# Research on Calculation Model of Voltage Sags Due to High Voltage and Great Power Motor Starting

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**Abstract: High voltage and great power motors' starting cause big impacts to power grids and introduce voltage sags. In severe cases, it will affect the normal operation of other devices. Voltage sags have been the most prominent problems of the power quality, and both sides of the power supply pay close attention to them. This paper mainly focuses on the starting process of the high voltage and great power induction motors which are widely used in industries. It's key to model the motor starting process, including selections of the equivalent circuit of motors with different structures, collections and checking of stators and rotors' impedance. Normally, lacking the delivery test materials, they should be obtained by experience. The key point to improve the simulation accuracy is to model mathematical expressions of motor stators and rotors' impedance in the starting process to get more accurate curve of motors' electromagnetic torque, including the collection and evaluation of motors' rotation inertia. It is directly related to the duration of the starting process. The collection and evaluation of load torque curve are related to acceleration torques. Finally, it determines the duration of the starting process. This paper also introduces techniques to reduce the starting current, to reduce the impact to the power grid, to control voltage sags levels in limits. The research has been successfully used in power quality evaluation for the integration of Shanghai Qingcaosha Raw Water Project, Shanghai Zizhuyuan Refrigeration Units project.**

**Keywords: Motor Starting, Voltage Sags, Calculation Model**

## 1. Introduction

These days, voltage sag becomes the most outstanding problem of the power quality when the number of the power quality sensitive equipments increases and the request of power quality is improved. According to the research of EU power department, voltage sag shared above 80% of the consumer complains about the power quality.

High voltage and great power motors fully start, it need take 5-8 times rating current from the power grid, when this current passes the system impedance, it will cause voltage sag on the supplying bus and the related bus. Voltage sag on the supplying bus results in two serious problems: first it will break the working condition of other running equipments, specially the power quality sensitive equipments. For example, when the voltage is below 80% rating voltage, the servers of the computer network will stop and the client computer will lose data. When the voltage is below 50% rating voltage, most contactor will disconnected, PLC controllers will stop working. Second, the receiving side of the motor cannot guarantee the starting torque which causes the motor cannot start finally.

This paper gives the mathematic model of the motor starting processing and provides a computer simulation case about water pump motor. However, this paper only focuses on the voltage sag caused by the starting of the motors, the effect to the motor by the starting will report in a separated paper.

## 2 The starting model of the motor

Normally, small power motors start with full power. The full power starting means the rating voltage adds to the motor stators directly, i.e. direct starting. The benefit is big starting moment and short starting time. The shortcoming is big starting current, if the power of motor is very big, the starting will cause a quite big voltage sag on the supplying bus and affect the other equipments' working condition.

In order to avoid the effect of the big transient current caused by the starting of the high power motor, the way to start the motor should be changed. In practice, the most starting mode is the low voltage starting and frequency change starting. Adding resistance or reactance starting mode is wide application in the high power motors because it is easy to apply and low cost.

Adding resistance to the stator circle during the starting, when the running speed is close to the working speed, the reactance will be cut off. This method increases the impedance in the stator circle and decreases the motor voltage which results in small starting current and minimizes the effect to the power grid. However, it would decrease the starting torque and increases the starting time, the worst case is the motor fails to start.

## 3 The mathematic model of the motor starting processing

### 3.1 Equivalent circuit of asynchronous motor

T type equivalent circuit of asynchronous motor added resistance in the stator circle is shown in figure 1.

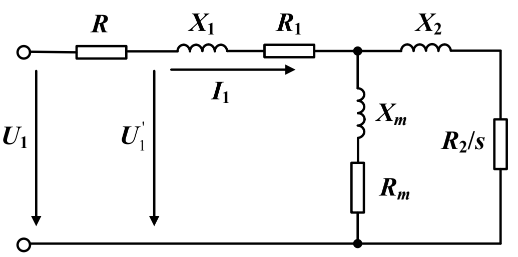


Figure 1: T type equivalent circuit of asynchronous motor

In fig. 2：stator impedance: $R_1$、$X_1$（Ω）

rotor impedance: $R_2$、$X_2$（Ω）

excitation impedance: $R_m$、$X_m$（Ω）

resistance in the stator circle（Ω）

motor voltage: $U_1$（V）

### 3.2 Motor current

Because the stator impedance is much bigger than the excitation impedance, the expression of stator current of asynchronous motor is

$$I_1 = \frac{U_1}{\sqrt{(R_1 + \frac{R_2}{S})^2 + (X_1 + X_2)^2}} \qquad (1)$$

When the motor stops, $n$=0，$s$=1, the current is the largest, the current effect will cause the voltage sag on the supplying bus.

The expression of starting current

$$I_e = \frac{U_1}{\sqrt{(R_1 + R_2)^2 + (X_1 + X_2)^2}} \qquad (2)$$

When the resistance 'R' adds to the stator circle, the expressions (1) and (2) are modified as

$$I_1^{'} = \frac{U_1}{\sqrt{(R + R_1 + \frac{R_2}{S})^2 + (X_1 + X_2)^2}} \qquad (3)$$

$$I_e^{'} = \frac{U_1}{\sqrt{(R + R_1 + R_2)^2 + (X_1 + X_2)^2}} \qquad (4)$$

### 3.3 Motor electromagnetic torque

According to the equivalent circuit, when the motor voltage is shown as $U$(kV), the expression of the motor electromagnetic torque is given as

$$T_e = \frac{9.5493U^2 \frac{R_2}{S} * 10^6}{n((R_1 + \frac{R_2}{S})^2 + (X_1 + X_2)^2)} \text{ (N-m)} \qquad (5)$$

where: n is the motor working speed (r.p.m)

The motor electromagnetic torque is changed by the motor speed. The biggest motor electromagnetic torque and starting torque are given by

The biggest torque

$$T_{em}=\frac{9.5493U^2*10^6}{2n(R_1+\sqrt{R_1^2+(X_1+X_2)^2})} \text{ (N-m)} \quad (6)$$

The speed difference when the torque is the biggest

$$s_m=\frac{R_2}{X_1+X_2} \quad (7)$$

The starting torque

$$T_{en}=\frac{9.5493R_2U^2*10^6}{n((R_1+R_2)^2+(X_1+X_2)^2)} \text{ (N-m)} \quad (8)$$

When the resistance 'R' adds to the stator circle, the expressions (5), (6) and (8) are modified as

$$T_e'=\frac{9.5493U^2\frac{R_2}{S}*10^6}{n((R+R_1+\frac{R_2}{S})^2+(X_1+X_2)^2)} \text{ (N-m)} \quad (9)$$

The biggest torque

$$T_{em}'=\frac{9.5493U^2*10^6}{2n(R_1+R+\sqrt{(R_1+R)^2+(X_1+X_2)^2})} \text{ (N-m)} \quad (10)$$

The starting torque

$$T_{en}'=\frac{9.5493R_2U^2*10^6}{n((R+R_1+R_2)^2+(X_1+X_2)^2)} \text{ (N-m)} \quad (11)$$

## 3.4 Rotor motion expression

When the motor starts, the increasing speed torque will increase the motor speed until it reach the working speed.

The motor rotor motion expression

$$J\frac{d\theta_m}{dt^2}=Ta \quad (12)$$

Where: J: the moment of inertia of rotor J=2H (N-m$^2$)

$\theta_m$: mechanical angle

$T_a$: Te-Tm the increasing speed torque

$T_e$: the electromagnetic torque

$T_m$: the load torque

The rotor motion expression in per-unit

$$\frac{M}{\omega_B}\frac{d\theta}{dt^2}=Tm^*-Te^* \quad (13)$$

where: $\omega_B$ is standard electric angular frequency (rad/s)

M is the motor inertia time (s)

$$M=\frac{J\omega^2_{Bm}}{S_B} \quad (14)$$

where, $J\omega^2_{Bm}$ is twice of the rotor kinetic energy under the working speed. The rotor moment of inertia is normally expressed as $GD^2$ which is four times than J. In the meter-kilo-second system, M can be calculated as

$$M=\frac{J\omega^2_{Bm}}{S_B}=\frac{2.74*GD^2*n^2}{1000*S_B} \text{ (s)} \quad (15)$$

n: the motor working speed (rpm)

$S_B$: standard capability

Several parameters, i.e. the motor speed, the motor voltage, the transmission line voltage, the motor stator and rotor current, the motor electromagnetic torque, the increasing speed torque, can be calculated by using the above equations.

## 4 The computer simulation of the motor starting processing

Now many power system programs can simulate the motor starting processing, e.g. MOTORSTART from CYME, the motor starting unit from ETAP and MOTORSTART in PTW from SKM.

The motor starting processing unit in this paper comes from SKM's PTW software. This program is based on the time domain analysis which can analyze all the parameters during the motor starting processing and cover 1500 motors in one system. It also can simulate the starting processing with different loads.

This program can export 12 parameters by figures: transmission line voltage, motor voltage, motor stator current, load torque, motor speed, motor rotor speed, increasing speed torque, speed difference, reactive power, power-factor, active power, apparent power, etc.

This program also can simulate the most motor starting mode, e.g. full power starting, adding resistance starting, series reactance starting, autotransformer starting, shunt reactor and partial circle starting, solid current limiter starting, solid voltage ramp starting, solid current ramp starting, etc.

## 5 Simulation example

### 5.1 Simulation results

There are 6 water pumps in a reservoir pump station, each water pump has a 6kv, 3100kw synchronous motor. The starting mode of this motor is asynchronous starting, when it reaches synchronous speed, the motor will run in synchronous mode. Then it is reasonable to use the asynchronous starting program to simulate the synchronous starting processing.

The parameters of the water pump motor are shown in table 1.

Table1 The parameters of the water pump motor

| | | | |
|---|---|---|---|
| model | TL3100-52/3450 | excitation voltage（V） | 150 |
| rated power（kW） | 3100 | Rated magnetizing current（A） | 280 |
| Rated voltage（kV） | 6 | Rated locked-rotor current | 6.0 |
| Rated current（A） | 348.90 | the moment of inertia GD2 | 153.65 t/m2 |
| Rated power-factor | 0.90（Leading） | Locked-rotor torque | 0.45 |
| Rated speed（r/min） | 115.4 | pull-in torque torque | 1.0 |
| Rated frequency（Hz） | 50 | The largest torque | 1.6 |
| Rated efficiency | 95% | Class of protection | IP44 |
| Poles | 52 | Class of insulation | Class F |

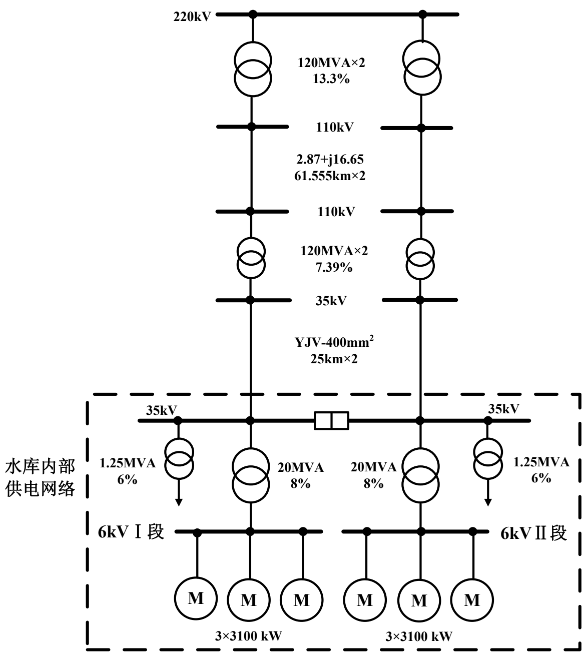


Figure2 The plane of power supply

The major equipments and parameters of the power grid have been shown in figure 2. The short capability of 6kv bus is 92MVA. Due to small short capability, it would be a bad factor for the starting.

6 solid soft starting equipments are used to minimize the effect of motor starting processing to the power grid. The parameters are 6kv, 3100kw, the starting current is adjustable form 2～4Ie.

### 5.2 Operation mode

Each bus has 3 motors. In order to test the effect to the grid voltage, there is 4 combination as shown in table 2.

Table 2 Operation mode f water pump motor

| operation mode | Instruction |
|---|---|
| mode 1 | One motor run, 2 stop. |
| mode 2 | One motor starts, 2 run |
| mode 3 | One bus overhauls, 35kv bus run, One motor starts, other 5 stop |
| mode 4 | One bus overhauls, 35kv bus run, One motor starts, other 5 run |

### 5.3 Results

According to the motor parameter and power supply, a model has been established in PTW, the results are shown as follows

Table 3 Computation results(Mode 1)

| | | Full voltage starting | Series resistance0.5Ω | Series resistance 1Ω | Series resistance 1.5Ω | Series resistance 2Ω |
|---|---|---|---|---|---|---|
| Biggest Voltage Drop(%) | 6kV Bus | 20.08 | 17.77 | 13.53 | 9.48 | 6.46 |
| | 35kV Bus in RESERVOIR | 13.14 | 11.72 | 9.02 | 6.37 | 4.38 |
| | 35kV Bus in power grid | 6.79 | 6.22 | 4.91 | 3.56 | 2.50 |
| Voltage Drop after starting(%) | 6kV Bus | 4.57 | 4.57 | 4.57 | 4.57 | 4.57 |
| | 35kV Bus in RESERVOIR | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| | 35kV Bus in power grid | 1.57 | 1.57 | 1.57 | 1.57 | 1.57 |
| Motor Stator current | Multiplying Factor of Rated current | 5.03 | 4.58 | 3.78 | 2.96 | 2.27 |
| Motor starting period | Multiplying Factor of Full Voltage starting | - | 1.09 | 1.28 | 1.52 | 1.95 |
| Motor voltage | Percentage of Rated voltage(%) | 84.82 | 82.09 | 76.51 | 69.23 | 61.66 |

Table 4 Computation results(Mode 2)

| | | Full voltage starting | Series resistance0.5Ω | Series resistance 1Ω | Series resistance 1.5Ω | Series resistance 2Ω |
|---|---|---|---|---|---|---|
| Biggest Voltage Drop(%) | 6kV Bus | 19.17 | 17.27 | 13.38 | 9.51 | 6.58 |
| | 35kV Bus in RESERVOIR | 4.37 | 4.37 | 4.37 | 4.37 | 4.37 |
| | 35kV Bus in power grid | 12.67 | 11.6 | 9.13 | 6.59 | 4.61 |
| Voltage Drop after starting(%) | 6kV Bus | 2.91 | 2.91 | 2.91 | 2.91 | 2.91 |
| | 35kV Bus in RESERVOIR | 6.6 | 6.21 | 5.04 | 3.73 | 2.67 |
| | 35kV Bus in power grid | 1.53 | 1.53 | 1.53 | 1.53 | 1.53 |
| Motor Stator current | Multiplying Factor of Rated current | 5.08 | 4.6 | 3.79 | 2.96 | 2.27 |
| Motor starting period | Multiplying Factor of Full Voltage starting | - | 1.06 | 1.24 | 1.55 | 1.93 |
| Motor voltage | Percentage of Rated voltage(%) | 85.74 | 82.54 | 76.61 | 69.17 | 61.56 |

Table 5　Computation results(Mode 2)

| | | Full voltage starting | Series resistance0.5Ω | Series resistance 1Ω | Series resistance 1.5Ω | Series resistance 2Ω |
|---|---|---|---|---|---|---|
| Biggest Voltage Drop(%) | 6kV Bus | 19.99 | 17.7 | 13.48 | 9.45 | 6.45 |
| | 35kV Bus in RESERVOIR | 4.59 | 4.59 | 4.59 | 4.59 | 4.59 |
| | 35kV Bus in power grid | 13.1 | 11.69 | 9 | 6.37 | 4.37 |
| Voltage Drop after starting(%) | 6kV Bus | 3.01 | 3.01 | 3.01 | 3.01 | 3.01 |
| | 35kV Bus in RESERVOIR | 6.77 | 6.2 | 4.91 | 3.56 | 2.5 |
| | 35kV Bus in power grid | 1.58 | 1.58 | 1.58 | 1.58 | 1.58 |
| Motor Stator current | Multiplying Factor of Rated current | 4.99 | 4.54 | 3.76 | 2.94 | 2.26 |
| Motor starting period | Multiplying Factor of Full Voltage starting | - | 1.07 | 1.24 | 1.53 | 1.93 |
| Motor voltage | Percentage of Rated voltage(%) | 84.25 | 81.54 | 75.99 | 68.77 | 61.26 |

Table6　Computation results(Mode 2)

| | | Full voltage starting | Series resistance0.5Ω | Series resistance 1Ω | Series resistance 1.5Ω | Series resistance 2Ω |
|---|---|---|---|---|---|---|
| Biggest Voltage | 6kV Bus | 18.38 | 16.73 | 13.07 | 9.37 | 6.53 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Drop(%) | 35kV Bus in RESERVOIR | 4.27 | 4.27 | 4.27 | 4.27 | 4.27 |
| | 35kV Bus in power grid | 12.26 | 11.39 | 9.11 | 6.65 | 4.71 |
| Voltage Drop after starting(%) | 6kV Bus | 2.87 | 2.87 | 2.87 | 2.87 | 2.87 |
| | 35kV Bus in RESERVOIR | 6.47 | 6.19 | 5.13 | 3.87 | 2.81 |
| | 35kV Bus in power grid | 1.53 | 1.53 | 1.53 | 1.53 | 1.53 |
| Motor Stator current | Multiplying Factor of Rated current | 5.03 | 4.54 | 3.73 | 2.91 | 2.23 |
| Motor starting period | Multiplying Factor of Full Voltage starting | - | 1.08 | 1.25 | 1.55 | 1.98 |
| Motor voltage | Percentage of Rated voltage(%) | 84.94 | 81.54 | 75.52 | 68.1 | 60.57 |

According to the results, there is the conclusion

- During the motor starting processing, there is no difference between each bus's voltage. As the electric distance increases, the voltage sag decreases.
- As the motor stator resistance increases, the depth of bus voltage sag decreases, but the starting time increases.
- There is no linear connection between voltage sag and resistance. The bigger resistance is , the more inconspicuous the voltage sag is.
- Before the motor starts, there is no effect of other motors to voltage sag.
- As the stator resistance increases, the starting current decreases; There is no linear connection between the starting current and resistance.
- As the stator resistance increases, the starting time increases; There is no linear connection between the starting time and resistance.
- The increasing stator resistance will result in decreasing the motor voltage.

### 5.4 The biggest series resistance

Adding resistance to stator circle will result in decreasing the motor voltage. This is because the motor electromagnetic torque and voltage has a square relation. Under the certain load starting torque, adding too big resistance to stator circle will cause the motor fail to start. The connection between the load starting torque and the biggest allowed resistance is shown as figure 3 and table 7.

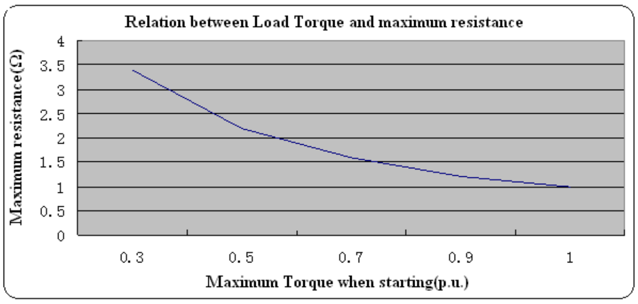


Figure 3 The connection curve between load torque and the biggest allowed resistance

Table 7 The load torque and the biggest allowed resistance during starting processing

| Biggest Torque of Load when starting (percentage of rated torque) | Biggest series resistance of motor stator circuit（Ω） |
|---|---|
| 30 | 3.4 |
| 50 | 2.2 |
| 70 | 1.6 |
| 90 | 1.2 |
| 100 | 1.0 |

## 6 Conclusion

（1）During the starting processing, the change of parameters, i.e. stator current, motor voltage, motor speed, is almost the same. Due to the effect of operation mode to the bus short capability, there is difference on voltage sag between the different operation modes. When one motor runs, other motors' condition will affect the bus voltage level and not affect the motor's parameters during starting processing.

（2）As the resistance increases, the starting time will increase. In order to shorten the starting time, it is reasonable to add small resistance to the motor stator.

（3）Because the motor electromagnetic torque and voltage has a square relation, the choice of resistance should have limit. In practice, the biggest value of resistance should according to the torque when the motor starts with load.

The theory in this paper is suitable to choose the starting mode of high voltage and power motor in order to control the rush current to the grid.

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