The Effect of Voltage Dips On Induction Motors

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1. INTRODUCTION

Voltage depressions caused by faults on the system affect the performance of induction motors, in terms of the production of both transient currents and transient torques. It is often desirable to minimize the effect of the voltage dip on both the induction motor and more importantly on the process where the motor is used. In order for the user to achieve optimum protection, he must prioritize the importance of the different processes, and then choose the appropriate method to minimize the effects of voltage dips, within the constraints of the supply and budget. The worst case scenario is that of a three phase fault which occurs electrically close to the motor. It is this scenario which will be examined in this paper.

When a voltage dip lasts longer than a cycle, many AC contactors will fall out, disconnecting the motor from the supply (and the fault). The user has the following options as to how the plant will react to such a situation.

1. Restart all the motors once the fault has cleared.
2 Restart the critical motors once the fault has cleared, then restart the remaining motors in a sequenced start so as to avoid excessive current being drawn from the supply .
3. Keep the critical motors connected to the supply; even under fault conditions. (The motor may drop out after a time when the process cannot be rescued)

Each of the above options has certain capital cost implications, as well as causing different stresses on the electrical system, the mechanical system and the motor. This paper will examine the effects which stress the motor, and then presents ways of determining the amount of these stresses.

2. CRITERIA FOR SAFE RESWITCHING

This section examines what conditions must prevail in order to switch the motor back on to a healthy supply assuming that flux still remains in the machine. Generally speaking, re closing (or bus transfer) should be avoided when the residual voltage and the oncoming system voltage exceed about 125% - 135% of the rated voltage of the motor. The American National Standards Institute (ANSI) standard 050.41-77 (Polyphase Induction Motors for Power Generating Stations) and a proposed National Electric Manufacturing Association (NEMA) standard would permit a maximum of 1.33 pu V/Hz (the units V/Hz gives a measure of the flux) for out-of-phase re switching. Thus, for example if the flux of the motor has not yet decayed, then the maximum phase difference between the voltage should be 83 electrical degrees. For a phase difference of 180 degrees, the residual voltage should be less than 0.33 pu V/Hz. It must be remembered that the flux will decay with a given time constant, (shown later) and that the frequency of the residual voltage is proportional to the speed of the motor.

3. WHAT HAPPENS WHEN A THREE PHASE FAULT OCCURS

This paper makes the assumption that the voltage dip is caused by a three phase fault which is electrically close to the motor which is normally valid for most plant. If this assumption is not valid, i.e. the impedance of the fault as seen by the motor, is of the same order as the leakage inductance of the motor, then the fault impedance can be added to the stator series impedance in the following analysis in order to obtain meaningful results.

When a three phase fault occurs close to the motor no electrical energy can enter or leave the motor. It is obvious that current can still flow in both the stator and the rotor windings, thus torque can be produced. The energy stored in the magnetic field can therefore be dissipated either as mechanical energy or as heat due to copper losses in the motor.

As the fault is applied, there is a large transient current of the order of the starting currant but with a DC offset. The peak current of this combined effect can be as large as eight times the rated RMS current. Both the AC and the DC component of the current die away very rapidly. The time constant of this decay can be approximated by the time constant associated with the sum of leakage inductances of the stator and rotor in series with the stator and rotor resistances. Typically the flux will decay to less than 30% of rated flux in 5 to 6 cycles. Since this transient is dominated by the decay in the main flux, the loading of the machine has only a small effect on the size of the transients. Associated with the transient current there is a torque transient with a characteristic initial large negative torque impulse of a typical magnitude of -8 pu. This torque impulse reaches its maximum within two cycles, but decays rapidly.

Since the flux decays rapidly, normally to less than 30% within 5-6 cycles, clearing of the fault and the subsequent re-establishment of the terminal voltage, produces transients of the same order as at startup which do not excessively stress the mechanical load or the motor. Matters are helped if the inertia is high and the speed has not decreased significantly. However if many motors are left connected to the system their combined effect could lead to a voltage depression due to large currents (a brown out), and all the motors might not be able to accelerate back to full speed. Thus it is common practice to allow the contactors to the non-essential motors to drop out, and only to be re closed at a later stage and in an orderly manner. However additional control equipment must be purchased in order to affect this.

4. WHAT HAPPENS WHEN A MOTOR IS OPEN CIRCUITED & RECONNECTED

In this scenario, a motor has experienced a fault and the contactors are allowed to drop out, effectively open circuiting the motor. At a time later, once the fault has been cleared, the motor is reconnected to the supply. This section explores what the effects are of the last two operations especially if the motor needs to be operated as soon as possible. When the motor terminals are disconnected from the supply, once again no energy can enter or leave the magnetic field via the electrical terminals. Further as there is no current in the stator, torque cannot be produced, thus energy cannot be transferred to the mechanical load.

At the instant when the stator current is interrupted, the net mmf in the motor must remain constant. This mmf balance is achieved-by an instantaneous increase in the current in the rotor windings (cage). The energy in the rotor must now decay due to the resistance of the rotor. The time constant for this process is that of the open rotor resistance in series with the rotor leakage inductance and the mutual inductance. This time constant is therefore much longer than for the case of the short circuited terminals and is typically in the order of seconds. Thus the flux remains much longer in the motor in this scenario and it will also remain stationary with respect to the rotor.

5. APPROXIMATE FORMULA

This section provides some readily accessible formula which can be used to give approximate figures to the effects on induction motors discussed in sections 2 and 3. It is advisable to perform a more detailed study, such as a simulation, for cases where the results are important.

5.1. Current under Short Circuit

The current of the stator at the time of the fault contains both an AC and a DC component. The magnitude of the AC component of current can be approximated by assuming that the phase voltage is applied to the leakage impedance, as shown in Figure 1. (The effect of the resistance can normally be ignored in determining the magnitude of the current). The RMS value of the AC component of the phase current is:

$$I_{psc} = \frac{V_p}{\left(X_1 + X_2'\right)} \tag{1}$$

The peak current can be calculated by (2):

$$I_p = 2I_{psc} \tag{2}$$

The time constant of the decay of the phase current is given by the stator and rotor resistance in series with the stator and rotor leakage inductance i.e.

$$\Upsilon_{sc} = \left(\frac{\left(X_1 + X_2\right)}{2\pi f\left(r_1 + r_2\right)}\right) \tag{3}$$

5.2. Torque under Sort Circuit

The peak torque under short current is not readily calculated since it is dependent on the magnitude of the rotor current and the flux and the angle between them. As a rough guide the ratio of the maximum torque to rated torque will be proportional to the short circuit current to the rated current. In practice this figure can be reduced by to about half of this value.

5.3. Calculating the Magnitude and Angle of the Flux when Open circuited.

When the motor is open circuited the rotor windings carry the current to maintain the mmf and hence the flux in the motor. This current (and hence the flux) will decay at a rate given by the time constant associated with the rotor resistance in series with the rotor leakage reactance and the magnetising reactance, i.e.

$$\Upsilon_{oc} = \left(\frac{X_m + X_2}{2\pi f r_2}\right) \tag{4}$$

The rate at which the angle between the flux wave and the incoming voltage will vary by is determined by the integral of the slip speed with respect to time. If the torque of the mechanical load is independent of speed, then the angle can be given by:

$$\theta_r = \frac{1}{2}\frac{M}{\omega}t^2 \tag{5}$$

5.4. Current when reswitching

The transient current experienced by an induction motor is dependant on the difference between the supply voltage and the voltage at the terminals of the motor due to the remaining flux in the machine. This voltage will decay at the same rate as the flux, and will have the same phase difference as calculated above. Taking the vector difference between these two voltages and dividing by the stator leakage inductance will give a good indication as to the magnitude of the transient current i.e.

$$I_{rs} = \frac{E_m - E_s}{\chi_1} \tag{6}$$

At worst, if the flux has not decayed significantly and the supply EMF is 180° out of phase with the motor EMF, then the current will be:

$$I_{rs} = \frac{2E_s}{\chi_1} \tag{7}$$

5.5. Torque when reswitching.

The torque produced when re closing the motor onto the system contains two components, a unidirectional torque and a fundamental system-frequency oscillatory torque [2]. The maximum value of the former occurs when re closing at an angle of 90° and the latter at the re closing angle of 180°. These values are

$$M_{uniderectional} = \frac{(E_s E_m)}{(X_1 + X_2')} \tag{8}$$

and

$$M_{oscillatory} = \frac{(\Delta E)E_m}{(X_1 + X_2')} \tag{9}$$

where ΔE is the phasor difference between the system voltage and the motor voltage at the time of re closure. If the voltage and the impedance are in per unit based on the rated motor voltage and the output power, then the toque will be the per unit value of rated torque. For values of flux between 0.8 and 1.0 pu the most critical closing angle is about 120° This peak value is given by:

$$M = \frac{E_s E_m}{X_1}\left[0.866 + \sqrt{1 + \left(\frac{E_m}{E_s}\right) + \left(\frac{E_m}{E_s}\right)^2}\right] \tag{10}$$

The above formula is the most useful formula for determining the worst torque possible, given the size of the supply and motor voltage.

6. CASE STUDY

The example is of a 55 kW induction motor supplying a load with a constant rated torque. The following figures have been derived from an accurate simulation program - CASED, which has been developed at Wits.

The first case is that of a 3 phase short circuit being applied to the motor. It is assumed that after 150ms the fault is cleared, and a healthy supply is fed to the motor. Fig 1 shows the rapid decay in the flux, in fact for this motor the flux has decayed to less than one third after 2 cycles. When the supply is restored, the flux in the motor is negligible and hence the re- starting transients are similar to that of start up. (It must be noted that since the speed had not decreased by more than 10%, the deep bar effects of startup will not play a significant role in this case.)

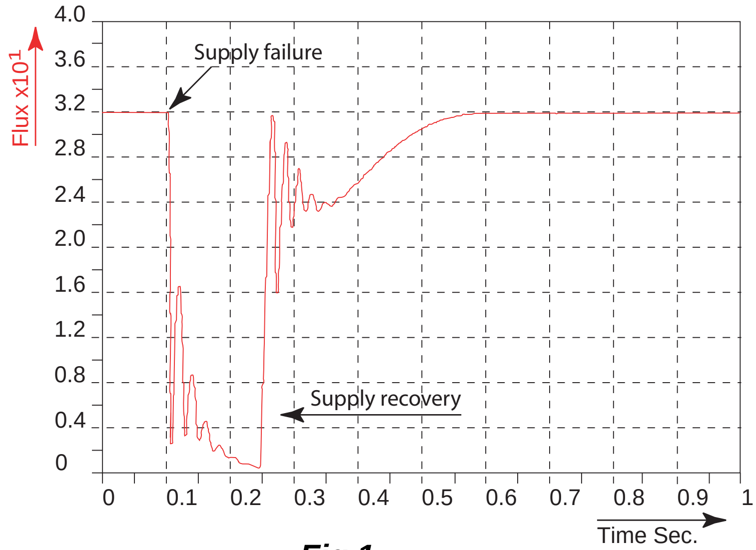

Fig 1

Motor Flux during supply failure, motor remains connected to the supply.

The trace of the torque transient given in Fig 2, shows that there is an initial torque impulse in the negative direction of the order of 4 pu. When the healthy supply is reconnected the toque transients are small. The current transients shown in Fig 3 are 5 times larger than the rated current, which is what one would expect.

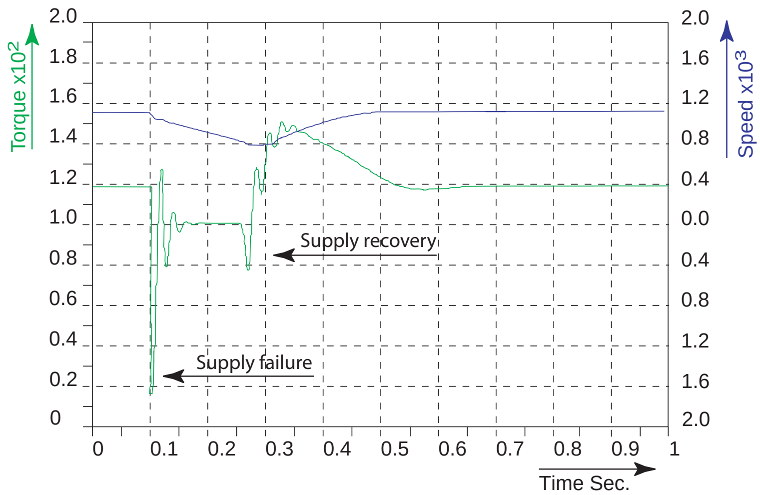

Fig 2

Motor Torque & Speed during supply failure, motor remains connected to the supply.

Consider the second case where the same motor is disconnected from the supply, and then reconnected at a short time later (in this example 280 ms, when the residual voltage is of opposite phase to the incoming supply). This could represent a bus transfer. Fig 4 shows the decay in the flux in the machine. It is important to note that the decay is very much slower than for the first case (Fig 1). Fig 5 shows that the electromagnetic torque of the motor becomes zero at the moment of disconnection,

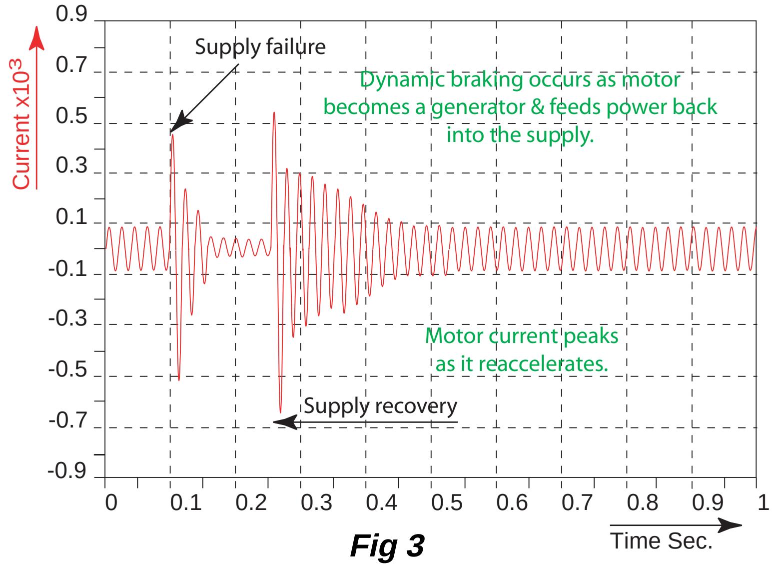

Fig 3

Motor Current during supply failure, motor remains connected to the supply.

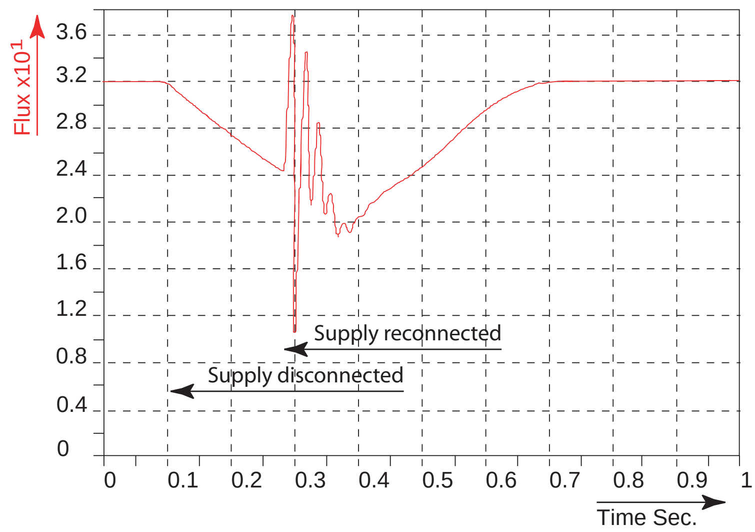

Fig 4

Motor Flux during supply failure, motor is disconnected from the supply.

i.e. there is no torque impulse. However when the healthy supply is restored there is a large negative torque impulse of the order of 8.8 pu. It is not uncommon for motors to have a maximum reverse torque impulse of up to 15 pu.

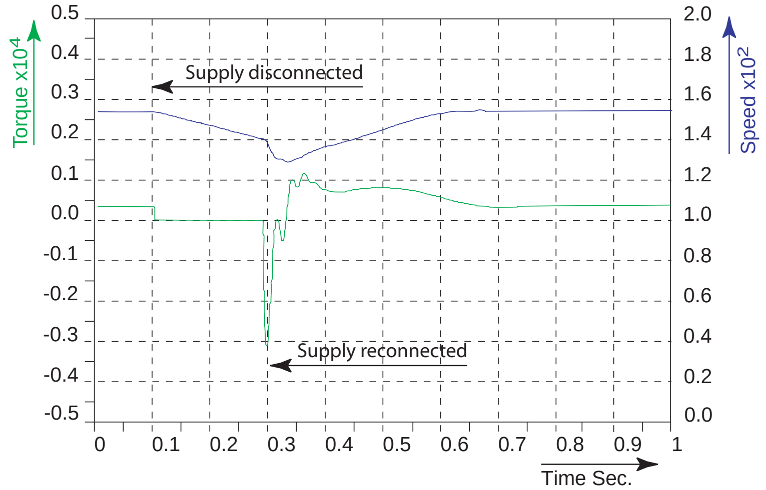

Fig 5

Motor Torque & Speed during supply failure, motor is disconnected from the supply.

Since the incoming voltage is 180 degrees out of phase, we expect a large current transient, which is shown is Fig 6. For this example the peak current is 12.9 pu, almost double the starting current. However it must be noted that the transient is of short duration and hence will not have a serious effect in terms of heating, but it can cause severe mechanical stresses on the windings of the machine.

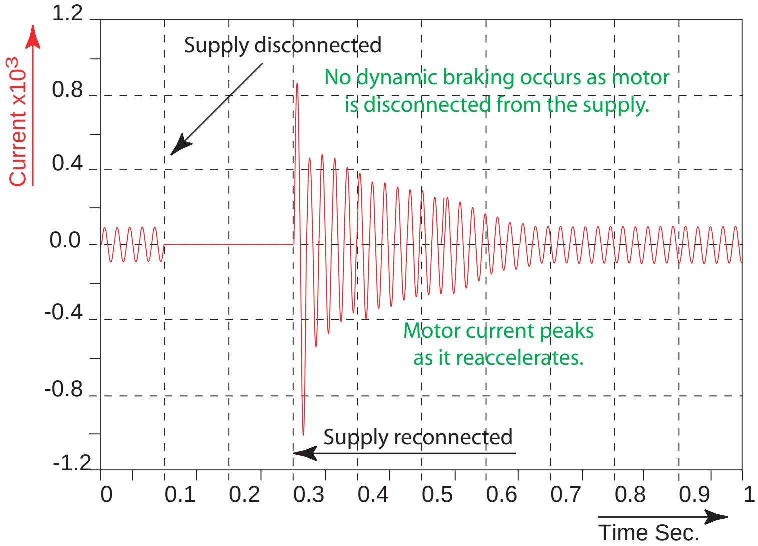

Fig 6

Motor Current during supply failure, motor is disconnected from the supply.

The third scenario is where a fault occurs on the system, the contactors fall out after 1 cycle, thus open circuiting the machine. A short time later (280ms) the motor is restored to a healthy supply. It is clear from Fig 7 that during the time of the short circuit, the flux decays to about half its value. When the motor is open circuited, the flux then decays further, but with a slower time constant. When the supply is restored the flux in the machine is very much smaller than for the previous case. From Fig 8 it can be noted that the initial torque pulse associated with the short circuit is still present. There is an additional torque impulse when the supply is reconnected. Fig 9 shows the current for this case.

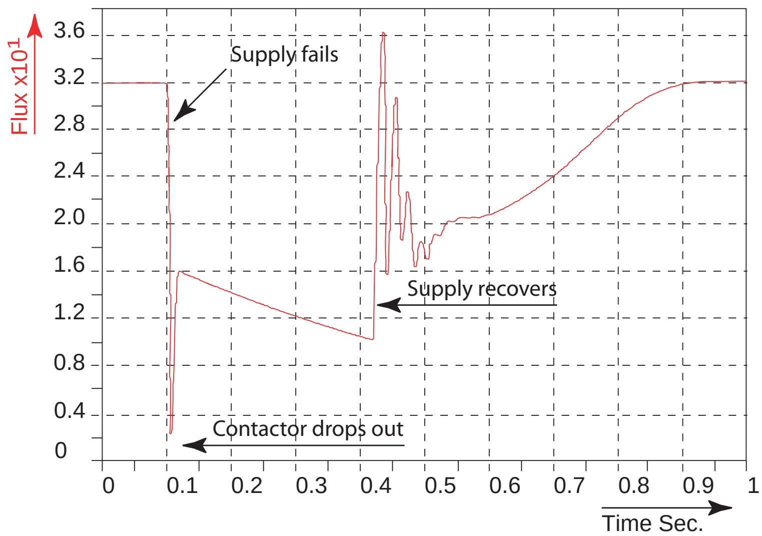

Fig 7

Motor Flux during supply failure, motor is connected then disconnected from the supply when the contactor drops out after one cycle.

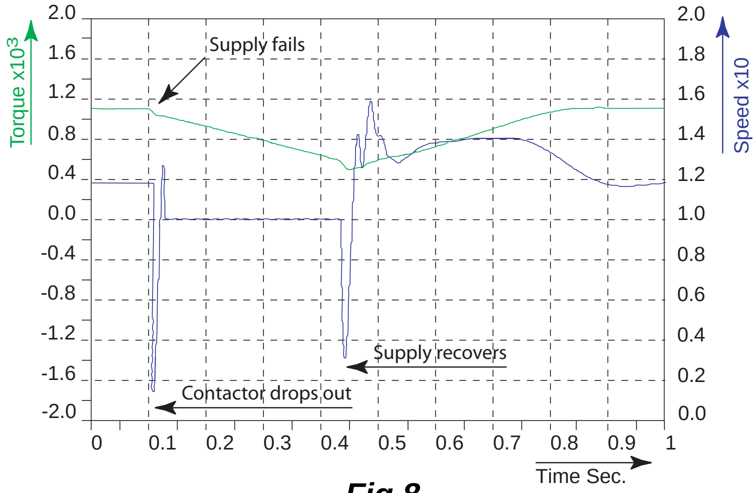

Fig 8

Motor Torque & Speed during supply failure, motor is connected then disconnected from the supply when the contactor drops out after one cycle.

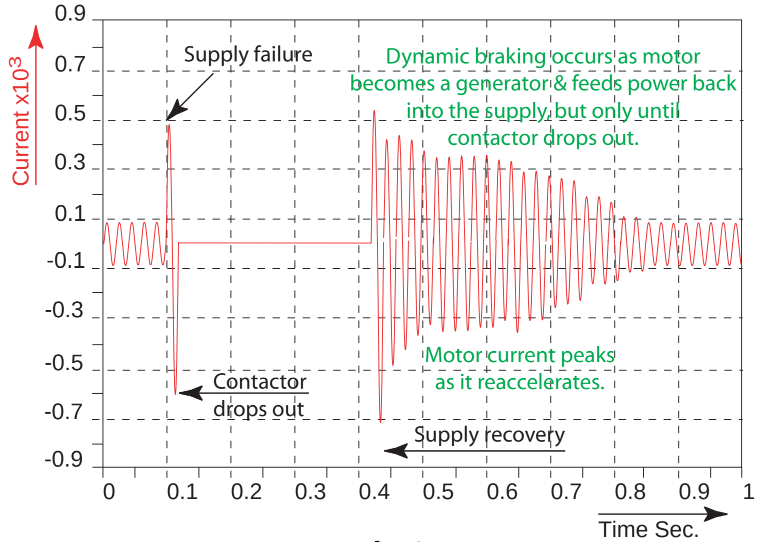

Fig 9

Motor Current during supply failure, motor is connected then disconnected from the supply when the contactor drops out after one cycle.

7. CONCLUSIONS

When designing a plant to withstand voltage dips, the designer must rate the induction motors in order of how critical they are to the process. The supply must then be evaluated to determine how many of these motors may be started simultaneously. For this set of motors, suitable contactors or appropriate modifications to existing contactors must be done so as to ensure that the contactors remain in. The length of time which they must be held in is determined by how the plant will be effected by the loss of power. This may be of the order of seconds.

The remaining motors should allow for the contactors to drop out, and then to be reapplied in a manner which minimizes the stress on both the mechanical system and the electrical system. This implies that either a time delay must be enforced to ensure that the flux in the motor has decayed sufficiently, or that the motor is switched onto the supply when the phase between the motor voltage and the supply voltage is less than say 30°.

8. LIST OF SYMBOLS

E_s Phase voltage of system.
E_m Residual phase voltage of motor.
I_{psc} Phase current under short circuit.
I_{rs} Phase current when re - switching.
M Torque.
X_1 Stator leakage reactance.
$X_2^{'}$ Rotor leakage reactance.
X_m Magnetising reactance.
γ_{oc} Open circuit time constant of flux decay.
γ_{sc} Short circuit time constant of flux decay.

9. REFERENCES

[1] Mulukutla S S, Gulachenski E M, "A critical survey of considerations in maintaining process continuity during voltage dips while protecting motors with reclosing and bus-transfer practices", IEEE, 1991

[2] Switchgear Manual 8th edition ABB

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