HARMONIC-FREE MAGNETIC (FCMA) SOFT STARTERS FOR LARGE CAPACITY HIGH VOLTAGE INDUCTION AND SYNCHRONOUS MOTORS DRIVING PUMPS AND COMPRESSORS

by

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ABSTRACT

Most of the water supply schemes use electrical power in large quantities. As such, optimization is needed for reducing life cycle cost of the entire establishment in terms of capital cost, minimum downtime, and maximum availability. It is also important to avoid disturbances in the power system in terms of overloading and other harmful effects like voltage and frequency dips and harmonics.

The large pumps, in many water systems, are driven by induction and synchronous motors. These motors pose a problem of high starting currents leading to voltage dips, large thrust on pumps, and jerks on equipment affecting the life of the system adversely.

This paper deals with innovative magnetic soft starters based on flux compensation technology (FCMA). The use of FCMA helps in optimizing power systems, increasing the life of components, and reducing the capital cost and maintenance expenditure of pumping systems. It also assists in enhancing motor efficiency.

This technology has been successfully implemented for about 600 MW motor power in the pumping sector.

INTRODUCTION

Water pumping is one of the most important public utilities. Large-scale pumping schemes are required for irrigation, drinking water supply, as well as sewage handling and treatment. For industry, water is required in large quantities for process industries and power stations. Most of the water pumping schemes use electrical power in large quantities. As such, optimization is needed for reducing the life cycle cost of the entire establishment in terms of capital cost, ease of operation and maintenance, energy cost, minimum downtime, and maximum availability of the scheme. It is also important to avoid disturbances in the power systems in terms of overloading and other ill effects such as voltage and frequency dips and harmonics, so that other users get a stable and clean power supply.

With the advancement of technology there has been a clear trend in the deployment of larger and larger rated pumps to improve the hydraulic and electrical efficiency, as well as reduce the overall capital cost. The motor drives employed for these pumps are generally induction motors or induction start synchronous run motors; the primary reason being their simplicity of construction, excellent reliability, and high efficiency coupled with negligible maintenance. Induction start motors however pose a problem of large starting current (typically four to eight times the full load current), which can disturb the power system in terms of voltage and frequency dips. Moreover, sudden uncontrolled acceleration of the pump from standstill may create large reverse thrusts on the mechanical and civil foundations as well as jerks on the drive elements.

This paper deals with an innovative magnetic soft starter technology based on the principle of flux compensation (FCMA) to achieve jerkless and harmonic-free soft starting of large pumps with substantially reduced starting current. This technology has been successfully implemented for a cumulative power of 600 Megawatts motor power with the largest single rating at 10.5 MW for operating voltages up to 11 kV. The soft starters are now under development for 25 MW and 67 MW single pump drives for irrigation applications.

This paper analyzes the following salient points:

- General benefits of FCMA soft starters for pumping schemes
- Technical considerations for soft starter application and optimization case studies bringing out the benefits to the pumping scheme

- Electrical connectivity of the soft starter in the switchgear scheme and comparative cost benefit analysis of connection schemes
- User case study on large-scale application of FCMA soft starters for pumps for reduction in operation and maintenance expenditure and life cycle cost
- User case study on starting of pumps with FCMA soft starters on captive power in sponge iron plant with a view to save capital cost and maintenance cost
- Case Study on starting of large pumps on limited power for pump test bed application
- Technological details of the FCMA
- Design case study on optimization of supply transformer rating for pumps with FCMA soft starters with a view to save capital cost and revenue cost
- Design case study on optimization of captive generator rating for pumps with FCMA soft starters with a view to save capital cost and running cost
- Design considerations on optimization of system fault level by providing FCMA soft starters to reduce the capital cost of the system and reducing fault damage
- Enhancement in motor design efficiency by matched design of a motor and FCMA soft starter
- Design case study for improvement in motor starting duty due to FCMA soft starters to achieve energy savings in cyclically loaded pumps
- Improvement in motor life due to FCMA soft starters
- Design considerations for increasing safety factors on the gear tooth load for gear driven concrete volute casing pump by starting with FCMA soft starters
- Reliability aspects of the FCMA technology for critical applications such as nuclear power plants

GENERAL BENEFITS OF FCMA SOFT STARTERS FOR PUMPING SCHEMES

FCMA soft starters benefit the pumping scheme from the electrical, mechanical, and civil aspects in the following manner:

- Reduced starting current limits the voltage drop in the power system to within acceptable limits.
- Harmonic-free starting and running eliminates electrical supply corruption.
- Transformers and generators can be sized for running power and need not be larger only for starting considerations.
- Lower fault level allows economical selection of cables and switchgear.
- Improvement in motor starting duty allows optimal start/stop cycle of pumps for energy conservation and restarting on power failure.
- Smooth starting with controlled torque minimizes impulse torques on rotating parts, thus increasing component life. Certain pumps, such as boiler feed-water pumps, require high rpm to generate high head, and hence are driven through step up gearboxes. Similarly, certain other pumps such as concrete volute casing pumps that have high flow and low head, require low rpm, and hence are driven through step down gear boxes to avoid the low power factor and efficiency associated with low rpm directly coupled induction motors. FCMA soft starters, by virtue of limiting the peak torque during entire acceleration, increase the safety factor for gear tooth load.
- Gradual acceleration of pump leads to gradual pressure buildup reducing stresses on pipelines.
- Gradual pressure buildup reduces reverse thrust particularly in vertical turbine pumps reducing foundation stresses.
- It is possible to improve design efficiency of the motor by relaxing the direct online (DOL) starting current limit and then control the starting current through an FCMA soft starter.
- It is possible to set the supply transformer output voltage at lower value and reduce core losses in the transformer as well as running motors while limiting the starting voltage dip through an FCMA soft starter.

TECHNICAL CONSIDERATIONS FOR FCMA SOFT STARTER APPLICATION

For the optimal performance of the soft starter and achieving maximum system benefits several technical considerations are important. The fundamental function of the soft starter is to accelerate the pump and motor combination smoothly with the least possible starting current value and in the optimum time.

The pump represents the load, which is defined by its torque speed characteristics during starting and rotating inertia (GD^2). The torque speed characteristics of the pump depend upon the type of the pump, e.g., radial flow, mixed flow, or axial flow, whether concrete volute casing or metal casing, also whether the discharge valve is closed or open during starting. For large turbine pump applications water depletion systems may be used for reducing the load during starting. For certain other applications variable filling fluid couplings may be used that provide reduced starting load. In such cases the corresponding torque speed curves are used for more effective soft starting with FCMA.

The relationship between the pump torque demand and speed is of parabolic nature governed by the following equation:

$$T \alpha N^2 \tag{1}$$

where T represents the torque demand and N represents the pump speed. The pump curves are well defined and do not differ much once the type of pump and discharge valve status is decided.

The motor represents the prime mover and is defined by its torque speed characteristics, current speed characteristics, thermal withstand time, and the rotating inertia. The motor designer has a substantial flexibility in choosing these characteristics so as to meet the demand effectively.

The FCMA soft starter essentially modulates the motor characteristics during starting for system optimization. The starting current is minimized and torque is controlled to ensure correct acceleration in optimum time.

The plots in Figure 1 elaborate the starting performance of a typical pump motor drive combination with FCMA soft starter.

The curve set which is drawn for a typical application brings out the following criteria:

- The DOL starting current, which is six times full load current, is brought down to three times with FCMA soft starter.
- The resultant reduced starting current remains constant in the acceleration range and then drops down to the normal value.
- The DOL current curve shows a droop in the current as the speed increases. The FCMA soft starter provides a voltage increment just enough to compensate for this droop and keep the reduced current constant.
- The voltage increment is reflected as a gradual increase in motor torque.
- The transition from soft starter mode to run mode (FCMA bypass) is a smooth closed transition and no current kick is observed.

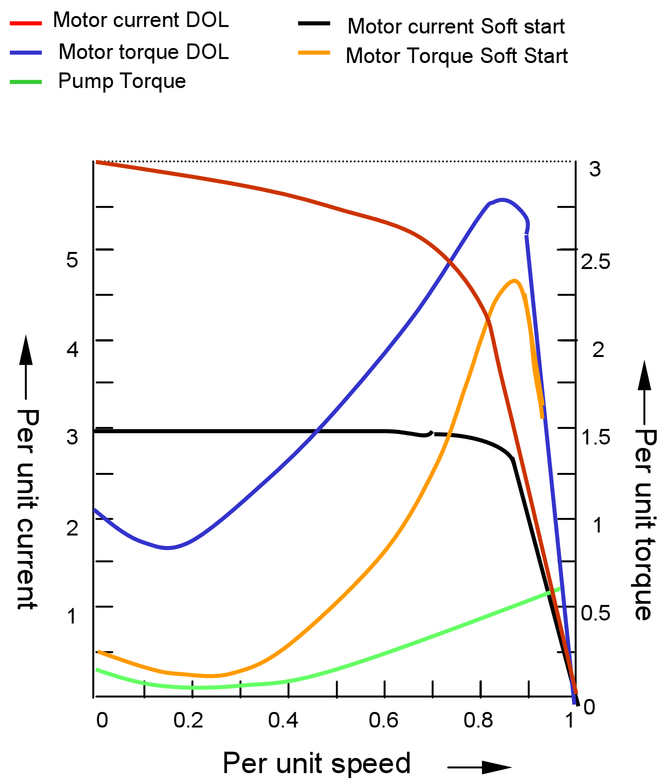

Figure 1. Acceleration Curve for Torque and Current.

• It is ensured through FCMA that the motor torque is always larger than the pump torque demand by 0.1 per unit (10 percent margin) ensuring gradual and continuous acceleration. This criterion is very important to prevent, dwelling at critical speeds and resultant vibrations during acceleration, especially for high peripheral speed large pumps.

ELECTRICAL CONNECTIVITY OF THE SOFT STARTER IN THE SWITCHGEAR SCHEME

The FCMA soft starters can be easily integrated into new electrical schemes or retrofitted into existing electrical schemes. For high voltage motors the FCMA can be connected in the line side or neutral side of the motor as shown in Figure 2. The operational sequence for both the connections is as follows:

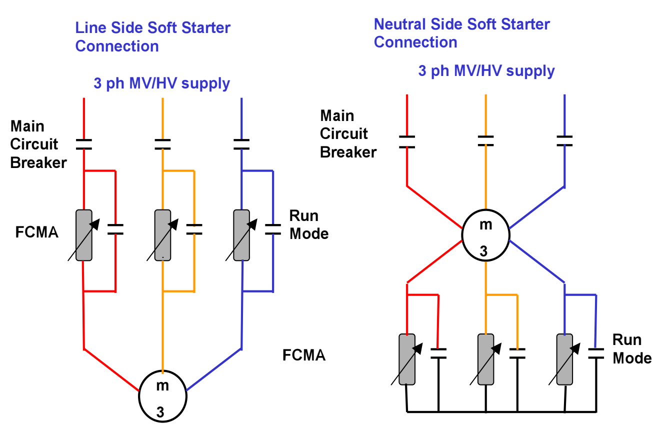

Figure 2. Line and Neutral Side FCMA Soft Starter.

• The discharge valve is set at open or closed condition as per the pump design to achieve minimum starting load.

• The motor is started by closing the main circuit breaker.

• The FCMA provides high impedance to limit the motor starting current to a low value.

• As the motor accelerates, the FCMA impedance decreases gradually and in a stepless manner thus providing incremental voltage and torque to the motor while keeping the current constant at reduced value. The motor voltage is incremented from the initial low value (typically 50 percent) to approximately 95 percent as the motor speed increases.

• The pump and motor gradually reach full speed as per the design values based on the plotted soft starting curves.

• The built-in run mode contactor automatically bypasses the FCMA through a time, speed, or current signal.

• The entire starting sequence is monitored by a supervisory control and interlocked with the main circuit breaker.

• The motor now operates at full supply voltage.

• Run mode command is generated to allow operation of the discharge valve and loading of the pump as per user's requirement.

The choice between the line side connection and neutral side connection is governed by the following criteria:

• Almost all of the medium and high voltage motors are star (Y) connected.

• Medium and high voltage equipment are designed both for the operating current as well as the short circuit current (fault level).

• The functioning of the FCMA is identical for both the line and neutral connections.

• The neutral side connection benefits from the fact that the fault level is substantially reduced due to the current limiting action of the motor winding impedance. Hence the neutral side FCMA is primarily designed for the operating currents and, therefore, economical.

• In the run mode the neutral side FCMA is operating at zero potential resulting in unlimited life expectancy.

• The neutral side FCMA requires only one power cable connection and hence is compact in size.

• For retrofitting, the neutral side FCMA is very convenient, as the line side power cables need not be disturbed.

• Normally the neutral side FCMA can be conveniently located near the pump and motor.

• The line side FCMA is preferred when the FCMA is to be located in the switchgear room due to constraint of area near the pump.

• The line side FCMA is designed both for the starting current as well as the let through fault current and hence is larger in size to the neutral side FCMA.

CASE STUDY ON LARGE-SCALE APPLICATION OF FCMA SOFT STARTERS FOR PUMPS FOR REDUCTION IN OPERATION AND MAINTENANCE EXPENDITURE AND LIFE CYCLE COST

Background

This scheme involves the pumping of clear water to Bangalore city in India. Water is supplied to Bangalore from the river Kaveri, located at a distance of 80 kilometers (49.7 miles). Twenty horizontal split case pumps discharge 1892 cubic meters per hour (499,813.5 gph) at 160 m (524.9 ft) head with motor ratings of 1250 kW, 6.6 kV are employed. The old starting system was with autotransformers and had a very large and frequent failure rate of motors and starters causing disruption in the city water supply.

The user decided to install FCMA soft starters for the above motors in the year 1999 to 2000 as a replacement of autotransformer starters. Neutral side FCMA soft starters were installed near each pump. Starting current for the motors was reduced from six times of full load current in DOL mode and 3.9 times in auto-transformer mode, to three times with FCMA soft starters.

Motor failures were entirely eliminated since the FCMA soft starters were installed and availability of pumps increased substantially. There was a substantial reduction (approximately 15 percent) in routine and breakdown maintenance expenditure. The user's analysis revealed that the benefits are largely attributable to installation of FCMA soft starters, which ensured smooth starting with lower starting current value leading to reduced electromagnetic and mechanical stresses.

Conclusion

Implementation of FCMA soft starters has led to overall reduction in the life cycle cost of the pumping system (roughly estimated at 2 percent). Based on the above experience the user has installed an additional 24 FCMA soft starters for further augmentation of the water supply scheme.

CASE STUDY ON STARTING OF PUMPS WITH FCMA SOFT STARTERS ON CAPTIVE POWER IN SPONGE IRON PLANT WITH A VIEW TO SAVE CAPITAL COST AND MAINTENANCE COST

A sponge iron plant is located at Revdanda near Mumbai in India. The electrical energy for the process is generated from the waste heat recovery augmented with diesel generating sets. The plant does not depend upon an electricity board supply for operations. For plant startup all the drives are started on diesel generating (DG) sets. The DG set ratings are 3.25 MVA.

The user decided to install FCMA soft starters for the 1750 hp, 1170 hp, and 700 hp 6.6 kV pump motors to enable smooth starting and to limit the voltage drop on the generators to within 10 percent. Alternatively an additional DG set of capacity 3.25 MVA would have been required to be installed, just to cater to the starting requirements due to high DOL starting currents of the large motors. Neutral side FCMA soft starters were installed for each pump in 1993.

Starting current for the motors was reduced from six times in DOL mode to three times with FCMA soft starters. Capital cost of one additional DG set of 3.25 MVA was saved. Fuel cost for running the additional DG set during each startup and tripping was saved. Yearly maintenance cost of the additional DG set was saved. There has been no maintenance cost for the FCMA soft starters since 1993 to date.

Based on the above experience the user is installing additional FCMA soft starters for further expansion.

CASE STUDY ON STARTING OF LARGE PUMP ON LIMITED POWER FOR PUMP TEST BED APPLICATION

A pump manufacturer in India has set up a large pump test facility at Kirloskarwadi in India for testing large pumps. The power supply system comprises 2 × 3.15 MVA transformers at 33/11 kV supply. For testing of the 2700 kW motor, the supply was found to be inadequate if DOL starting were to be employed. The transformer rating is not suitable and other users on the 33 kV grid would be adversely affected due to large voltage drop during DOL starting. For DOL starting the supply capacity would have been augmented to 200 percent, i.e., 12.5 MVA on the users' premises. The feeder transmission line would have to be replaced with higher capacity. The supply authority transformer would have been required to be increased by 25 percent.

It was important to maintain harmonic-free supply because the electrical power measurement is used for pump power computations with a tested motor. The pump efficiency is calculated based on motor output power, which is derived by subtracting the calibrated motor losses from the motor electrical input power.

The user decided to install an FCMA soft starter to reduce the starting current load as well as to ensure harmonic-free power measurement. The starting current value with the FCMA soft starter was achieved at 2.5 times full load current instead of the six times DOL current.

The user saved capital cost for supply augmentation on their premises as well as the power supply authority. The user also saved the time for implementation of the supply augmentation. The user has now decided to implement the FCMA starters for testing of 4.5 MW pumps on the same supply system.

TECHNOLOGICAL DETAILS OF THE FCMA

FCMA soft starters work on the principle of impedance control by superimposing two-phase opposed alternating fluxes on a common magnetic core. Such controlled impedance, when connected in series with the motor, provides a constant current incremental voltage to the motor resulting in incremental torque as the motor speed increases.

In its simplest form FCMA consists of two windings wound on a common magnetic core. The first winding is called the main winding and is connected in series with the motor windings as shown in Figure 3 and carries the main motor current. The second winding is called the feedback winding or compensating winding and is wound with a polarity opposite to the main winding. This winding is excited with the counter electromotive force (emf) generated by the motor. The core is subjected to two simultaneous sinusoidal fluxes opposing each other due to the magnetomotive force (mmf) created by the main and compensating windings. As both the fluxes are sinusoidal in nature, the net flux in the core is sinusoidal. As the motor speed increases the compensating flux increases, thus reducing the net flux in the core. The impedance of the main winding hence decreases with motor speed, to keep the motor current constant and increment the motor voltage. The voltage increment is obtained by correcting the natural droop in the motor current with speed. Thus the effective motor voltage increases from a low value (typically 50 percent) at start, to near full value (typically 95 percent) when the motor reaches full speed. As the FCMA impedance varies in a stepless manner the voltage increment is also stepless. The voltage increment feature is very advantageous for acceleration of centrifugal drives such as pumps, because the pump torque demand also increases with speed, in a near parabolic fashion. The FCMA core is always subjected to alternating fluxes and works in the linear zone, thus ensuring that the voltage and current waveforms are purely sinusoidal in nature and totally harmonic free (Figure 4). When the drive accelerates to full speed the run mode contactor bypasses the FCMA with closed transition. FCMA soft starters control the amplitude of motor current without distorting the current waveform. This leads to zero harmonics and substantially low starting current.

DESIGN CASE STUDY ON OPTIMIZATION OF SUPPLY TRANSFORMER RATING FOR PUMPS WITH FCMA SOFT STARTERS WITH A VIEW TO SAVE CAPITAL COST AND REVENUE COST

Background

Pumping schemes are normally designed with multiple pumps to cater to the demand pattern. These pumps are started and stopped sequentially. It is preferred to use fewer large capacity pumps to achieve better energy efficiency. In such cases, the ratio of transformer size to the kW rating of a single pump is low. Thus DOL starting of such pumps presents a large starting MVA on the transformer. In such cases, the transformer sizing is governed, not only by the cumulative running loads of the pumps, but also by the starting MVA demand of the last started pump. FCMA soft starters, by virtue of their capability to reduce the starting MVA demand, allow optimum sizing of the transformer, nearer to the running load demand.

HARMONIC-FREE MAGNETIC (FCMA) SOFT STARTERS FOR LARGE CAPACITY HIGH VOLTAGE INDUCTION AND SYNCHRONOUS MOTORS DRIVING PUMPS AND COMPRESSORS

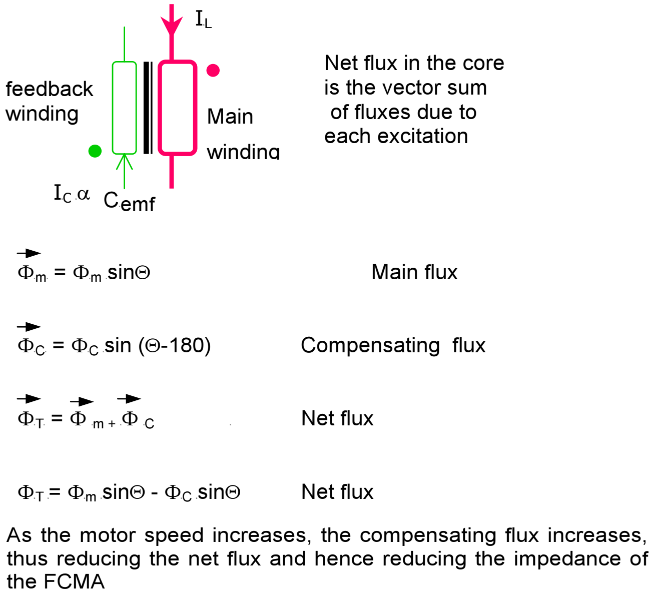

Figure 3. Flux Compensation Principle.

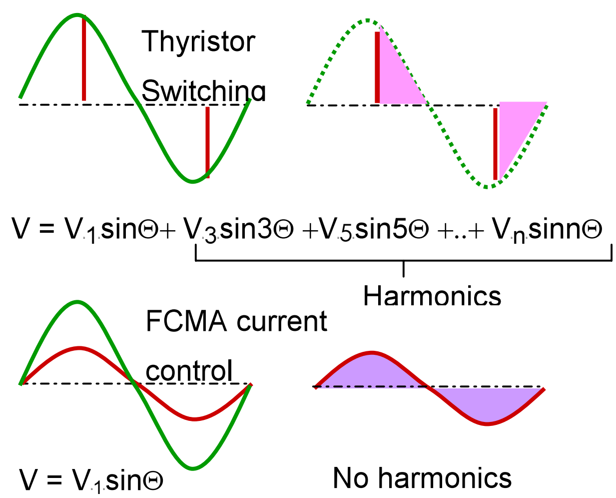

Figure 4. Wave Form Comparison.

A typical sizing calculation (Table 1, please refer to APPENDIX A for detailed calculations) highlights the optimization and consequential cost savings. The technical considerations for selection are as follows:

Table 1. Supply Transformer Capacity Optimization.

Description	DOL starting	FCMA soft starting
Pump rating	1700 KW	1700 KW
Quantity	3	3
Starting current (times full load)	6	3
Motor full load KVA	1886	1886
Motor starting KVA	11317	5655
Transformer KVA load for 3 motors running	5655	5655
Transformer KVA load for 2 motors running and third motor starting	13582	8205
Transformer rating with 1.5 overload factor	9055	5470
Selected transformer nominal rating KVA	10000	6000

- Supply voltage drop during starting of any motor to be limited within 10 percent of nominal voltage
- Transformer per unit impedance is assumed at 7 percent
- Transformer is rated for 150 percent overload for one minute

Conclusions

The nominal rating of the supply transformer is reduced from 10,000 kVA for DOL starting to 6000 kVA for FCMA soft starting, resulting in capital cost savings. When contract demand and minimum electricity charges are based on transformer rating, the FCMA soft starter scheme, due to lower transformer nominal rating, will result in lower revenue cost.

DESIGN CASE STUDY ON OPTIMIZATION OF CAPTIVE GENERATOR RATING FOR PUMPS WITH FCMA SOFT STARTERS WITH A VIEW TO SAVE CAPITAL COST AND RUNNING COST

Background

Particularly in developing countries, due to power shortages, pumps may have to run on captive power generating sets. Moreover, for emergency applications, such as firefighting and disaster management, captive generators may be employed. DOL starting of pumps presents a large step loading on the generator leading to excessive frequency and voltage drops. The generator sizing is governed, not only by the cumulative running loads of the pumps, but also by the starting demand of the last started pump.

FCMA soft starters, by virtue of their capability to reduce the step kW and kVA demand, allow optimum sizing of the generators nearer to the running load demand. A typical sizing calculation (Table 2, please refer to APPENDIX B for detailed calculations) highlights the optimization and consequential cost savings. The technical considerations for selection are as follows:

- Generator voltage drop during starting of any motor to be limited within 10 percent of nominal voltage
- Generator transient impedance (X'd) is assumed at 15 percent
- Generator step load capability is 40 percent of balance kW rating after subtracting the base load
- Alternator is rated for 150 percent overload for one minute for low power factor (pf) loads.
- Base load of 250 kVA is considered

Table 2. Generator Capacity Optimization.

Description	DOL starting	FCMA soft starting
Pump rating	1700 KW	1700 KW
Quantity	3	3
Starting current (times full load)	6	3
Motor full load KVA	1886	1886
Motor starting KVA	11317	5658
Base load of auxiliaries KVA at o.8 pf lagging	250	250
Generator KVA load for 3 motors running	5903	5903
Generator KVA load for 2 motors running and third motor starting	13779	8424
Selected Generator nominal rating KVA at 0.8 pf lagging	12500	7500
Maximum voltage drop percent	9.45	5.03
Percentage generator KW loading during running	53.5	89

Conclusions

Nominal rating of the generator is reduced from 12,500 kVA for DOL starting to 7500 kVA for FCMA soft starting, resulting in capital cost savings.

The generator kW loading for a DOL scheme is only 53.5 percent and will lead to low fuel efficiency and poor engine performance. This will also mean improper combustion and higher exhaust pollution. The generator kW loading for an FCMA soft starter scheme is 89 percent, which will lead to optimum fuel efficiency and minimum exhaust pollution. There will be a direct and continuous saving in the fuel cost (approximately 10 percent).

DESIGN CONSIDERATIONS ON OPTIMIZATION OF SYSTEM FAULT LEVEL BY PROVIDING FCMA SOFT STARTERS TO REDUCE THE CAPITAL COST OF THE SYSTEM AND REDUCE FAULT DAMAGE

In large power stations, boiler feedwater pumps comprise the single largest load. For a typical pump rating of 9 MW (10 MVA) the DOL starting MVA is designed to be 4.5 times, i.e., 45 MVA. For limiting the starting voltage drop to within 10 percent, the system fault level is designed at 45/0.1 = 450 MVA. Thus, all the cable and switchgear have to be necessarily designed for the next standard fault level at 500 MVA. Moreover, in case of an actual fault, the system is subjected to 450 MVA stresses. By employing FCMA soft starters, the starting MVA can be reduced to 2.5 times, i.e., 25 MVA. Thus to satisfy the condition of 10 percent voltage drop during starting, the system needs to be designed only for a 250 MVA fault rating. This leads to substantial reduction in cable cost as well as switchgear cost. Moreover, in the event of an actual fault, the stress level on the system will reduce to half. Reduced fault level also allows better discrimination of backup protection relays preventing block tripping of the system.

ENHANCEMENT IN MOTOR DESIGN EFFICIENCY BY MATCHED DESIGN OF MOTOR AND FCMA SOFT STARTER

Induction motor design is essentially a tradeoff, between the starting characteristics and running performance. The running performance is designated by the following important parameters:

- Efficiency
- Full load speed
- Power factor

The starting characteristics are designated by the following important parameters:

- Torque-speed curve
- Starting current

Conventionally, for the sake of simplicity in starting switchgear, direct online starting was employed, and hence the DOL starting current was preferred to be within six times the full load current of the motor. In fact, motor designers were encouraged to design motors with less than 4.5 times starting current.

Lower DOL starting currents can be provided for motors only by increasing the rotor resistance or the stator leakage reactance, which directly leads to a decrease in motor design efficiency. Conversely, relaxing the limit of DOL starting currents allows a decrease in rotor resistance and stator leakage reactance. This is made possible by improved magnetic materials, improved conducting materials, and lower air gap designs and tailored slot designs coupled with better winding techniques.

Thus the motor designer, if allowed to relax the starting current limits, can design a more efficient motor. For example, a 1492 kW, 11 kV, four-pole motor with a starting current relaxation up to eight times full load current can be designed with 0.4 percent enhanced efficiency than the same motor with starting current limitation at six times. The starting current in practice is reduced to 3.5 times by employing an FCMA soft starter. Thus, both the objectives of increased motor efficiency and reduced starting current are achieved by matched design of motor and FCMA soft starter.

DESIGN CASE STUDY FOR IMPROVEMENT IN MOTOR STARTING DUTY DUE TO FCMA SOFT STARTERS TO ACHIEVE ENERGY SAVINGS IN CYCLICALLY LOADED PUMPS

In certain pumping schemes, depending on the actual water demand, the flow may need to be varied with time. This can either be achieved by throttling the discharge valves, varying the pump speed, or frequent starting and stopping of the pumps. Discharge valve throttling is not energy efficient at all. Varying the pump speed will have limitations for high static head applications, as well as high capital cost. The method of frequent starting and stopping of the pumps is most energy efficient but has a limitation from the number of DOL starts per hour allowed by the motor.

FCMA soft starters enhance the starting duty of the motors substantially. The limit on the permissible number of starts for a motor relates to its thermal withstand capability, which is normally referred to as the I^2t capability and is governed by the following equation:

$$\left(I_{st} / I_{fl} - 1\right)^2 t * s = K \quad (2)$$

where:
I_{st} = Starting current in amps
I_{fl} = Motor full load current
t = Acceleration time
K = Design constant
s = Number of consecutive starts

Thus for a DOL starting current of six times full load current and acceleration time of four seconds and an allowable starting duty of two consecutive starts, the value of K will be:

$$K = (6-1)^2 * 4 * 2 = 200 \quad (3)$$

For FCMA soft starting with a starting current of three times and acceleration time of 10 seconds and design constant K at 200, the available starting duty will be:

$$s = 200 / \left(10 * (3-1)^2\right) = 5 \quad (4)$$

Thus, for the same motor, the starting duty is enhanced from two to five consecutive starts. This enhancement will facilitate frequent start-stop of the pump, without increase in stresses to save energy during low demand period.

IMPROVEMENT IN MOTOR LIFE DUE TO FCMA SOFT STARTERS

A large number of motor failures are associated with stator winding overhang failures and rotor bar failures, due to stresses generated during starting.

It is a well-known fact that the magnetic attraction and repulsion forces in the stator winding overhang are proportional to the square of the current passing through the windings. With FCMA soft starters, the starting current is reduced typically to three times as compared to DOL starting current of six times. As a result the forces are reduced by a factor $(6/3)^2$, i.e., by a factor of four. Hence the end winding failures due to starting stress are eliminated.

Pump motors with frequent start-stops may fail due to rotor bar failure. In cage rotors, the weakest point is the joint between rotor bars and end rings. As per basic motor theory, the kinetic energy gained during starting is equal to the rotor electrical loss during starting. DOL starting time will be generally three to four seconds. The rotor heat is thus generated in a short time leading to hot spots and differential thermal expansion. This leads to mechanical stresses on the joints and subsequent failure of the rotor bars. With FCMA soft starters, the starting time is increased to around 10 to 12 seconds, whereas the total rotor heat input remains the same. Longer starting time at lower current allows gradual heat buildup and better heat spread. This reduces the rotor hot spot temperatures and differential thermal expansion during starting, thus reducing or eliminating rotor bar failures.

DESIGN CONSIDERATIONS FOR INCREASING SAFETY FACTORS ON GEAR TOOTH LOAD FOR GEAR DRIVEN CONCRETE VOLUTE CASING PUMP BY STARTING WITH FCMA SOFT STARTERS

General Considerations

- Concrete volute casing pumps are special pumps, which are normally used for low head and high discharge flow applications. The pumps run at a very low speed (typically 200 rpm). The drive train hence consists of the motor (typically 750 rpm), planetary gearbox, and the pump itself.
- Concrete volute casing pumps are of large ratings such as 3000 kW to 10,000 kW. The drive design hence has to be reliable and economical.
- The most critical part in terms of drive design is the planetary gearbox as the torque ratings are very high.
- The gearbox also has to cater to the starting surges, particularly the peak torque exerted by the motor during acceleration (pullout torque typically 220 percent of full load torque). When the supply voltage is higher than the nominal voltage (say by 5 percent), the peak torque transient increases (240 percent) by a factor of square of the supply voltage increase.
- In the event of stalling or jamming of the pump the drive train is subjected to a high transient torque, which is the pullout torque of the motor (typically 220 percent of full load torque).

FCMA soft starters control the torque of the motor through the acceleration range so that the peak torque can be limited within 150 percent of full load torque. FCMA soft starters can also be used as torque limiters to reduce the stall torques within 150 percent.

The plot in Figure 5 brings out the peak torque during acceleration with and without an FCMA soft starter. It can be seen from these plots that the peak torque exerted by the motor during acceleration at 105 percent voltage with DOL starting is 240 percent of rated torque. With FCMA soft starting the motor peak torque is limited to 150 percent. The effect of these torques as reflected on the gear design for a typical concrete volute casing pump is illustrated in Table 3.

With Table 3, the inference is that with DOL starting the gear teeth are subjected to a peak load of 2.43 times nominal load, which is higher than the service factor considered and may gradually lead to gear damage. With an FCMA soft starter the gear teeth are subjected to a peak load of 1.5 times the nominal load, which is lower than the service factor and hence is safe.

RELIABILITY ASPECTS OF THE FCMA TECHNOLOGY FOR CRITICAL APPLICATIONS SUCH AS NUCLEAR POWER PLANTS

FCMA soft starters are used in nuclear power plants for critical applications such as fuel moderator supply pumps. These pumps are to be started on uninterrupted power supply (UPS) systems in case of power failures. In view of the critical nature of the usage, the FCMA soft starters are tested for seismic qualification and harmonic-free operation to establish a purely sinusoidal waveform.

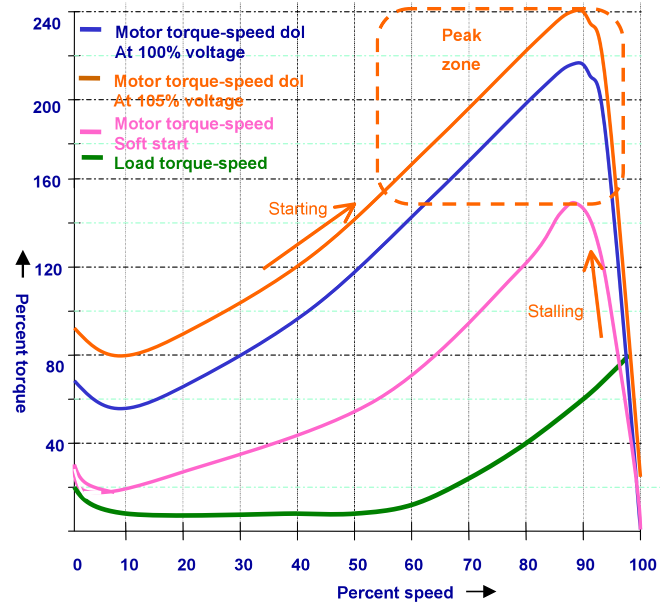

Figure 5. Torque Transient Curves During Acceleration and Stall for Typical Concrete Volute Casing Pump.

Table 3. Gear Box Peak Torque Analysis for Concrete Volute Casing Pump.

Pump rated torque Nominal torque	18400 Kg-m
Gearbox output shaft rated torque	18400 Kg-m
Gear ratio	5:1
Gear efficiency	0.98
Gearbox input shaft rated torque	3755 Kg-m
Service factor	2
Motor rated torque at 735 rpm, 3250 KW	4305 Kg-m
Motor peak torque at rated voltage	220%, 9471 Kg-m
Motor peak torque at 11KV+5%	10441 Kg-m
Peak to nominal torque ratio at maximum input voltage with DOL starting	10441/3755 = 2.78
Peak to nominal torque ratio at maximum input voltage with soft starter	1.5

The FCMA is tested to operate without any control supply functions for one hour in case of emergency.

NOMENCLATURE

η	=	Efficiency
3 ph	=	Three-phase
DOL	=	Direct online
emf	=	Electromotive force
FCMA	=	Flux compensated magnetic amplifier
G_{caprun}	=	Generator capacity as per running
$G_{capstart}$	=	Generator capacity as per running
hp	=	Horsepower
HV	=	High voltage
I	=	Current
I_{dol}	=	Starting current direct online
I_{dolpu}	=	Starting direct online current per unit
I_{fl}	=	Full load current
kV	=	Kilovolts
kVA	=	Kilovolt-amperes
kVAR	=	Kilovolt-ampere reactive
kW	=	Kilowatts
kW_b	=	Kilowatts base
kW_{trun}	=	Total running kilowatts
m	=	Meters
mmf	=	Magnetomotive force
MV	=	Medium voltage

MVA = Megavolt-ampere
MW = Megawatts
pf = Power factor
pu = Per unit
rpm = Revolutions per minute
UPS = Uninterrupted power supply
V = Volts
Y = Star connection
Z = Transformer impedance

APPENDIX A

Case 1—DOL Starting

Table A-1. Case 1—DOL Starting.

Transformer Selection with DOL Starter for 3 numbers 1700 KW, 6.6KV pumps				
Description	**Symbol**	**Formulae**	**Value**	**Unit**
Motor Details				
Motor rating	KW	Considered	1700	KW
Motor voltage	V	Considered	6600	V
Motor efficiency	η	Considered	0.95	
Motor pf	$Cos\phi$	Considered	0.95	
Motor $Sin\phi$	$Sin\phi$	SQRT $(1-Cos\phi^2)$	0.31	
Motor full load current	Ifl	$(KWx1000/1.732xVxCos\phi x\eta)$	165	Amps
Motor starting current p.u. DOL.	Idolpu	Considered	6	p.u.
Motor starting current DOL.	Idol	Idolpu x Ifl	990	Amps
Motor starting pf	$Cos\phi_{start}$	Considered	0.20	
Motor starting $Sin\phi$	$Sin\phi_{start}$	SQRT $(1-Cos\phi_{start}{}^2)$	0.98	
Starting of 1700 KW motor with DOL Starter				
Starting KVA of motor with dol	KVA_{dol}	(1.732 x V x Idol)/1000	**11317**	KVA
Starting active power of motor with dol	KW_{dol}	KVA_{dol} x $Cos\phi_{start}$	2263	KW
Starting reactive power of motor with dol	$KVAR_{dol}$	KVA_{dol} x $Sin\phi_{start}$	11090	KVAR
Running of 1700 KW motor				
Running KVA of motor	KVA_{run}	(1.732 x V x Ifl)/1000	**1886**	KVA
Running active power of motor	KW_{run}	KVA_{run} x $Cos\phi$	1792	KW
Running reactive power of motor	$KVAR_{run}$	KVA_{run} x $Sin\phi$	585	KVAR
Total Load on Transformer during starting of third motor when two motors are running				
Total KW load during starting	KW_{Tstart}	$(2xKW_{run})+KW_{dol}$	5847	KW
Total KVAR load during starting	$KVAR_{Tstart}$	$(2xKVAR_{run})+KVAR_{dol}$	12260	KVAR
Total KVA load during starting	KVA_{Tstart}	SQRT $(KW_{Tstart}{}^2+KVAR_{Tstart}{}^2)$	13582	KVA
Total Load on Transformer during running of 3 numbers 1700 KW motors				
Total KW load during running	KW_{Trun}	$3xKW_{run}$	5376	KW
Total KVAR load during running	$KVAR_{Trun}$	$3xKVAR_{run}$	1755	KVAR
Total KVA load during running	KVA_{Trun}	SQRT $(KW_{Trun}{}^2+KVAR_{Trun}{}^2)$	5655	KVA
Transformer Selection				
Transformer Capacity as per starting	Tcapstart	KVA_{Tstart} / 1.5	9055	KVA
Transformer Capacity as per running	Tcaprun	KVA_{Trun}	5655	KVA
Transformer rating Selected	T		10000	KVA
Transformer Impedance	Z	Assumed	0.07	p.u.
Voltage drop while starting last motor with Two motors running	VD	$((KVA_{Tstart}/T)*Z)*100$	9.5	percent

Case 2—FCMA Soft Starter

Table A-2. Case 2—FCMA Soft Starter.

Transformer Selection with FCMA soft starter for 3 numbers 1700 KW, 6.6KV pumps				
Description	**Symbol**	**Formulae**	**Value**	**Unit**
Motor Details				
Motor rating	KW	Considered	1700	KW
Motor voltage	V	Considered	6600	V
Motor efficiency	η	Considered	0.95	
Motor pf	$Cos\phi$	Considered	0.95	
Motor $Sin\phi$	$Sin\phi$	SQRT $(1\text{-}Cos\phi^2)$	0.31	
Motor full load current	Ifl	$=(KWx1000/1.732xVxCos\phi x\eta)$	165	Amps
Motor starting current p.u. DOL.	Idolpu	Considered	6.00	p.u.
Motor starting current DOL.	Idol	Idolpu x Ifl	990	Amps
Motor starting pf	$Cos\phi_{start}$	Considered	0.20	
Motor starting $Sin\phi$	$Sin\phi_{start}$	$SQRT(1\text{-}Cos\phi_{start}^2)$	0.98	
Starting of 1700KW motor with Soft Starter				
Designed starting current with SS p.u.	Isspu	Considered	**3.00**	p.u.
Designed starting current with SS	Iss	Isspu x Ifl	495	Amps
Starting KVA of motor with SS	KVA_{SS}	(1.732 x V x Iss)/1000	**5658**	KVA
Starting active power of motor with SS	KW_{SS}	KVA_{SS} x $Cos\phi_{start}$	1132	KW
Starting reactive power of motor with SS	$KVAR_{SS}$	KVA_{SS} x $Sin\phi_{start}$	5544	KVAR
Running of 1700 KW motor				
Running KVA of motor	KVA_{run}	(1.732 x V x Ifl)/1000	**1886**	KVA
Running active power of motor	KW_{run}	KVA_{run} x $Cos\phi$	1792	KW
Running reactive power of motor	$KVAR_{run}$	KVA_{run} x $Sin\phi$	585	KVAR
Total Load on Transformer during starting of third motor when two motors are running				
Total KW load during starting	KW_{Tstart}	$(2xKW_{run})+KW_{SS}$	4716	KW
Total KVAR load during starting	$KVAR_{Tstart}$	$(2xKVAR_{run})+KVAR_{SS}$	6714	KVAR
Total KVA load during starting	KVA_{Tstart}	$SQRT(KW_{Tstart}^2+KVAR_{Tstart}^2)$	8205	KVA
Total Load on Transformer during running of 3 numbers 1700 KW motors				
Total KW load during running	KW_{Trun}	$3xKW_{run}$	5376	KW
Total KVAR load during running	$KVAR_{Trun}$	$3xKVAR_{run}$	1755	KVAR
Total KVA load during running	KVA_{Trun}	$SQRT(KW_{Trun}^2+KVAR_{Trun}^2)$	5655	KVA
Transformer Selection				
Transformer Capacity as per starting	Tcapstart	KVA_{Tstart} / 1.5	5470	KVA
Transformer Capacity as per running	Tcaprun	KVA_{Trun}	5655	KVA
Transformer rating Selected	T		6000	KVA
Transformer Impedance	Z	Assumed	0.07	p.u.
Voltage drop while starting third motor with Two motors running.	VD	$((KVA_{Tstart}/T)*Z)*100$	9.6	percent

APPENDIX B

Case 1—DOL Starting

Table B-1. Case 1—DOL Starting.

3 numbers 1700 KW pumps sequentially started on DOL and run on Generator				
Description	**Symbol**	**Formulae**	**Value**	**Unit**
Motor Details				
Motor rating	KW	Considered	1700	KW
Motor voltage	V	Considered	6600	V
Motor efficiency	h	Considered	0.95	
Motor pf	Cosϕ	Considered	0.95	
Motor Sinϕ	Sinϕ	SQRT $(1-Cos\phi^2)$	0.31	
Motor full load current	Ifl	=(KWx1000/1.732xVxCosϕxh)	165	Amps
Motor starting current p.u. DOL.	Idolpu	Considered	6.00	p.u.
Motor starting current DOL.	Idol	Idolpu x Ifl	990	Amps
Motor starting pf	$Cos\phi_{start}$	Considered	0.20	
Motor starting Sinϕ	$Sin\phi_{start}$	SQRT $(1-Cos\phi_{start}^2)$	0.98	
Starting of 1700KW motor with DOL Starter				
Starting KVA of motor with dol	KVA_{dol}	(1.732 x V x Idol)/1000	**11317**	KVA
Starting active power of motor with dol	KW_{dol}	KVA_{dol} x $Cos\phi_{start}$	2263	KW
Starting reactive power of motor with dol	$KVAR_{dol}$	KVA_{dol} x $Sin\phi_{start}$	11090	KVAR
Running of 1700 KW motor				
Running KVA of motor	KVA_{run}	(1.732 x V x Ifl)/1000	**1886**	KVA
Running active power of motor	KW_{run}	KVA_{run} x Cosϕ	1792	KW
Running reactive power of motor	$KVAR_{run}$	KVA_{run} x Sinϕ	585	KVAR
Base Load Details				
Base Load in KVA	KVA_b	Considered	250	KVA
Base Load pϕ	$Cos\phi_b$	Considered	0.90	
Base Load Sinϕ	$Sin\phi_b$	SQRT $(1-Cos\phi_b^2)$	0.44	
Base load in KW	KW_b	KVA_b * $Cos\phi_b$	225	KW
Base load in KVAR	$KVAR_b$	KVA_b * $Sin\phi_b$	110	KVAR
Total Load on Generator during starting of 1700 KW motor when two motors are running				
Total KW load during starting	KW_{Tstart}	$(2xKW_{run})+KW_b+KW_{dol}$	6072	KW
Total KVAR load during starting	$KVAR_{Tstart}$	$(2xKVAR_{run})+KVAR_b+KVAR_{dol}$	12369	KVAR
Total KVA load during starting	KVA_{Tstart}	$SQRT(KW_{Tstart}^2+KVAR_{Tstart}^2)$	13779	KVA
Total Load on Generator during running of 3x1700 KW pumps				
Total KW load during running	KW_{Trun}	$3xKW_{run}+KW_b$	5601	KW
Total KVAR load during running	$KVAR_{Trun}$	$3xKVAR_{run}+KVAR_b$	1865	KVAR
Total KVA load during running	KVA_{Trun}	$SQRT (KW_{Trun}^2+KVAR_{Trun}^2)$	5903	KVA
Generator Selection				
Generator Capacity as per starting	Gcapstart	KVA_{Tstart} / 1.5	9186	KVA
Generator Capacity as per running	Gcaprun	KVA_{Trun}	5903	KVA
Generator Selection				
G1 KVA Capacity	$G1_{KVA}$	Considered	12500	KVA
G1 KVA Capacity overload	$G1_{KVAO/L}$	$G1_{KVA}$ * 1.5	18750	KVA
G1 Impedance	$G1_{X'd}$	Considered	0.150	p.u.
pf of G1	$G1_{cos\phi}$	Considered	0.80	
Sinϕ of G1	$G1_{sin\phi}$	SQRT $(1-G1_{cos\phi}^2)$	0.60	
G1 KW Capacity	$G1_{KW}$	$G1_{KVA}$ * $G1_{cos\phi}$	10000	KW
G1 KVAR Capacity	$G1_{KVAR}$	$G1_{KVA}$ * $G1_{sin\phi}$	7500	KVAR
G1 KVAR Capacity overload	$G1_{KVARO/L}$	$G1_{KVAR}$ * 1.75	13125	KVAR
KW Safety Margin during Starting	KWsafe1	$G1_{KW}$ - KW_{Tstart}	3928	KW
KVA Safety Margin during Starting	KVAsafe1	$G1_{KVAO/L}$ - KVA_{Tstart}	4965	KVA
KVAR Safety Margin during Starting	KVARsafe1	$G1_{KVARO/L}$ - $KVAR_{Tstart}$	750	KVAR
KW Safety Margin during running	KWsafe1	$G1_{KW}$ - KW_{Trun}	4399	KW
KVA Safety Margin during running	KVAsafe1	$G1_{KVA}$ - KVA_{Trun}	6597	KVA
KVAR Safety Margin during running	KVARsafe1	$G1_{KVAR}$ - $KVAR_{Trun}$	5635	KVAR
Step KVA on DG	KVA_S	KVA_{Tstart} - KVA_b- (3*KVA_{run})	7877	KVA
Voltage drop while starting third motor When two motors are running	VD	$((KVA_S/G1_{KVA})*G1_{X'd})*100$	9.45	percent

Case 2—FCMA Soft Starter

Table B-2. Case 2—FCMA Soft Starter.

3 numbers 1700 KW pumps sequentially started on FCMA soft starter and run on Generator				
Description	**Symbol**	**Formulae**	**Value**	**Unit**
Motor Details				
Motor rating	KW	Considered	1700	KW
Motor voltage	V	Considered	6600	V
Motor efficiency	η	Considered	0.95	
Motor pf	$\cos\phi$	Considered	0.95	
Motor $\sin\phi$	$\sin\phi$	SQRT $(1-\cos\phi^2)$	0.31	
Motor full load current	Ifl	=(KWx1000/1.732xVxCosϕxη)	165	Amps
Motor starting current p.u. DOL.	Idolpu	Considered	6.00	p.u.
Motor starting current DOL.	Idol	Idolpu x Ifl	990	Amps
Motor starting pf	$\cos\phi_{start}$	Considered	0.20	
Motor starting $\sin\phi$	$\sin\phi_{start}$	SQRT $(1-\cos\phi_{start}^2)$	0.98	
Starting of 1700KW motor with Soft Starter				
Desired starting current with SS p.u.	Isspu	Considered	**3.00**	p.u.
Desired starting current with SS	Iss	Isspu x Ifl	495	Amps
Starting KVA of motor with SS	KVA_{SS}	(1.732 x V x Iss)/1000	**5658**	KVA
Starting active power of motor with SS	KW_{SS}	KVA_{SS} x $\cos\phi_{start}$	1132	KW
Starting reactive power of motor with SS	$KVAR_{SS}$	KVA_{SS} x $\sin\phi_{start}$	5544	KVAR
Running of 1700 KW motor				
Running KVA of motor	KVA_{run}	(1.732 x V x Ifl)/1000	**1886**	KVA
Running active power of motor	KW_{run}	KVA_{run} x $\cos\phi$	1792	KW
Running reactive power of motor	$KVAR_{run}$	KVA_{run} x $\sin\phi$	585	KVAR
Base Load Details				
Base Load in KVA	KVA_b	Considered	250	KVA
Base Load pf	$\cos\phi_b$	Considered	0.90	
Base Load $\sin\phi$	$\sin\phi_b$	SQRT$(1-\cos\phi_b^2)$	0.44	
Base load in KW	KW_b	$KVA_b * \cos\phi_b$	225	KW
Base load in KVAR	$KVAR_b$	$KVA_b * \sin\phi_b$	110	KVAR
Total KW load during starting	KW_{Tstart}	$(2xKW_{run})+KW_b+KW_{SS}$	4941	KW
Total KVAR load during starting	$KVAR_{Tstart}$	$(2xKVAR_{run})+KVAR_b+KVAR_{SS}$	6831	KVAR
Total KVA load during starting	KVA_{Tstart}	SQRT $(KW_{Tstart}^2+KVAR_{Tstart}^2)$	8431	KVA
Total KW load during running	KW_{Trun}	$3xKW_{run}+KW_b$	5601	KW
Total KVAR load during running	$KVAR_{Trun}$	$3xKVAR_{run}+KVAR_b$	1865	KVAR
Total KVA load during running	KVA_{Trun}	SQRT $(KW_{Trun}^2+KVAR_{Trun}^2)$	5903	KVA
Generator Selection				
Generator Capacity as per starting	Gcapstart	KVA_{Tstart} / 1.5	5616	KVA
Generator Capacity as per running	Gcaprun	KVA_{Trun}	5903	KVA
Generator Selection				
G1 KVA Capacity	$G1_{KVA}$	Considered	7500	KVA
G1 KVA Capacity overload	$G1_{KVAO/L}$	$G1_{KVA}$ * 1.5	11250	KVA
G1 Impedance	$G1_{X'd}$	Considered	0.150	p.u.
pf of G1	$G1_{\cos\phi}$	Considered	0.80	
$\sin\phi$ of G1	$G1_{\sin\phi}$	SQRT $(1-G1_{\cos\phi}^2)$	0.60	
G1 KW Capacity	$G1_{KW}$	$G1_{KVA} * G1_{\cos\phi}$	6000	KW
G1 KVAR Capacity	$G1_{KVAR}$	$G1_{KVA} * G1_{\sin\phi}$	4500	KVAR
G1 KVAR Capacity overload	$G1_{KVARO/L}$	$G1_{KVAR}$ * 1.75	7875	KVAR
KW Safety Margin during Starting	KWsafe1	$G1_{KW} - KW_{Tstart}$	1060	KW
KVA Safety Margin during Starting	KVAsafe1	$G1_{KVAO/L} - KVA_{Tstart}$	2819	KVA
KVAR Safety Margin during Starting	KVARsafe1	$G1_{KVARO/L} - KVAR_{Tstart}$	1052	KVAR
KW Safety Margin during running	KWsafe1	$G1_{KW} - KW_{Trun}$	399	KW
KVA Safety Margin during running	KVAsafe1	$G1_{KVA} - KVA_{Trun}$	1597	KVA
KVAR Safety Margin during running	KVARsafe1	$G1_{KVAR} - KVAR_{Trun}$	2635	KVAR
Step KVA on DG	KVA_S	$KVA_{Tstart} - KVA_b - (3*KVA_{run})$	2516	KVA
Voltage drop while starting third motor When two motors are running	VD	$((KVA_S/G1_{KVA})*G1_{X'd})*100$	5.03	percent