drop is hardly noticeable. Both back emf and speed drops can be simply emulated by exponential curves, where it is only necessary to determine both time constants.
Figure 7 shows the back emf variation (open circuit) for two different mechanical load conditions, where the voltage and speed drops cause phase differences at the reclosing instant. Figure 8 shows the voltage differences as time function obtained by using voltage and speed drop time constants, where the maximum recommended delay can be determined, e.g., 142 ms for 1.33 p.u.

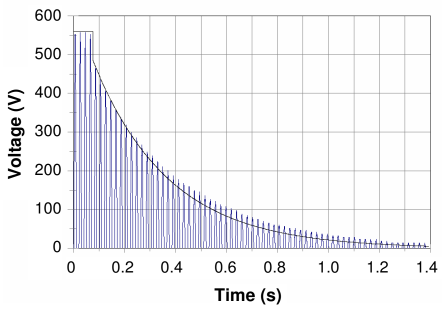

Figure 6 Voltage drop at motor terminals due to a short interruption.

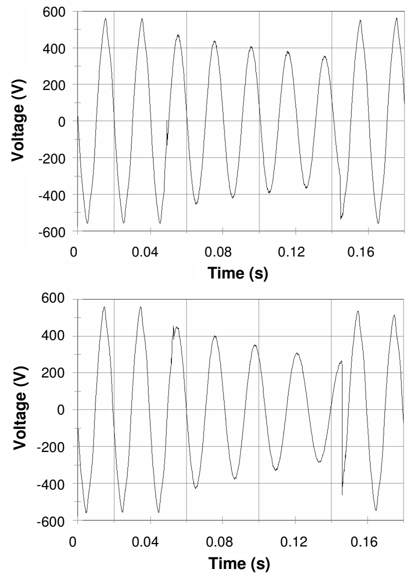

Figure 7 Back emf voltage variation for a short interruption of nearly 5 cycles, at no-load and 85% of rated value.

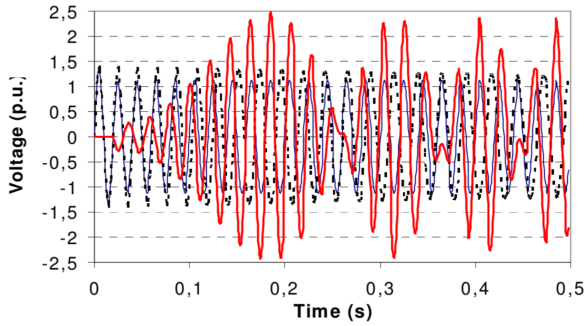

Figure 8 Back emf and supply voltage difference by applying simple methodology.

If the circuit opening point is not close to motor terminals, the present situation is similar to the case previously analyzed, during voltage sag occurrence. The voltage drop can be easily calculated. Figure 9 shows both analytical and experimental results. The transient is quickly damped out thus – despite analytical errors in voltage drop assessment – the voltage values at reclosing time are not affected. Therefore, the current condition would lie between the two extremes, open or closed circuit.

Behavior when the full voltage magnitude is recovered:

At the moment when the perturbation cause disappears, a voltage recovery transient takes place. The recovery transient involves two phenomena, electrical (back emf and supply voltage) and mechanical balances, which will reach the final situation after some voltage and torque oscillations. The relationship between voltage sag magnitude and recovery overcurrent values are presented in [6]. Given the rotating load percentage and the average short-circuit power, the supply voltage can be estimated. If the number of dynamic loads under acceleration is too high, the starting process would be practically frozen in time, keeping constant the overcurrent value, voltage drop, and motor speed [6]. In general applications the voltage border for a successful restarting is at 85 % of rated value. If the current magnitude is too high or the duration too long, the windings could be overheated. Therefore, the correctly adjusted protective devices will operate to disconnect the protected motor. This disconnection will allow the restarting of the remaining non-disconnected loads or lead to a system blackout.

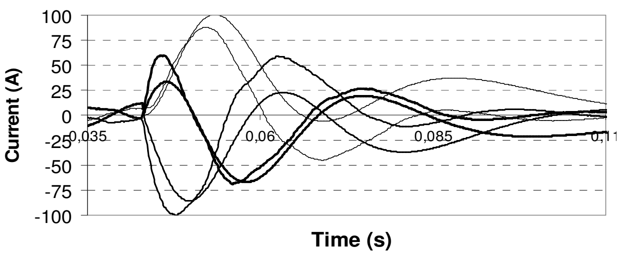

Figure 9 Analytical – experimental comparison of motor current supply during faraway short interruption.

PROPOSED METHODOLOGY

Based on the explained phenomena, the following methodology for the determination of the time to keep the rotating loads connected is proposed:

- Determine the essential loads to keep connected during voltage sags and short interruptions.
- Organize the delayed restarting scheme for the non-essential loads, avoiding simultaneous restart.
- Determine if the speed drop of the essential loads allow the production process to be continued, otherwise it must be stopped.
- Experimentally obtain the starting current versus time record under rated voltage for the essential loads.
- Determine the restarting voltage drop for the kept-connected loads.
- Calculate the restarting time for the supply voltage of the rotating load with the heaviest starting process.
- Compare the specific energy with the starting one; if the new value is higher, verify the thermal stress.
- If necessary, the protective-device operating time can be increased.

If the calculated speed drop is too high, contactors must open. Similarly, if the restarting process takes too much time that would put the motors to risk, contactors must open to stop the production process.

CONCLUSIONS

A simplified analytical methodology is presented, that allows industrialists to determine the maximum duration that their production-line sensitive equipment must be kept *in-condition* for a successful process to restart. The methodology can include both the system hot-load pickup and the shedding scheme data. The interaction between immunity, shedding, and load pickup can be easily assessed by applying the proposed technique. After an agreement is reached between the customer and utility regarding voltage sags and short interruptions, a significant reduction in loss cost can be obtained by using the proposed methodology.

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