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Star-Delta Starting and Dual Voltage Motors Explained.

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STAR-DELTA STARTING and DUAL VOLTAGE MOTORS EXPLAINED.

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Introductions

In our efforts to assist our valued customers, we often answer customers' technical questions. Two such questions are answered in this paper:

Firstly: What is the application and use of "Star-Delta" starting?

Secondly: What does it mean when a motor's rating plate lists two different supply Voltages?

Background:

Traditionally each motor was custom designed for it's specific application. Unfortunately competition, market pressures and cheap imports forced suppliers of electrical motors to standardise on designs and constructions, to change the manufacturing cycle to high volume production lines. Governing bodies like IEC, NEMA, and SABS compiled standards to assist both the end users, as well as the manufacturers to ensure similar constructions between different manufacturers.

These standards aim to define specific performance values, construction types and rating classes. For the most part these specifications succeeded in this regard! Sadly it also relieved the end user of much of his responsibility to understand the application, usage, and design of the electric motor and the load it drives.

Thus, today, the end users are for the most part delivered to the mercy of the electric motor manufacturer!

We receive frequent complaints of customers that purchase "standard" motors that are just not able to perform to the end users expectation. Investigations into the route cause of the problem more often than not reveal that the "off-the-shelf" motor is just not suitable for the end user's application. On several occasions we then analysed the existing motor's design and the end user's application, and performed a complete design change. Sometimes this change even exceeded the price of a brand new *standard* motor! But we still received the order for this change, because the new *standard* motor would still not be able to do the required work!

[1] *Vector* is the Journal of the Institution of Certified Mechanical and Electrical Engineers and the Journal of South African Institute of Electrical Technician Engineer.

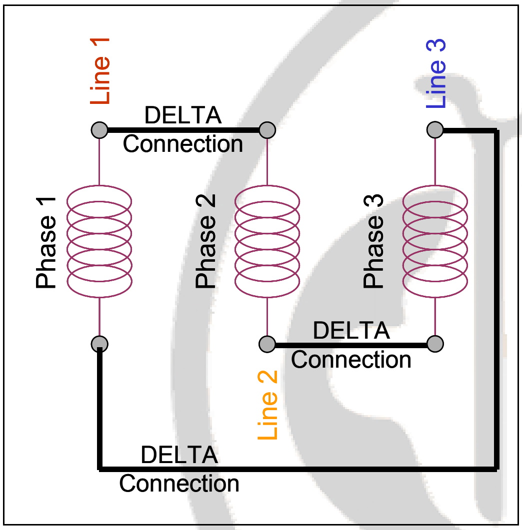
A. Star Delta Starting:

Star-Delta starting is frequently referred to as "Soft-starting" a motor. But what is soft about this starting method? Why is it used? What are the advantages? What are the disadvantages?

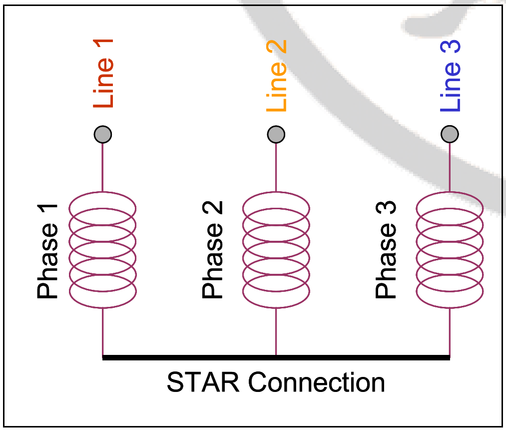
Let's first analyse what Star Delta starting is! It will be explained by using an example motor.

What is Star Delta starting?

Star Delta starting is when the motor is connected (normally externally from the motor) in STAR during the starting sequence. When the motor has accelerated to close to the normal running speed, the motor is connected in DELTA. Pictures 1 and 2 show the two connections for a series connected, three phase motor.



Picture 1: DELTA Connection



Picture 2: STAR Connection

The change of the external connection of the motor from Star to Delta is normally achieved by what is commonly referred to a soft starter or a Star Delta starter. This starter is simply a number of contactors (switches) that connect the different leads together to form the required connection, i.e. Star or Delta.

These starters are normally set to a specific starting sequence, mostly using a time setting to switch between Star and Delta. There can be extensive protection on these starters, monitoring the starting time, current, Voltage, motor speed etc.

The cost of the soft starter will depend on the number of starts required per hour, run-up time, Voltage, power rating, and protection devices required.

Why is Star Delta Starting used?

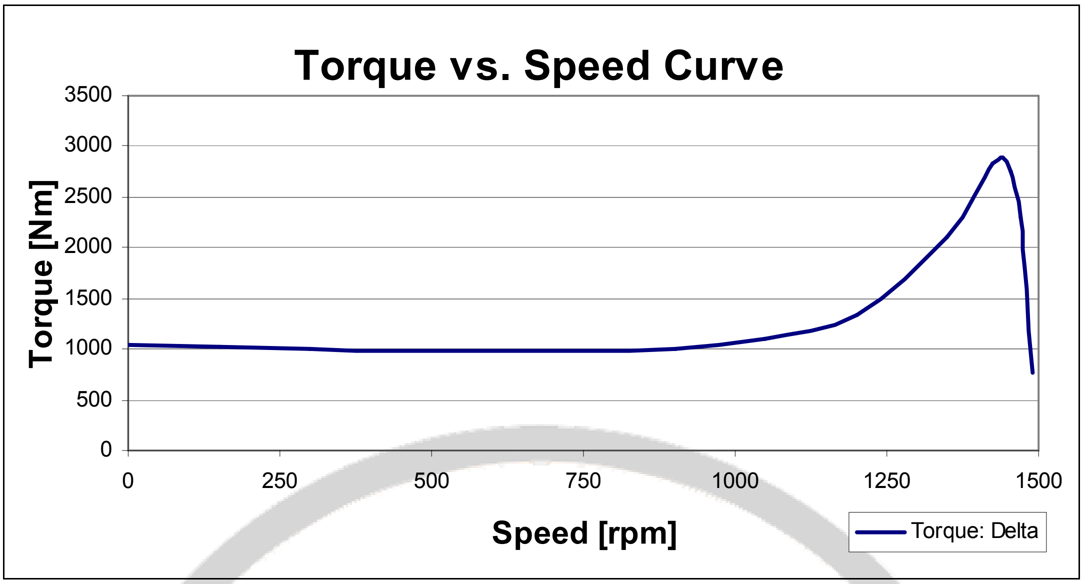
Let's consider an example motor: 120kW, 4 Pole, 380 Volt, Delta connected, 3 Phase, 50 Hz.

First we will examine the normal running condition, i.e. when the motor is connected in Delta.

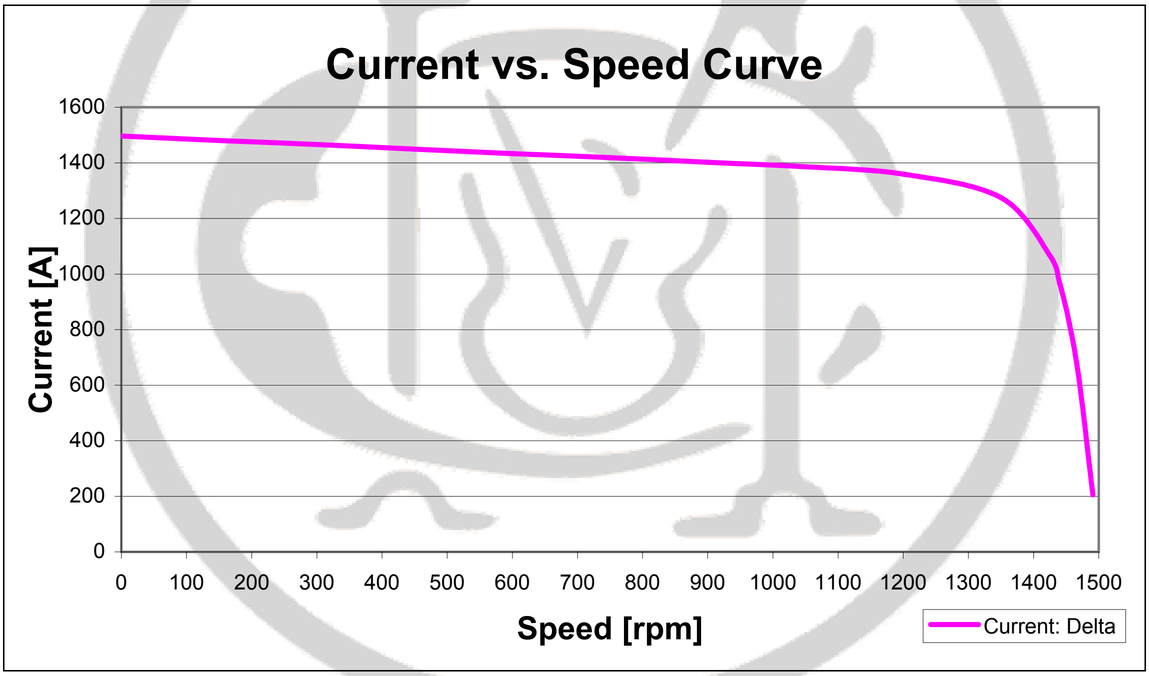
The motor's performance values are listed in table 1. It is crucial that we also examine the torque vs. speed and current vs. speed curves. These curves are shown in graphs 1 and 2.

Item	Load		
	Full Load	Starting	Unit
Power	120	101	kW
Voltage	380	380	V
Current	210	1530	A
	1.00	7.30	pu
Efficiency	93.9	0.0	%
Power Factor	0.87	0.10	
Speed	1491	0	rpm
Torque	769	1038	Nm
	1.00	1.35	pu

Table 1: 120kW motor's performance values running in DELTA



Graph 1: Torque vs. speed curve for Delta connection

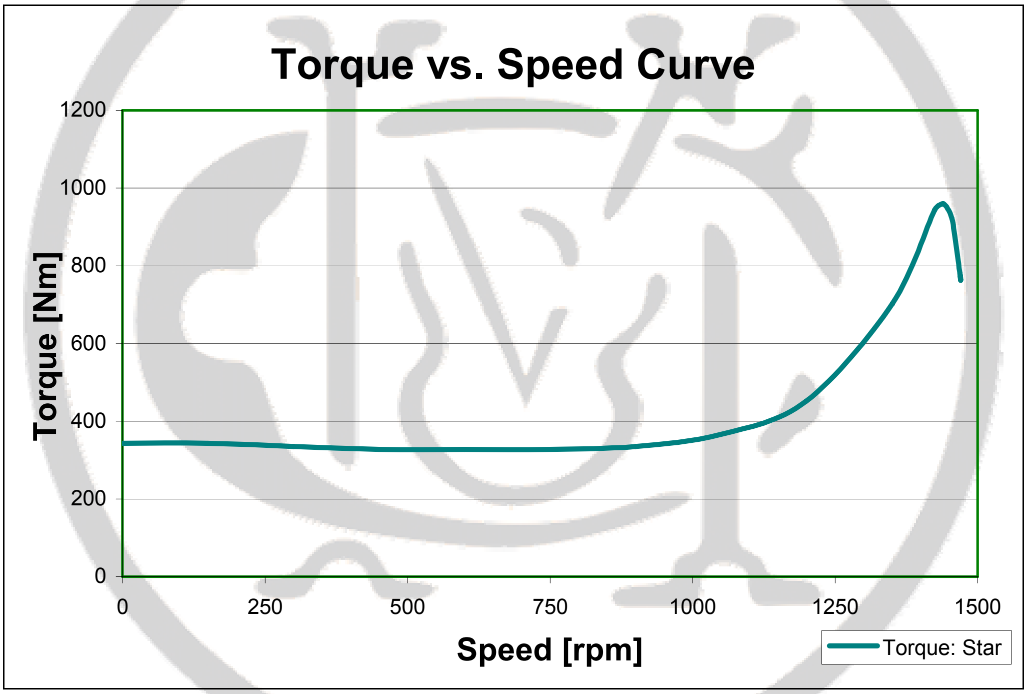


Graph 2: Current vs. speed curve for Delta connection

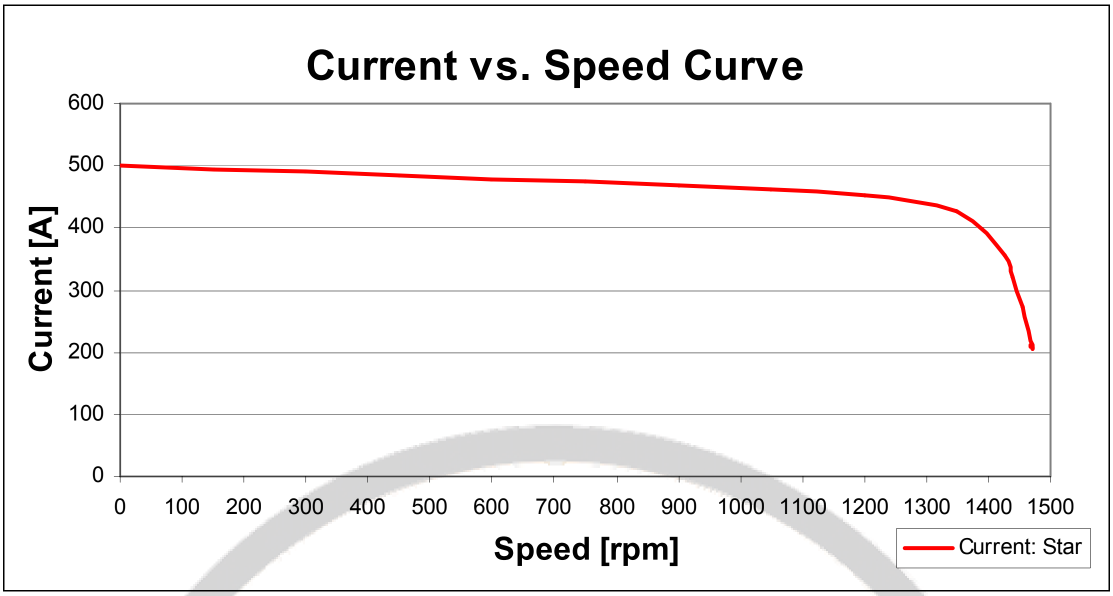
Now let's have a look what happens when the motor is connected in STAR, i.e. in the starting condition. The performance values are listed in Table 2. Graphs 3 and 4 again show the torque vs. speed and current vs. speed curves.

Item	Load		Unit
	Full Load	Starting	
Power	120	33	kW
Voltage	380	380	V
Current	212	500	A
	1.00	2.36	pu
Efficiency	92.3	0.0	%
Power Factor	0.86	0.10	
Speed	1469	0	rpm
Torque	780	343	Nm
	1.00	0.44	pu

Table 2: 120kW motor connected in STAR



Graph 3: Torque vs. speed curve for Star connection

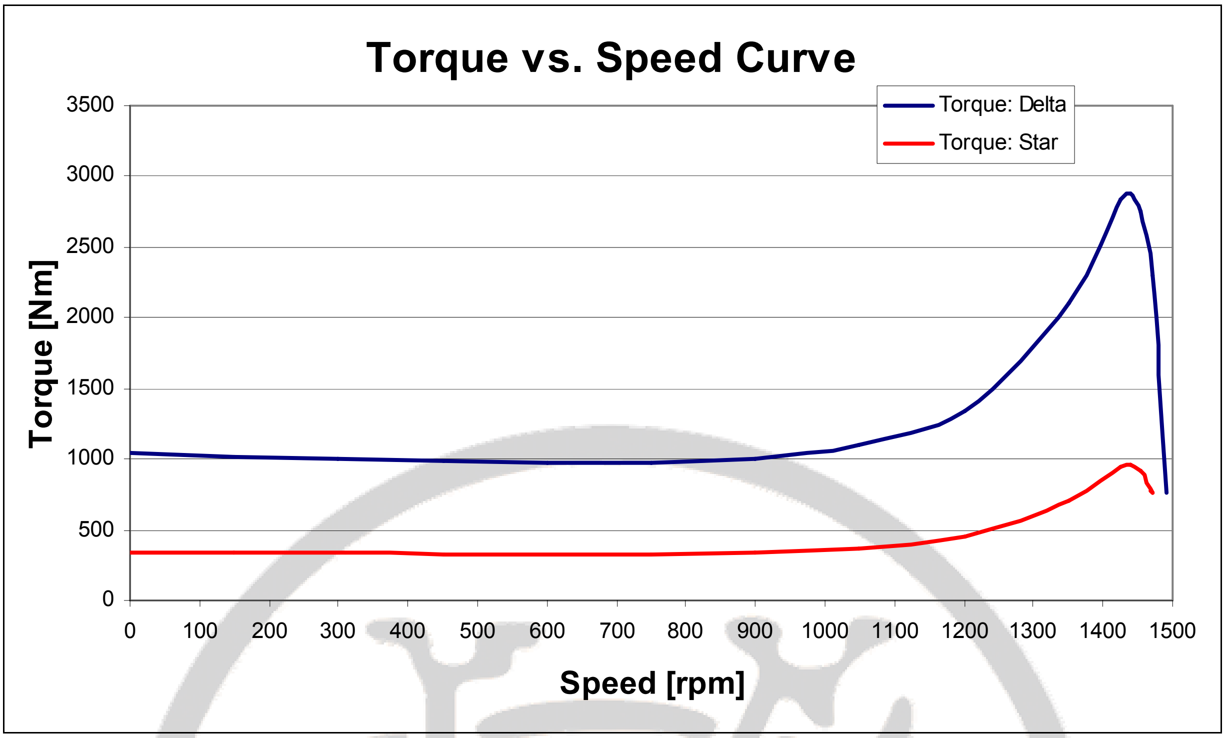


Graph 4: Current vs. speed curve for Star connection

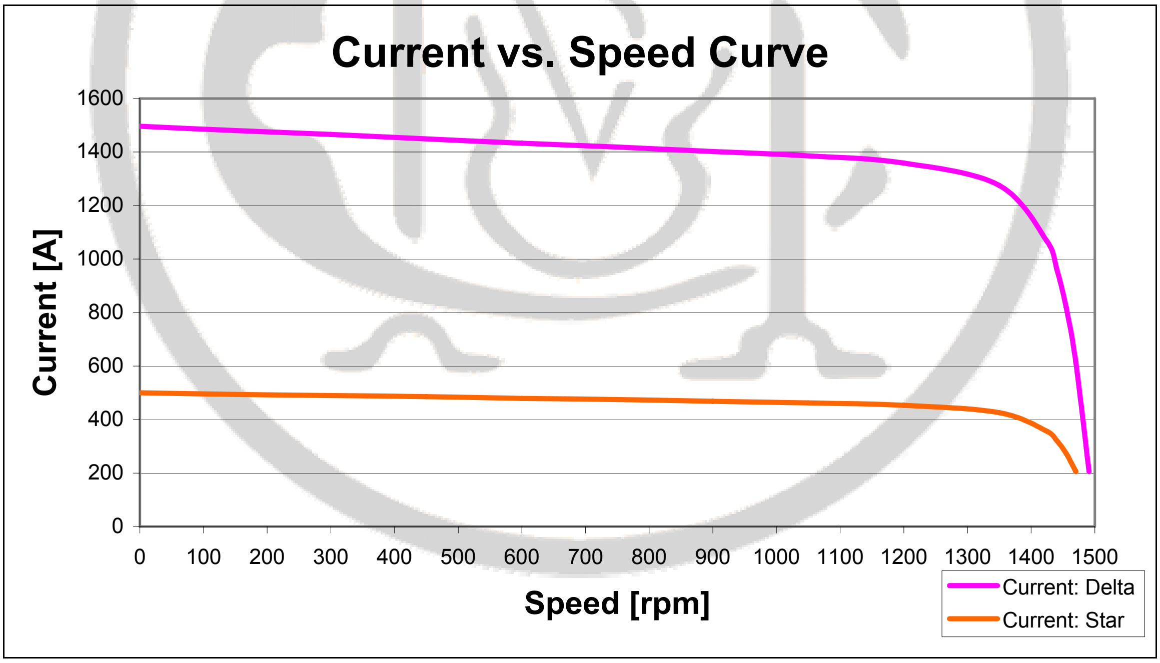
To truly grasp the differences between these two starting methods, we will list the values next to each other in table 3, and on graphs 5 and 6.

	DELTA CONNECTED		STAR CONNECTED		
Item	**Load**		**Load**		
	Full Load	**Starting**	**Full Load**	**Starting**	**Unit**
Power	120	98	120	33	kW
Voltage	380	380	380	380	V
Current	205	1495	212	500	A
	1.00	7.30	1.00	2.36	pu
Efficiency	93.9	0.0	92.3	0.0	%
Power Factor	0.89	0.10	0.86	0.10	
Speed	1491	0	1469	0	rpm
Torque	769	1038	780	343	Nm
	1.00	1.35	1.00	0.44	pu

Table 3: 120kW motor performance values: Delta and Star connection comparison



Graph 5: Torque vs. speed curve: Star and Delta connections compared



Graph 6: Current vs. speed curve: Star and Delta connections compared

Immediately we notice the primary reasons for using star delta starters on electric motors: The starting power is reduced from 98 kW to 33 kW (by approximately 67%), the starting current is reduced from 1495 A to 500 A (by approximately 67%). Because the motor is not intended to actually run in this connection, the reduction in full load speed, power factor and efficiency is not significant for this discussion.

One major disadvantage of the star delta starting is the reduction in the starting torque from 1038 Nm to 343 Nm (by approximately 67%). This will be discussed in depth later on.

The reason for these 67% changes becomes clear when we examine the phase voltage on the motor, we see that the phase voltage when the motor is connected in Delta is 380 Volt. When the motor is however connected in Star, the Phase Voltage will be 219.3 Volt. The relations for star and delta connections are as listed in Table 4:

	Star	Delta
Voltage	$V_{Line} = \sqrt{3} \times V_{Phase}$	$V_{Line} = V_{Phase}$
Current	$I_{Line} = I_{Phase}$	$I_{Line} = \sqrt{3} \times I_{Phase}$

Table 4: Relation between phase and line Currents and Voltage

Thus, when the motor is started in the star connection, the phase voltage of the motor is reduced by a factor of √3.

The reductions in starting current, starting power, and starting torques for a reduced Voltage can each be calculated by using equation 1 (This ignores other factors like saturation, etc.):

$$\text{Reduction in Value}[\%] = \left[1 - \left(\frac{\text{Nominal Voltage}}{\text{Reduced Voltage}}\right)^2\right] \times 100$$

Equation 1: Reduction in percentage for reduced Voltage

If we apply this equation for the star delta starting, we see from equation 2 where the 67% reduction comes from:

$$\text{Reduction} = \left[1 - \left(\frac{V_{Line\ Delta}}{V_{Line\ Star}}\right)^2\right] \times 100 = \left[1 - \left(\frac{V_{Phase}}{\sqrt{3} \times V_{Phase}}\right)^2\right] \times 100 = \left[1 - \left(\frac{1}{\sqrt{3}}\right)^2\right] \times 100 = 66.6666\%$$

Equation 2: Reduction due to star delta starting

What are the advantages of using Star Delta starting?

As calculated above, the most significant advantage is the reduction in starting current. The starting current will to a large extent determine the size of the cables used, the size of the circuit breakers, the size of the fuses, as well as the transformers.

Requiring 67% less starting current can have a tremendous cost saving implication!

The most significant advantage of using Star-Delta starting is the huge reduction in the starting current of the motor, which will result in a significant cost saving on cables, transformers and switch gear.

Does that mean that we should immediately install soft starters on all our existing motors?

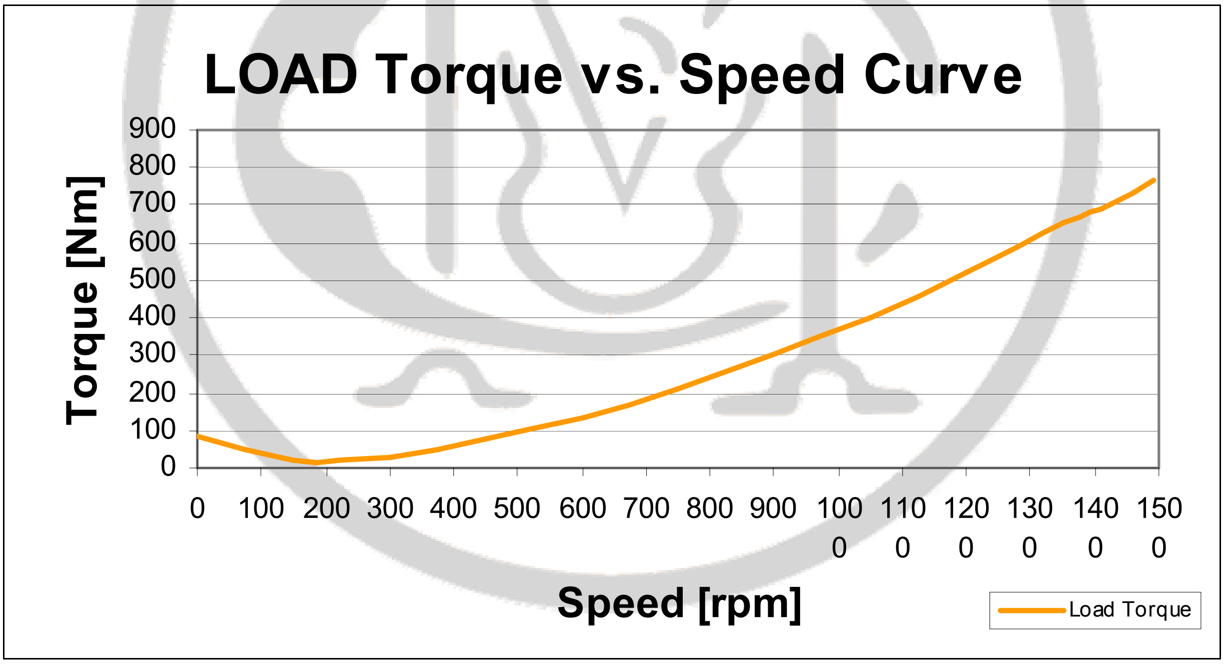
Firstly: No! The cost reductions will only result when a new installation is done! If the transformers, switch gear, cables and protection were initially selected for the high starting currents, there would not be a significant cost saving by installing a soft starter.

Secondly: Let us first further explore the 67% reduction in the motor's starting torque.

What are the disadvantages of using Star Delta starting?

As calculated above, the disadvantage of using star delta starting is the reduction in starting torque. This fact might not seem significant, but let us further explore the implications of this.

Consider a typical torque vs. speed curve of a fan (120 kW in this example), with an open damper starting condition. The initial torque requirement is as low as 10% of full load torque (0.10 pu). The square law curve then increases to 1.00 pu. Graph 8 shows this load curve.

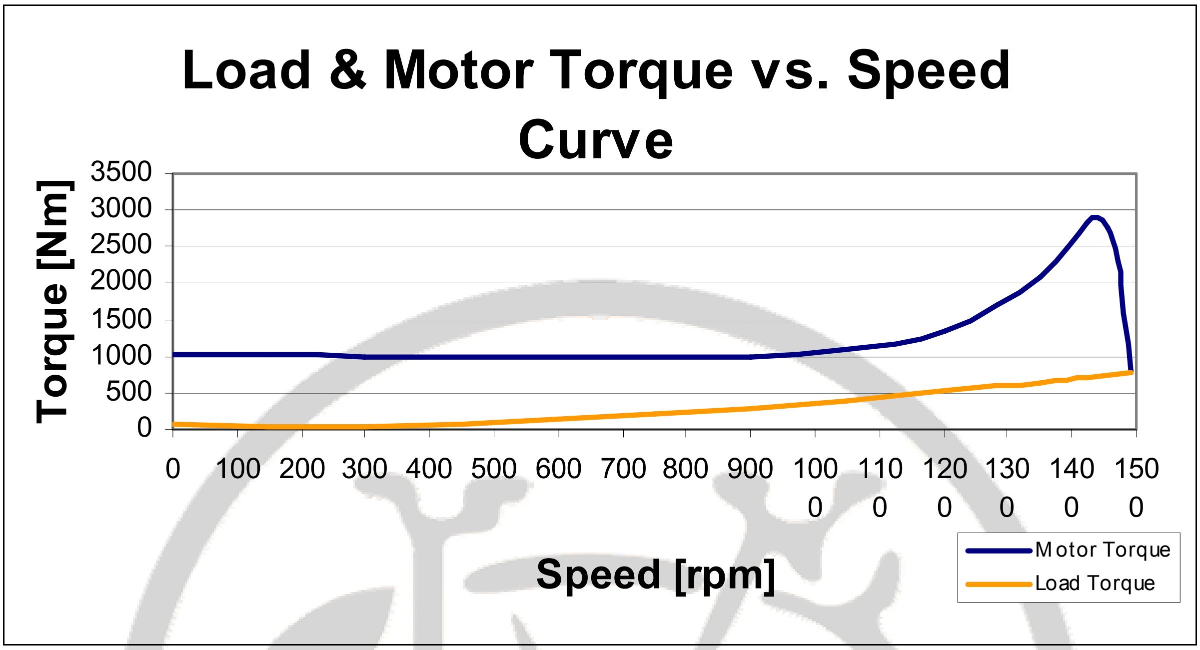


Graph 7: Load torque vs. speed curve for the 120kW example fan

When we superimpose the fan's load curve on the motor's torque vs. speed curve for the Delta connection, we see a healthy accelerating torque. The accelerating torque is the torque that accelerates the motor.

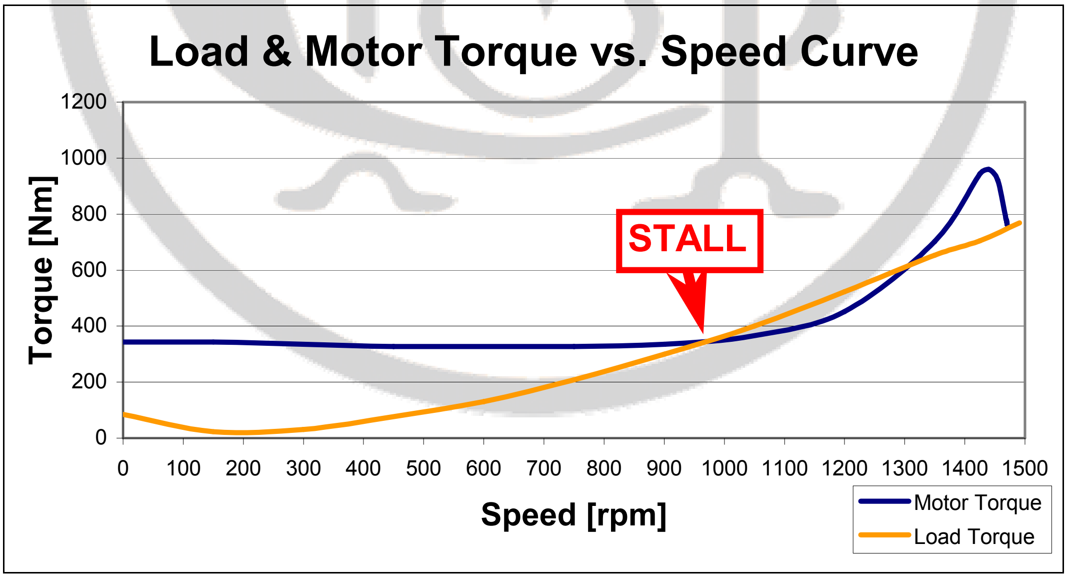
If the load torque is equal to the motor's torque, no acceleration will occur.

Graph 8 shows this comparison.



Graph 8: Load torque vs. speed curve superimposed on motor's torque vs. speed curve: Delta connection

Let's now also superimpose the fan's load curve on the Star connection's torque vs. speed curve, as shown in graph 9.



Graph 9: Load torque vs. speed curve superimposed on motor's torque vs. speed curve: Star connection

The red arrow indicates what is called a "*Stall*" condition. At this point, the motor **cannot accelerate**, because it does not have sufficient torque to overcome the load requirement!

One of two scenarios will then follow:

- If the protection system of the motor is sufficiently advanced, it would detect the stall condition, and trip the motor. This will protect the cables, transformers, switch gear, fuses and motor. BUT the plant will not run! What then normally follows is what is commonly referred to as the "*blou-draad*-principle". (The electrician will be told to disable this protection feature.)
- Otherwise, if the protection system does not detect the stall condition (or the "blou-draad-principle" was used) the motor will run at this low speed until the switch gear switches it over to the Delta connection. Then the motor will quickly accelerate to full load speed. The problems with this are:
  1. The reduced (star connection) starting current will now be maintained for a much longer period – until the motor is switched to Delta.
  2. When the switch over occurs, the stator current will jump rapidly to the Delta connection starting current, which negates any of the possible advantages of using a star delta starter in the first place.
  3. At switch over, there will be a huge amount of energy used. This energy can result in a flash-over, commutation, etc. Thus damaging the switch gear.

Even if the motor's torque was higher than the load torque, the run-up time of the motor would be greatly increased. This will result in much higher temperatures in both the rotor as well as the stator. In time, this can seriously compromise the long term reliability of the motor!

The most significant disadvantage of using Star-Delta starting is the huge reduction in the starting torque of the motor, which will result in a significantly increased run-up time, and may even result in a stall condition. Eventually this may lead to serious damage to the motor.

For this reason, even if there are potential cost savings by installing soft starters, customer's should be very careful to install them on each and every motor.

B. Dual Voltage Motors:

Reading a motor's rating plate can be an intimidating experience. Especially if the rating plate also lists two different Voltages!

Take another example motor: 185 kW, 4 Pole, 220 / 380 Volt.

The rating plate might look as shown in picture 3:

Manufacturer ABC

Power	185 kW	**Poles**	4
Voltage	220 / 380 V	**Duty**	S1
Current	539 / 312 A	**Enclosure**	TEFC

Picture 3: Example rating plate

NOTE: The explanation given here is what the connections in the motor SHOULD be, please consult you electric motor supplier to ensure that they use the same convention!

Let's again examine the motor's performance values as listed in table 5:

	DELTA CONNECTED		STAR CONNECTED		
Item	Load		Load		
	Full Load	Starting	Full Load	Starting	Unit
Power	185	103	185	103	kW
Voltage	**220**	**220**	**380**	**380**	V
Current	539	2697	312	1562	A
	1.00	5.00	1.00	5.00	pu
Efficiency	94.1	0.0	94.1	0.0	%
Power Factor	0.90	0.10	0.90	0.10	
Speed	1487	0	1487	0	rpm
Torque	1188	1045	1188	1045	Nm
	1.00	0.88	1.00	0.88	pu

Table 5: Dual Voltage motor performance values

I'm sure it is clear how this motor works.

- If the motor is connected to a 220 Volt, 3 phase supply, the motor should externally be connected in DELTA. It **does not** mean that the motor can be connected to a single phase power supply!
- If the motor is connected to a 380 Volt, 3 phase supply, the motor should externally be connected in STAR.

The dual Voltage is purely for versatility sake, and NOT to reduce starting currents.

What happens if the dual Voltage motor is incorrectly connected?

In the same example, let us now connect the motor incorrectly, and examine the consequences, as listed in tables 6 and 7.

Item	DELTA CONNECTED Load		DELTA CONNECTED Load		Unit
	Full Load	Starting	Full Load	Starting	
Power	185	103	185	292	kW
Voltage	220	220	380	380	V
Current	539	2697	1480	4440	A
	1.00	5.00	1.00	3.00	pu
Efficiency	94.1	0.0	78.7	0.0	%
Power Factor	0.90	0.10	0.19	0.10	
Speed	1487	0	1495	0	rpm
Torque	1188	1045	1182	2671	Nm
	1.00	0.88	1.00	2.26	pu

Table 6: Performance comparison for motor incorrectly connected: Delta

Item	STAR CONNECTED Load		STAR CONNECTED Load		Unit
	Full Load	Starting	Full Load	Starting	
Power	185	103	125	33	kW
Voltage	380	380	220	220	V
Current	312	1562	386	868	A
	1.00	5.00	1.00	2.25	pu
Efficiency	94.1	0.0	90.5	0.0	%
Power Factor	0.90	0.10	0.85	0.10	
Speed	1487	0	1465	0	rpm
Torque	1188	1045	815	350	Nm
	1.00	0.88	1.00	0.43	pu

Table 7: Performance comparison for motor incorrectly connected: Star

We can see that connecting the motor in Delta to a 380 Volt supply will result in a huge starting current. This is because the core flux densities will drive the core deep into saturation. This can also be seen from the very low power factor. Excessive heat will be generated, and the switch gear, cables, fuses, and transformers may also be damaged.

In the case of the star connection connected to 220 Volt, the motor could not deliver the required 185 kW. It could only deliver 125 kW. The full load speed is also greatly reduced, even at this lower power. The most likely scenario is that the motor will stall, because it cannot produce sufficient torque to drive the load, this will probably result in premature failure of the motor.

Conclusion:

If we lived in a perfect world, we would not have had global warming, the need for nuclear weapons, riot gear, and unscrupulous manufacturers, importers, and dealers! Back on planet earth, we know that Adam and Eve were chucked out of paradise a long time ago!

Everybody wants to make the quick buck, even if it means sacrificing his brother's job in a South African factory in order to sell a cheaper import from a country far-far away. Because of these unscrupulous dealers – and their customers, even local suppliers have been forced to cut costs and unfortunately sometimes also long term reliability!

Ensure that your electric motor supplier is reputable and able to fully assist you in selecting the correct motor for the correct application, using the correct connections and starting conditions!

We are proud to engineer quality solutions for our valued customers.

Henk de Swardt
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Henk de Swardt has a B. Sc. in Electrical and Electronic Engineering. He has more than eleven years of electric motors experience, both in the electric motor repair industry, as well as the electric motor manufacturing industry. He was employed for several years by the Largest OEM in South Africa. He also received specialized training in France on the designing of Electrical Motors. He is currently serving the Electric Motor industry at the Largest repairer of MV and HV motors in Africa. For a full C.V. visit http://www.qtime.co.za/CV_Main.html

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- The effects of an increased air gap of an electric motor.
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