The effects of a brief voltage dip on the performance of a power system with motor loads.

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0. SYNOPSIS

The effect of a brief supply voltage dip on the performance of common power system components is discussed. Special attention is paid to the behavior of induction motors (and their loads) during, and after, a voltage dip. A simplified model is used to show how system impedance, load inertia, load torque and the duration of a voltage dip affect an example motor system.

1. INTRODUCTION

The behavior of a power electrical system during and after a brief dip in supply voltage depends on the parameters of that system. This paper aims to show how different system parameters affect the response of a simple system during and after a voltage dip.

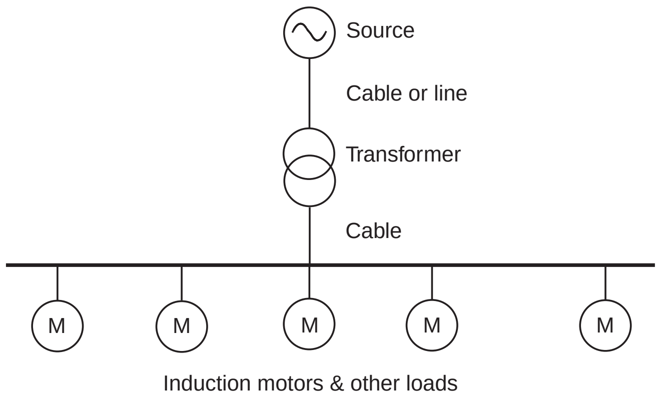

Fig 1

Example power system

The system that will be considered consists of induction motor loads fed from an infinite bus via a transformer and cables, see Fig 1 above. This represents a type of system which is often found in industry. Due to the high starting current drawn by the motors and the limitations of the system, it would often not be possible to start all the motors simultaneously. Rather, they would be started one by one so as not to overload the system. Further, the combined starting current of all the motors would increase the voltage drop across the transformer and the cable impedances, reducing the amount of torque available to accelerate the loads, thus increasing the starting time. It is possible that the load torque of a motor could exceed the available motor torque under such conditions, causing the motor to stall.

The conditions described above could also arise after a supply voltage dip. When the supply voltage is lost the motors and their loads start to decelerate. When the voltage is returned to normal, all the machines will try to accelerate to their previous operating speed. Long acceleration times, or even a stall condition, will now result due to the reduced available torque.

Accurate dynamic modeling of the type of system described above is complex and requires the use of a computer and specialized software. This paper will describe a simpler system model that is relatively easy to solve, although still requiring the use of a computer. This model will then be used to describe a system of the type shown in Fig 1 under various voltage dip conditions and to show the effect of changes in the system parameters.

2. SYSTEM MODEL

The system model described below is not intended to be valid for all systems of the type under discussion, but rather to give the engineer a first indication of whether or not problems can be expected under voltage dip conditions. A number of assumptions are made:

1. No torque is developed by the motors during a voltage dip.
2. The electrical time constants of the system are much shorter than the mechanical time constants, and will not significantly affect the acceleration or deceleration times of the motors.

2.1 Motor/Mechanical load model

In order to determine the operating condition of a machine and its load after a voltage depression, the rotating mechanical system has to be considered. The following equation is used to describe the behavior of an induction motor and load system during any acceleration or deceleration situation [1, p.20; 2, p.53]:

$$Tm(w) = 2H\frac{dw}{dt} + Tl(w) \qquad (2.1)$$

Where :

$w =$ speed (pu)

$Tl(w) =$ Load torque as a function of speed (pu)

$Tm(w) =$ Torque exerted by the motor (pu)

$H =$ Inertia constant of the complete rotating system

Writing (2.1) in terms of slip :

$$Tm(s) = -2H\frac{ds}{dt} + Tl(s) \qquad (2.2)$$

Where :

$s =$ slip

$Tl(s) =$ Load torque as a function of slip (pu)

$Tm(s) =$ Torque exerted by the motor (pu)

Tl (s) depends on the type of load connected to the motor. *Fan* or *centrifugal pump* loads follow a quadratic function ($Tl(s) = ks^2$ or $Tl(s) = k_1s^2 + k_2s + k_3$) while *mill* or *conveyor* type loads can be approximated by a constant torque function (*Tl(s) = k*).

Tm(s) depends on the type and design of the induction motor that is employed to drive the load, i.e. single or double cage rotor etc. Further, if *Tm(s)* is to be determined accurately, effects like saturation, deep bar effect etc. have to be taken into account when calculating a torque-slip curve. However, as this paper aims to simplify matters, a simple single-cage model based on the well known induction machine equivalent circuit [3] will be used. Then:

$$Tm(s) = (I_2)^2\frac{R_2}{s} \qquad (2.3)$$

Where:

$R_2 =$ Rotor resistance in pu

$I_2 =$ Rotor current

The inertia constant, H, is defined as the per unit energy stored in the total, rotating system at synchronous speed. Typical values of 2H are 0.6 to 1.5 for *pump drives*, 3.5 for *coal mills* as found in many ESCOM power stations and as high as 15.0 for *large direct driven fans.* The presence of a gearbox will affect the inertia constant (as seen from the motor) by the square of the gearbox ratio. I. e. a speed reduction gearbox, will also reduce the inertia constant of the load when it is referred to the motor side of the gearbox.

The differential equation (2.2) is normally very difficult to solve analytically but a numerical method, like the Runge-Kutta method [4, p.661] is fairly simple and can be implemented on a personal computer with relative ease.

2.2 Modeling of other system components

The transformer and cable components of the system shown in Fig 1 are simply represented by their equivalent p.u. reactance.

2.3 The complete (lumped) system model

To determine how each of the motors (assuming that they are not identical or do not have identical loads) shown in Fig 1 will react under voltage dip conditions, would require simultaneous solution of the equations describing each of the motor systems and the rest of the network. Even when using simple models this will be a fairly complex and time consuming task, normally requiring the use of specialized software. For the purposes of this paper, it will be assumed that all the motors and their loads are identical, making it possible to lump all the motors and loads into a single motor-load model. This yields a simple model that can easily be solved on a personal computer.

The following steps are followed during a simulation run:

1. Determine the operating point of the system under normal steady state conditions (pre-voltage dip condition). This is accomplished by finding the slip at which *Tm(s) = Tl(s)*. When *Tm(s) > Tl(s)* the load will be accelerated or decelerated when *Tm(s)<Tl(s).*

2. A voltage depression of duration t_d now occurs. It is assumed that *Tm(s) = 0* for the duration of the depression. Equation (2.2) can now be solved, using the initial conditions obtained in 1 above, to determine the motor speed at the end of the voltage depression.

3. The system voltage has been restored. *Tm(s)* is no longer equal to 0 pu at all slips. Equation (2.2) is solved again, using the final condition obtained in 2. above as initial condition. The equation is solved until a steady state condition is reached (slip constant). The period of time over which the solution was obtained is the time taken to run the machine up to its pre-voltage depression operating point. If *Tl(s)) > Tm(s)* when the system voltage returns to normal, a stall condition arises.

The model described above is a pseudo-dynamic model. The dynamics of the motor load are considered in detail, but Tm(s) is determined from steady state equations. However, for relatively slow rates of acceleration or deceleration this is acceptable when it is assumed that the electrical transients in the machine occur much faster than the mechanical transients.

3. SIMULATION STUDIES AND RESULTS

3.1 The effect of system impedance

This section will present the results of a number of simulation runs, showing the effect of various parameters on the response of the example system. A parameter, C, will be introduced here and will be used to describe the effect of *system impedance*. C is defined as the ratio of the fault level at the motor terminals to the motor rating:

$$C = \frac{\text{Fault level at motor terminals}}{\text{Lumped motor rating}}$$

Fig 2(a) shows the motor and load torque-speed curves and the current-slip curve of the lumped motor when it is connected to a system of negligible source impedance (infinite fault level at motor terminals). A simple quadratic function is used to represent the load torque. It can be seen that the motor torque is higher than the load torque at all speeds below the operating speed. This means that the motors will always be able to accelerate their loads to full speed, even after a voltage dip that was long enough to allow the motors to stop completely. Fig 2 (b) shows the behavior of the lumped motor system after a voltage dip. The rotating system had an inertia constant of H = 0.5. After a voltage dip of duration 0.5 sec. the speed of the motors has reduced to 0.65 p.u. Once the terminal voltage returns the motors accelerate to full speed in under 0.4 seconds.

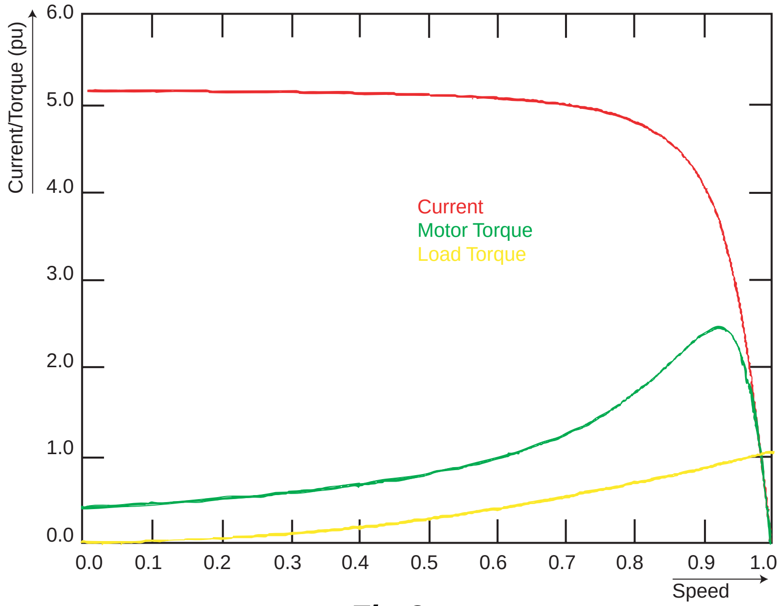

Fig 2a

Torque / current - speed curvers with C→∞

The next case that will be considered is identical to the first, with the exception that the fault level at the motor terminals now has a finite value, with C = 9.1. This means that the fault level at the motor terminals is 9.1 times higher than the total motor rating. Fig 3(a) shows the motor and load torque-speed curves which apply for this case. The motor torque-speed curve was calculated by incorporating the source impedance in the stator circuit of the lumped motor model. It can be seen that the load and motor torques are very close at around 0.7 p.u. speed. This is only the case for the lumped model. The torque-speed curves for each of the motors that the lumped model consists of would look more like the curve in Fig 2 (a) , but only if each of those motors were to be started separately. If all the motors are started together, less motor torque is developed. This is caused by the higher current drawn from the source, reducing the terminal voltage of all the machines. If only one motor is started at a time, the total current drawn from the source is less, giving a higher motor terminal voltage

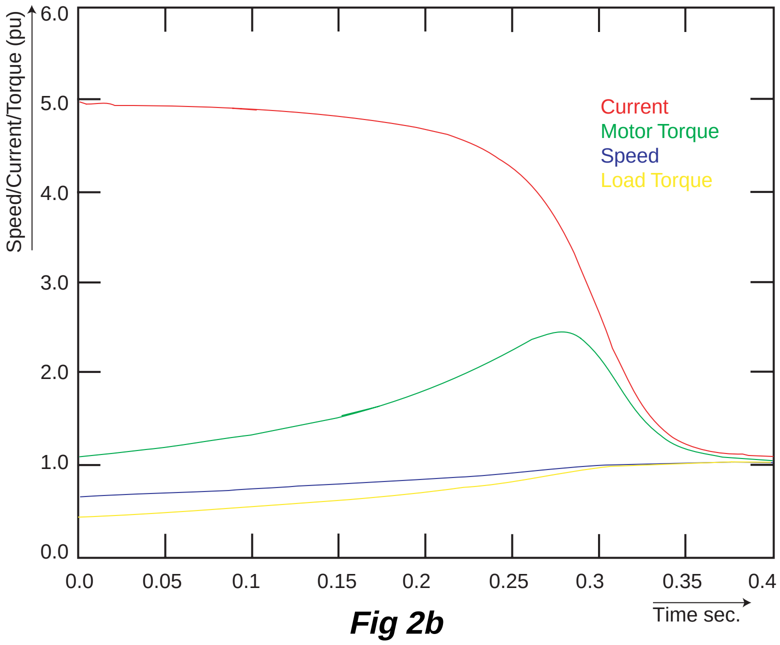

Fig 2b

Run up after voltage dip of 0.5sec. (H = 0.5 & C→∞)

which increases the torque developed by the machine. However, after a voltage dip all the motors connected to a common bus will draw starting current until the pre-voltage dip operating point has been reached again. This is the case which is shown in Figs 3(a) and 3(b). After the voltage dip the speed has again reduced to 0.65 p.u. From Fig 3(b) it can be seen that the system requires almost 8.5 s to reach a stable operating point. For most of this period of time full starting current is drawn by all the motors. This could cause inverse time over current protection relays to operate.

If the (identical) motors are started in sequence each motor will take slightly longer than the previous one to reach operating speed due to the reduction in terminal voltage caused by the machines that have already reached operating speed. However, the terminal voltage (and thus developed torque) will never be as low as when all the motors are started simultaneously.

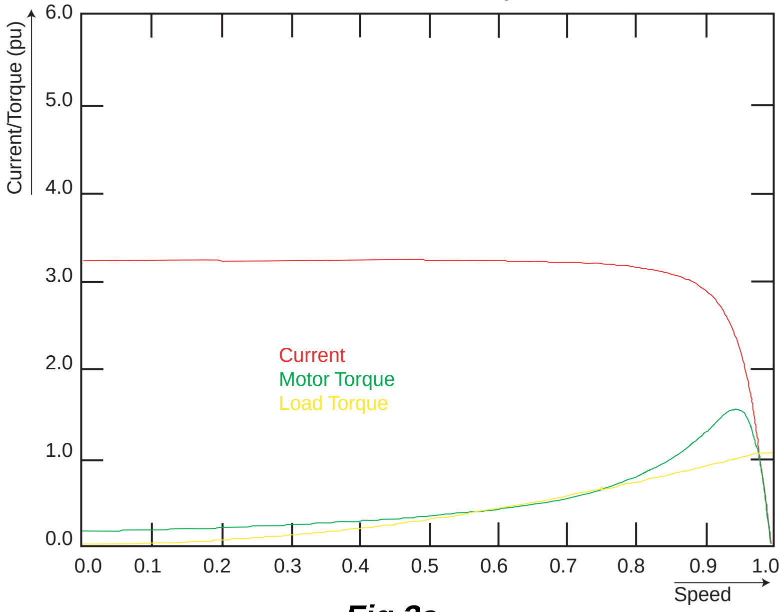

Fig 3a

Torque / current - speed curvers with C = 9.1

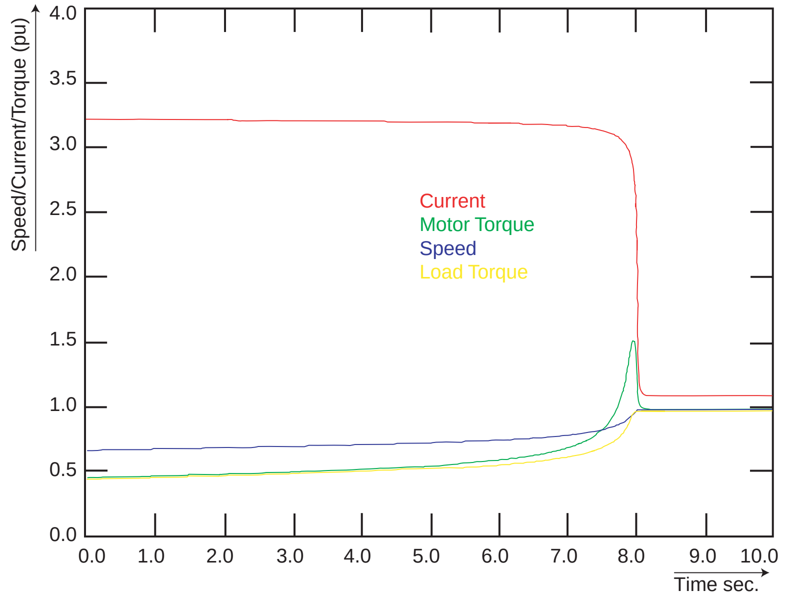

Fig 3b

Run up after voltage dip of 0.5sec. (H = 0.5 & C = 9.1)

Fig 4 shows the result when C is reduced to 6.7. If the speed after a voltage dip is lower than 0.85 p.u. the motors will stall, i.e. they will not be able to reach the operating point that existed before the voltage dip occurred. This type of situation will eventually cause over current (overload) protection relays to operate, in order to protect the motor. The above scenario may seem extreme, but it can occur where a large number of motors, with low inertia loads, are connected to a “weak” (low fault level) system.

A low C value is typically obtained where the rating of the transformer is close to the total motor load it supplies. Eg. if a 1.25 MVA, 13% transformer is used to supply a total motor load of 1.0 MVA, a value of 10.4 is obtained for C. Cable impedance is ignored above, but long cables will reduce C further.

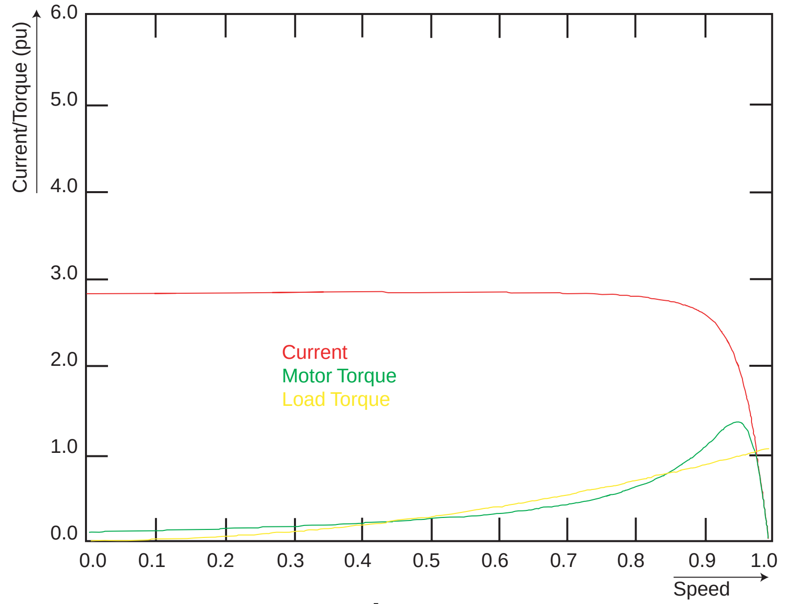

Fig 4

Torque / current - speed curve with c = 6.7

3.2 The effects of inertia and voltage dip duration.

A number of simulation runs were performed to investigate the effects of voltage dip duration, inertia of the rotating system and the factor C on the run up time of the lumped motor system described above. Figs 5(a) to 5(c) show the results of these studies for inertia constants of 0.25, 0.5 and 2 respectively. High inertia constant values mean that the motors lose very little speed during a voltage dip. When the supply voltage returns after a dip, the motors for the high inertia case will develop close to their peak (pull-out) torque, leading to a quick return to their pre voltage-dip operating point. Systems with low inertia constants, *e*.g. pumps, will decelerate rapidly during a voltage dip and will, after the dip, attempt to accelerate the load from an operating point where the difference between motor torque and the load torque is small, leading to much longer acceleration times. (The nature of the load torque function will, of course, also have an effect on deceleration and acceleration performance of a motor as no acceleration or deceleration can take place if a torque is not applied to the rotating system.)

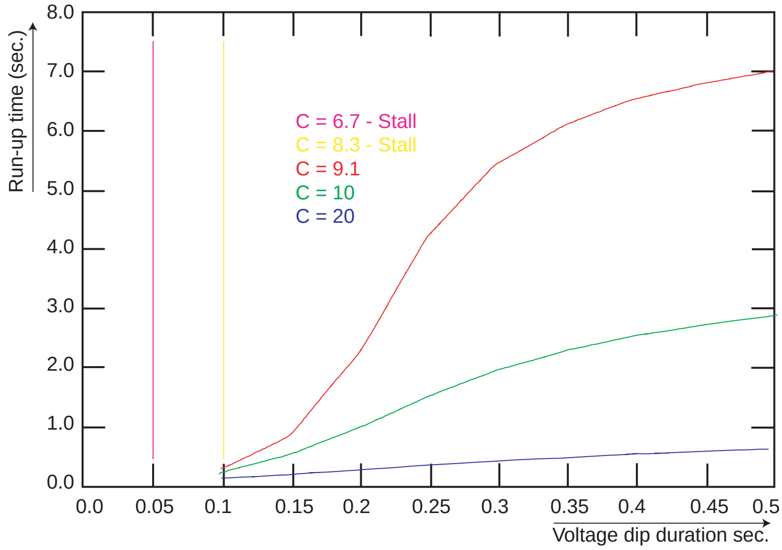

Fig 5a

Run up time as a function of voltage dip duration (2H = 0.5)

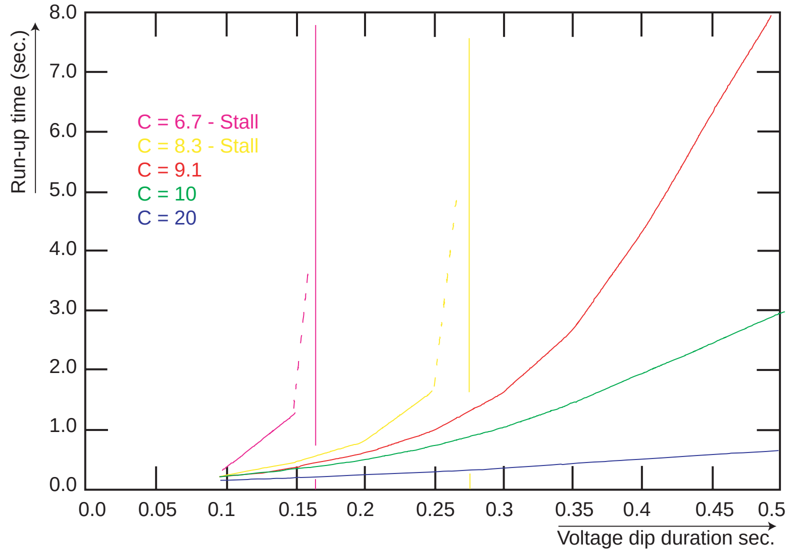

Fig 5b

Run up time as a function of voltage dip duration (2H = 1.0)

The duration of a voltage dip, of course, also has an effect on the acceleration time of a motor system after a voltage dip. Shorter voltage dips mean less deceleration of the load and thus faster acceleration to the pre-voltage dip operating point.

From figures 5(a) to 5(c) it can be seen that the worst situations arise when the inertia constant (H) and C have low values.

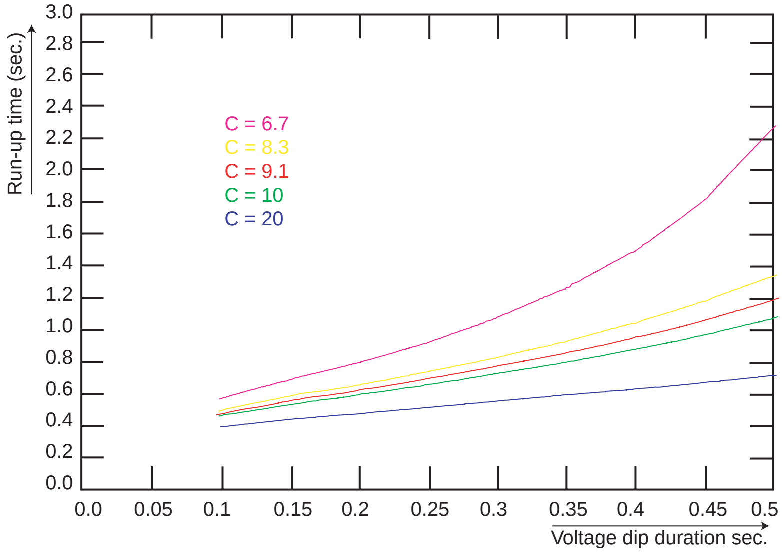

Fig 5c

Run up time as a function of voltage dip duration (2H = 4.0)

3.3 Other system components

It is unlikely that system components like transformers and cables will be overloaded due to high currents drawn by motors after a voltage dip as these components have fairly high overload capabilities. In a practical system the motor protection relays will operate before transformers or cables are overloaded.

4. CONCLUSION

The system models used in the above are not meant to be representative of all systems of the type shown in figure 1., but rather to give an illustration of how a typical supply-motor system can react under voltage dip conditions.

The greatest shortcoming of the model used above is that it cannot be used to describe a system which has greatly differing motors as loads. Unfortunately, the calculations required to determine the voltage dip performance of all the motors in such a system are very complex and will normally require the use of specialized dynamic simulation software.

Systems where the fault level at the motor terminals is fairly low and where the motor loads .have a low inertia constant have to be considered carefully as stall or long run up time conditions can arise. The reaction of such a system to a voltage dip should ideally be studied during the design phase.

5. REFERENCES

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