Induction Motor Response to Voltage Dips

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***Abstract* – This paper presents a study using the EMTP to investigate the dynamic response of induction motors to voltage dips. The machine response is related to the voltage dip magnitude and duration. Dips represented include single and multi phase dips as well as sequential dips due to re-closing operations. The survivability of the motor operation is assessed against typical induction machine protection settings. It is demonstrated that protection settings can be adjusted to improve the motor operation survivability of voltage dips without endangering the safety of the motor.**

Keywords – Dynamic response of Induction motors, Power Quality, Voltage Dips, Protection of Induction Motors.

I. INTRODUCTION

Voltage dips and their impact on customer loads constitute the most prevalent power quality problem in distribution systems. Voltage dips can result in tripping of customer equipment and shutting down of production lines leading to production loss and expensive restart procedures. Sensitive equipment to voltage dips include: computer-controlled processes, variable speed drives (VSD) and induction motors.

System modifications can be implemented to minimize the magnitude and duration of voltage dips. Special measures can be implemented at the customer end to reduce equipment sensitivity to voltage dips.

Among the different types of equipment, which are susceptible to voltage dips, induction motors are the most commonly used and are the easiest to deal with.

II. EFFECT OF VOLTAGE DIPS ON INDUCTION MOTORS

Voltage dips are mostly due to system short circuits. Their magnitudes depend on the short circuit level of the feeding network and the proximity of the fault to the affected bus bar. Their durations depend on the clearing time of the fault. After the fault is removed the system voltage may recover to a value higher than its pre-fault value. This is due to loss of load, and the accompanying voltage drop, upon removal of feeding lines during the fault clearing process.

As the supply voltage to the induction motor decreases, the motor speed decreases. Depending on the size and the duration of the voltage dip, the motor speed may recover to its normal value as the voltage amplitude recovers. If the voltage dip magnitude and/or duration exceed certain limits the motor may stall and would be taken out of the system by the locked rotor protection. Maximum voltage dip magnitude and/or duration, which the motor operation can survive, depend on the motor parameters and the torque-speed characteristic of the driven load.

Motor recovering process after voltage dips is dynamically similar to motor starting process and is accompanied by large inrush currents. Depending on motor protection settings, these currents can trigger short circuit or locked rotor protection of the motor resulting in the tripping of the motor.

Most of induction machine protection settings are too conservative. This leaves room for adjusting these settings without causing any threat to the motor safety. Many of the unnecessary motor tripping incidents can be avoided by simple adjustment to the motor protection settings.

III. INVESTIGATED SYSTEM

Simulation studies were conducted using the DCG/EPRI version of the EMTP. The simulated system, shown in Fig. 1, represents a 6 kV induction motor of 3.4 MW capacity driving a compressor load. The motor is connected to the 6 kV bus of a customer substation through an auto-transformer used for starting purpose.

Validation of the induction motor model used was carried out by duplication of its behaviour during the starting process. Starting of the motor was simulated for the conditions of full voltage start as well for reduced voltage, 60 %, start using the auto-transformer.

Simulation was then conducted for different voltage dips applied to the 63 kV bus bar.

A. Used Model

The induction motor was modeled using the Universal Machine Model type 40. This setup requires nameplate parameters of the machine as input. It processes this input to produce the physical parameters of the machine, which are needed for the Universal Machine Model. The name plate motor parameters are given below.

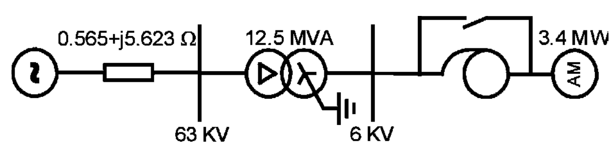

Fig. 1 System Used for EMTP Simulation.

Motor Characteristics:

Nominal Voltage:	6 kV
Rated active power:	3.4 MW
Synchronous rotational speed:	1 500 rpm
Rated load rotational speed:	1 490 rpm
Rated efficiency:	0.96 pu
Rated power factor:	0.89 pu
Relative Starting Current:	5 pu
Start current at reduced voltage:	3.218 pu
Reduced voltage start up voltage:	0.6436 pu
Average starting torque at rated voltage:	0.98 pu
Starting period duration:	22.8 sec
Rotor moment of inertia:	242 kg.m^2

The induction motor drives a compressor load with the following characteristics.

Compressor Characteristics:

Rated nominal power:	3.023 MW
Rotor moment of inertia:	570 kg.m^2

Motor Protection:

Motor protection systems susceptible to tripping due to voltage dips are phase overcurrent, minimum voltage and locked rotor protection. Settings of these protection systems are given in table I for the investigated motor.

B. *Motor Starting at Full Voltage*

Tests were conducted to validate the model involving motor starting at full and reduced voltages. Motor starting current at full voltage is shown in Fig. 2.

Table I Motor Protections Settings

Function	Settings	
Phase overcurrent	1 460 A	0,1 sec
Earth fault	4 A	0,15 sec
Minimum voltage	4,8 kV	1,5 sec
Locked rotor	800A	1 sec

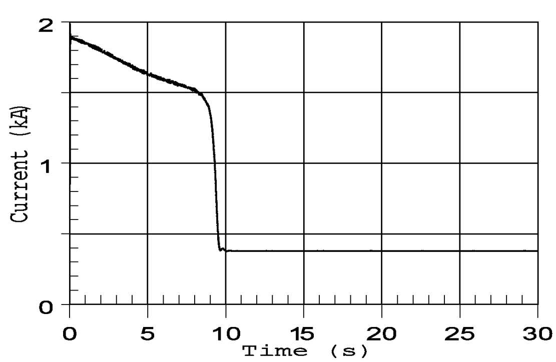

Fig. 2 Motor Starting Current at Full Voltage

The motor starting current reaches 4.7 times the nominal current. The motor current reaches its steady state value of 400 A. after 9 seconds. These starting conditions coincide with the manufacturer predicted values.

The torque/speed behaviour of the motor and the load are shown in fig. 3. During the starting both of the motor and load torque increase. Speed increases while motor torque is higher than load torque. After having reached its maximum value, motor torque decreases as speed keeps increasing. When motor and load torques coincide equilibrium is established, after a small transient, at the rated speed of 1420 rpm (156 rad.s^{-1}).

C. *Motor Starting at Reduced Voltage*

Motor is normally started at a reduced voltage (60 %) using an auto-transformer. The auto-transformer is shorted out, using the parallel switch shown in Fig.1, after 18 seconds. Fig. 4 shows the starting currents under this scenario. Steady state is reached after 22.8 seconds as predicted by the manufacturer and both the starting and steady state currents correspond to rated values.

The torque/speed behaviour of the motor and the load, during the auto-transformer starting process, are shown in Fig. 5.

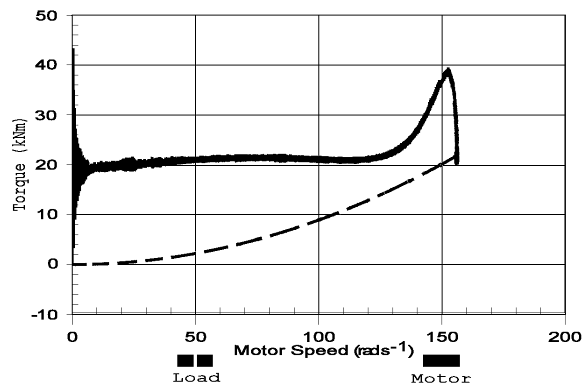

Fig. 3 Load and Motor Torque as Functions of Speed.

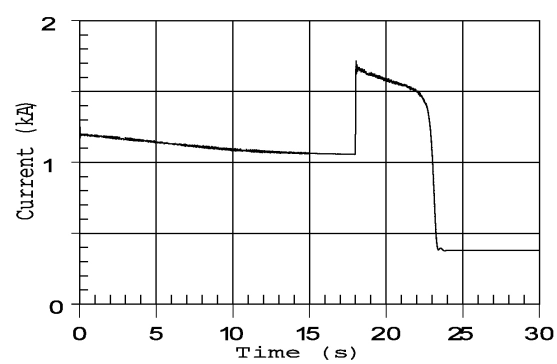

Fig. 4 Motor Starting Current at Reduced Voltage.

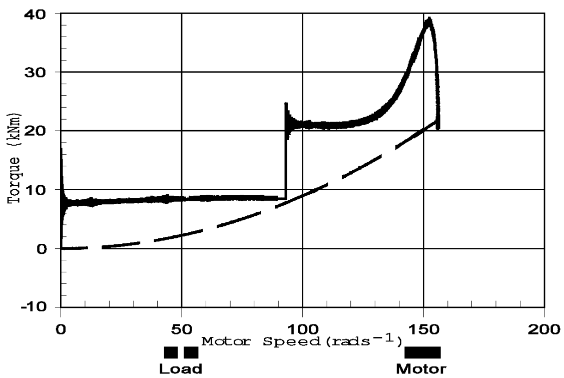

Fig. 5 Load and Motor Torque as Function of Speed, Starting with Auto-transformer.

Motor speed reaches its nominal value (156 rad.s^{-1}) in two steps. The simulation shows that maintaining the reduced voltage for 18 seconds makes it barely possible for the motor to start. If the reduced voltage is to be kept longer than 18 seconds the motor will, most likely be unable to start.

This simulation shows that each time the motor starts it will carry a current of 1100 A during 18 seconds, followed by a current of 1600 A for further 4 seconds. It, therefore, can be concluded that the motor should stand currents of these magnitudes and durations without sustaining damage.

IV. RESPONSE TO VOLTAGE DIPS

A. Symmetrical Voltage Dip – Limit Conditions

Using the model developed for the motor, simulations were conducted in order to study the response of the motor to voltage dips. The limit conditions for which the motor operation would survive the voltage dip were identified and are described below.

A three-phase voltage dip is applied at the 60 kV bus bar with 40% magnitude and 1 sec duration. After the dip, the voltage rises to a value 10 % above the pre-dip voltage. Voltage rise over pre-dip voltage, due to load dropping, is often observed in monitored voltage dips.

Motor speed variation during the voltage dip is shown in Fig. 6. The first 500 ms correspond to the starting of the motor. The motor is stated from close to its rated speed to shorten the simulation time. This period is not relevant for the analysis. During the period between 500 ms and 1000 ms the motor is in steady state. The voltage dip is applied at 1000 ms and ends at 2000 ms. The motor speed decreases by 5% of its nominal value during the voltage dip. After voltage recovering, speed recovers its nominal value within 600 ms.

The motor current before, during and after the voltage dip is shown in Fig. 7. During the dip, the current rises to 1,75 times its nominal value. After the dip, the current increases rapidly to 1300 A (about 4 times the nominal value). Under this scenario the current does not reach high values for long enough time to trigger any of the motor's protection systems.

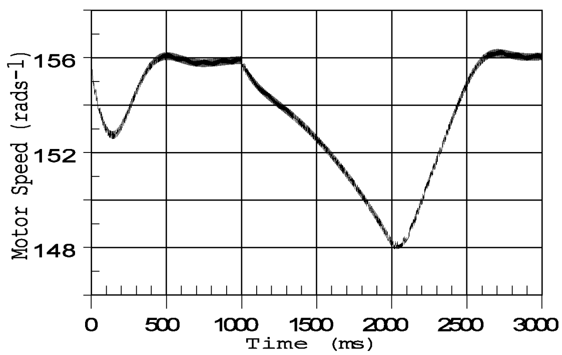

Fig. 6 Motor Speed Variation for a 1 Sec. 40% Voltage Dip.

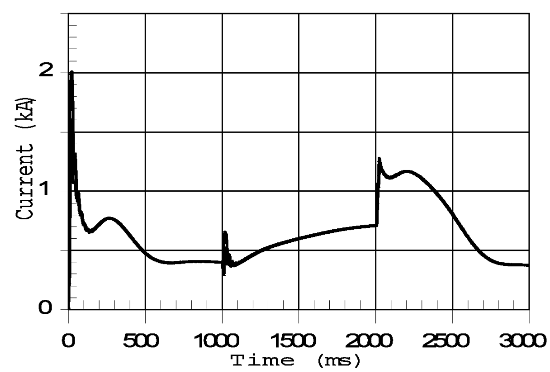

Fig. 7 Motor Current Variation for a 1 Sec. 40% Voltage Dip.

B. Symmetrical Voltage Dip – Locked Rotor Protection Tripping

In this case a three-phase voltage dip, similar to the previously used, was applied at the 60 kV bus bar. The voltage magnitude dip is increased to 50% while the duration is maintained at 1 sec. The post dip voltage rises 10 % over its pre-dip value as in the previous case.

Motor speed is shown; before, during and after the voltage dip in Fig. 8. The figure shows that the motor speed decreases during the voltage dip, applied between 1000 and 2000 ms, by 8% of its nominal value. Speed recovers its nominal value within 1000 ms from the voltage recovery.

Fig. 9 shows motor current variation for the simulated case. The figure shows that during the dip, the current rises to 1,75 times its nominal value. After the dip, the current increases rapidly to more than 800 A during more than 1 sec. This triggers the locked rotor protection.

The motor current reaches much higher values and lasts for much longer time than indicated in Fig. 9 during normal starting process. It can be concluded that the protection settings could be increased in order for the motor operation to survive such voltage dip without causing damage to the motor.

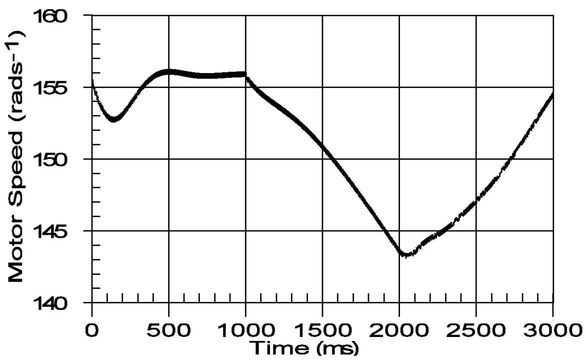

Fig. 8 Motor Speed Variation for a 1 Sec. 50% Voltage Dip.

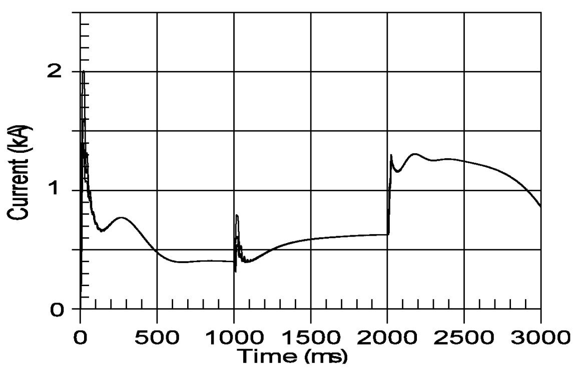

Fig. 9 Motor Current Variation for a 1 Sec. 50% Voltage Dip.

C. Symmetrical Voltage Dip with Re-Closure

The induction motor could be exposed to two or more successive dips due to automatic or manual re-closing attempts. The initial fault clearing time is of the order of 100 ms followed by an automatic re-closure after 300 ms. If the re-closure is not successful the protection system will clear the fault permanently after 500 ms. The impact of this scenario on the induction motor is examined next.

A voltage dip with the characteristics shown in Fig. 10 is applied at the 60 kV bus bar to represent this situation. As the figure shows the first dip has 50% magnitude and 100 ms duration followed by voltage recovery for 300 ms followed by another 50 % voltage dip for 500 ms.

Motor speed is shown in Fig. 11.

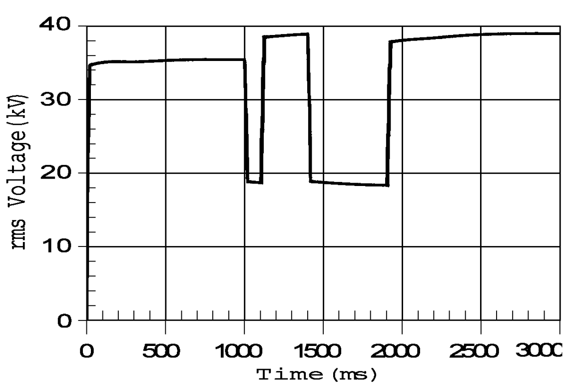

Fig. 10 Applied Voltage dip

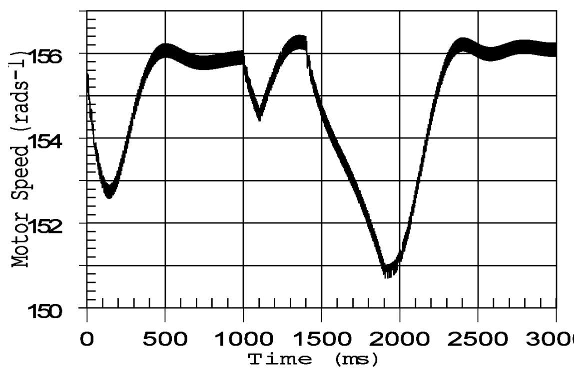

Fig. 11 Motor Speed Variation for Successive Voltage Dips due to Automatic Re-closure

The figure shows that the motor speed decreases by 1% and 5% of its rated value during the first and second dips respectively and recovers its nominal value within 400 ms from the voltage recovery.

Fig. 12 shows motor current variation for the simulated case. The figure shows that the current increase during the voltage dips is recovering but does not reach trigger levels for long enough time to initiate protection action.

D. Dependence of Response on Motor Characteristics

A second induction motor was connected at the 6 kV bus bar. The additional motor was identical to the original motor except for the value of its starting current. The second motor has a higher starting current, 8 pu versus 5 pu.

The two motors are subjected to an asymmetrical voltage dip at the 6 kV terminals. The voltage dipped 50 % of the pre-incident value in 2 phases and 80 % in the third phase for 1 sec.

The speed variations of the two motors during and after the dip are shown in Fig. 13. This shows that the motor with high starting current recovers under the simulated voltage dip while the other motor stalls.

This emphasizes the importance of the motor parameters on its response to voltage dips. It also shows that simulation of motor and load dynamic behaviours makes it possible to predict whether the motor will seize to operate under voltage dip conditions, for reasons other than protection settings, or not.

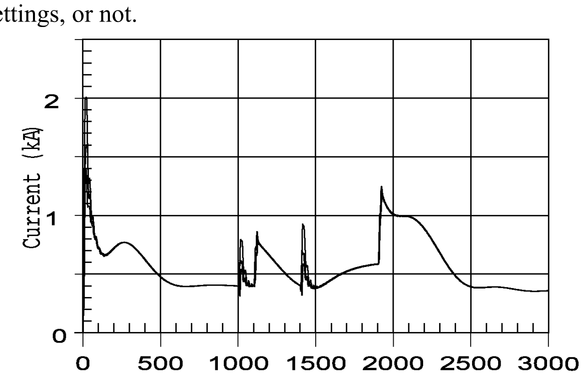

Fig. 12 Motor Current Variation for Successive Voltage Dips

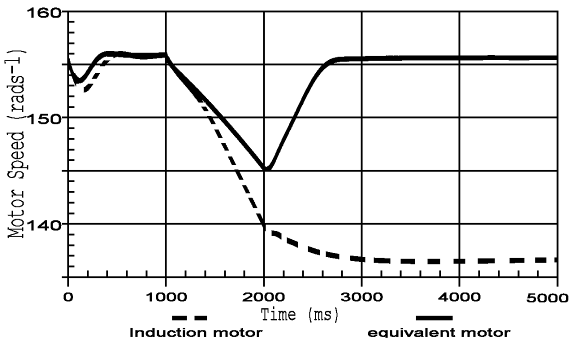

Fig. 13 Speed Variations of Two Different Motors under an Asymmetrical Voltage Dip.

IV. CONCLUSIONS

A study was conducted using the DCG/EPRI EMTP to investigate the response of induction motors to voltage dips. The use of the Universal Machine model made it possible to use nameplate motor data directly.

Simulation of a 6 kV, 3.4 MW induction motor driving a compressor load was conducted. Duplication of motor starting process at full and reduced voltages, against manufacturer supplied specifications, was used to verify the accuracy of the model.

Motor response to the applied voltage dips show that this motor can support most commonly encountered voltage dips. However, protection settings are normally too sensitive resulting in the unnecessary loss of motor operation that can be otherwise avoided.

It has been demonstrated that the dynamic behaviour of induction motors is sensitive to the values of the motor parameters. It is, therefore paramount to use the proper values of parameters for the simulated motor.

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