Abstract

This paper will serve as a guide for those that plan to use the method of “capacitor assist” for starting of large high voltage motors on weak independent power system networks. A case study from the Western Australian mining environment will show how this uncommon motor starting method was adopted and put to use to reduce costs while maintaining suitable system conditions. The concepts and methods employed are given and the outcomes of commissioning the system are summarised. Additionally general information on motor starting methods is provided for reference.

I Introduction

For the majority of installations the staring of large motors is generally done using a few of the available methods. The most common methods used would be secondary resistance starting, soft starting and DOL being the most common. All methods of starting with the variance in costs associated with each method have their place. For instance on a strong network it would be more than feasible to start a 4MW motor DOL, however with weak networks the choices are reduced so as to avoid adverse power quality events such as voltage sag which could lead to vapor lighting extinguishing.

The starting of large motors may result in frequency fluctuations and serious voltage sag problems. It is therefore important for the system planner to consider that an isolated power system can be operated successfully in any operation condition. This paper discusses a system used whereby captive transformers and capacitor assist is used to effectively start large motors to reduce power quality issues such as voltage sag and other system effects. A discussion on starting methods is also provided for reference.

Two separate systems are presented as case studies, with each system incorporating a different starting method. Case A refers to an existing LNG plant installation located in the Pilbara area of Western Australia that is considered as an Independent Power Producer (IPP), due to supplying power to a customer having an Air Separation Plant (ASU) installed nearby. Large motors ranging from 700kW up to 2238kW between the two plants are started by using a combination of captive transformer and capacitor assist to maintain system voltage and reduce generation requirements.
Case study B refers to a gold plant installation in central Western Australia where a 600kW ball mill motor is started by use of a secondary liquid resistance starter. This is provided as a comparison to case study A.

II Background

A. Case Study A – ASU Plant Capacitor Starting

The LNG plant system under discussion is an existing system without connection to the grid, and runs under its own gas generated power and had been installed around five years prior. Recently another company constructed an ASU (Air Separation Unit) plant on the existing site and had arranged to purchase power from the LNG site. To meet with the existing methods and maintain power quality the starting methods employed had to be as per the existing arrangement, being capacitor assisted start with the use of step down transformers, as captive transformers.

The existing system is 11kV with generation at the same voltage level. The large HV motors in the LNG plant being started are compressor drives and are 2238kW and 700kW. The additional large HV motors added are the ASU plant drives of 1305kW and 900kW. The generation supply of the system is by three 4375kVA (i.e. 3500kW at 0.8pf) gas driven reciprocating engines with de-rated power ratings of 2886kWe for generator 1, and 2641kWe for generator 2 and 3, and are operated in an N+1 redundant configuration, typically only two generators are running at one time.

The existing plant with two generators running is able to start the 2238kW motor with minor levels of visible flicker during the starting sequence. With the additional load of the ASU plant, three generators are required to start the ASU HV motors with the LNG plant running. Once started however the third generator can be shut down during the cooler months of the year. Figure 1 shows the single line diagram for the LNG and ASU plant system.

![Figure 1: Single Line Diagram of LNG and ASU Plant.](image-url)
B. Case Study B – 600kW Mill Secondary Starting

The system under discussion is an existing gold processing plant without connection to the grid. The network is powered by diesel generators at 415V, and has a ball mill driven by a 3.3kV 600kW motor fed from a step up transformer. The mill motor is started by use of a secondary liquid resistance starter. The process plant has recently been refurbished after being shut down for around two years. The power system design is unchanged and works relating to the power station was that of testing and recommissioning only.

During commissioning a power analyser had been used for measuring the power quality of the network during ball mill starting. This has allowed network data to be gathered to check the operation of the mill secondary starter and as such is made available for reference in this paper. The site power station has available 3x 1250kVA generating sets in an N+1 arrangement, and an additional 500kVA generating set is available for base load power when the process plant is not in operation. Starting of the mill is possible by either using two of the 1250kVA sets or one 1250kVA and the 500kVA set.

No theoretical analysis had been performed on the system, due to being an existing plant. Commissioning on site involved testing the LRS for the correct resistance to ensure the mill motor would develop ample torque to accelerate the mill. The nominal three phase voltage level of the system is run at 420VAC. The HV system networks are stepped up via step-up transformers to 3.3kV for the mill and 11kV for distribution around the site. The motor transformer is normally energised; unlike for case A where they are only energised when the motor is started.

C. General Motor Starting Information

There are several factors to be considered when selecting the type of starting method for any electric motor driven load. These include, but are not limited to the following:

- Characteristics of the power source and the effects the motor starting currents will have on the supplying bus and the stability of the system voltage;
- Starting and breakdown torque characteristics of the motor (motor speed–torque characteristics);
- Load torque characteristics including breakaway torque, accelerating torque (inertia), and load torque at different speeds;
- Operating speed range of the connected load;
- Process considerations: shock, vibration, mechanical hammer;
- Control and maintenance of different starting methods.

The means of selecting an appropriate starting method is very much an iterative process, the main points of consideration are the voltage drop, the
resulting motor torque, the thermal limits of the motor, and cost of the overall equipment. Figure 2 presents this process as a flow chart.

Figure 2: Iterative Process for Motor Starting Methods Selection.

An important point is to note the selected motor’s torque speed curve, as different makes and types of motors have differing curves. For instance high efficiency motors generally will have less available starting torque due to the reduction in resistance in the rotor windings that is used to reduce motor losses. Care should be taken not to oversize the motor to create additional torque; the use of motors with higher torque profiles should be used. Figure 3 shows a typical motor torque speed curve.

Figure 3: Typical Motor Torque vs. Speed Curve.
III General Motor Starting Principles

The following is a brief synopsis of the general principles and physics which govern the start of a motor. The aim of each starting method is to minimise the voltage drop at the motor terminals, the power distribution or utility bus or to provide for a soft start of the driven equipment while still providing adequate accelerating torque to the driven equipment. Depending on the applicable requirements and the characteristics of the utility network, criteria for selecting a starting method is set.

The following general principles apply:

- The equivalent circuit for each starting method is a series connection of a number of impedances to which the network voltage is applied. During starting these impedances are mainly reactive. The voltage across each of the impedances and the motor during starting is a function of their individual values.

- The current in the circuit to the motor will also be reactive and be reduced linearly with the voltage encountered in the circuit. Consequently, a reduction of current in the circuit during starting will improve the available terminal voltage at the motor. Some of the starting methods take advantage of this principle.

- A capacitor start for example, takes advantage of its capacitive current producing capability to cancel out a large portion of the reactive current drawn by the motor during acceleration, thereby reducing the resistive current in the circuit.

- A jacking motor start takes advantage of a change in impedance of the main drive motor as it reaches operating speed and thereby reduces motor inrush current.

- The type of motor selected affects the inrush current in the motor circuit. Induction and synchronous motors have different reactances and inrush currents depending on the number of poles/speed of the motor. Another factor in the selection of the starting method is the voltage drop permissible at a given location. The permissible voltage drop at the motor can be as much as 33% for synchronous motors with constant excitation and 21% for induction motors. It may be preferable in some instances to select a synchronous motor over an induction motor. Table I indicates typical ranges of motor reactances and inrush current per motor type.

- The motor needs to develop sufficient starting and acceleration torque in order to successfully reach operating speed without overheating. The motor starting torque for both induction and synchronous motors (started as induction motors) is reduced by the square of the voltage remaining across the motor terminals during starting. Adequate break away torque needs to be guaranteed to accelerate the driven equipment. For instance, a centrifugal compressor has a smaller break away torque versus a positive displacement or screw type compressor. Therefore centrifugal type equipment can sustain a higher voltage drop at the motor terminals without jeopardising a successful start.
The magnitude of the voltage drop during starting of a motor is a function of the following variables:

- The inrush current of the motor, as discussed above.
- The minimum short circuit capacity of the utility network available.
- The impedance in the circuit from the main bus to the motor.

Certain voltage drop limits are often imposed at specific points in the distribution network reducing further the design flexibility. One has also to keep in mind that reactances of motors, transformers and reactors can be customised to improve on borderline situations. Table I gives typical reactance values for varying motor types.

### TABLE I

**Typical Motor Reactance For Types Of Motors.**

<table>
<thead>
<tr>
<th>Motor Type</th>
<th>Number of Poles</th>
<th>Reactance</th>
<th>Inrush Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous</td>
<td>2</td>
<td>14 – 21%</td>
<td>7.1 – 4.8 x</td>
</tr>
<tr>
<td>Synchronous</td>
<td>10 to 28</td>
<td>22 – 26%</td>
<td>4.5 – 3.8 x</td>
</tr>
<tr>
<td>Induction</td>
<td>2</td>
<td>20 – 22%</td>
<td>5.0 – 4.5 x</td>
</tr>
<tr>
<td>Induction</td>
<td>4</td>
<td>18 – 23%</td>
<td>5.6 – 4.3 x</td>
</tr>
<tr>
<td>Induction</td>
<td>10 to 28</td>
<td>21 – 25%</td>
<td>4.8 – 4.0 x</td>
</tr>
</tbody>
</table>

### IV Starting Methods Available

#### A. Direct Online System Starting

Direct online (DOL) starting is the most widely used method of starting motors. The network voltage is directly applied to the motor via closing a contactor to the supply. Larger medium voltage motors require circuit breakers usually over 630 Amps. The impedance diagram and the applicable formulas for the DOL start are shown in Figure 4.

![Figure 4: DOL Starting Single Line Diagram.](image-url)
$X_n = \text{Network reactance [Ohms/Phase]}

$X_m = \text{Motor reactance [Ohms/Phase]}

$V_n = \text{Nominal supply voltage (bus voltage) [kV]}

$I_s = \text{Starting current of motor [Amps]}

$V_{dn} = \text{Voltage at the motor terminals in percent of the nominal motor supply voltage}

$P_n = \text{Minimum short circuit capacity available at the point of motor supply [MVA]}

The network reactance in Ohms/Phase is:

$$X_n = \frac{V_n^2}{P_n} \quad (1)$$

The motor reactance in Ohms/Phase at start is:

$$X_m = \frac{V_n}{\sqrt{3} \times I_s} \quad (2)$$

The voltage at the motor in percent is:

$$V_m = \frac{X_m}{X_m + X_n} \times 100 \quad (3)$$

The voltage drop in percent in the network is:

$$V_{dn} = \frac{X_n}{X_m + X_n} \times 100 \quad (4)$$

The starting current in Amps becomes:

$$I_n = \left(\frac{V_n}{X_m + X_n}\right) \times \sqrt{3} \quad (5)$$

The DOL starting method is the simplest and most economical method of starting a motor. However it requires a stiff supply network (grid) because of the high starting currents involved. This can be an advantage when a high accelerating torque is required for driving high inertia loads. With this method short acceleration times can usually be achieved thereby keeping the rotor temperature rise of the motor low. In DOL starting of a synchronous motor, high accelerating and oscillating torques may prove to give mechanical
problems requiring reduced voltage start. Close coordination with the driven equipment manufacturer is required to arrive at the optimum drive start method.

**B. Reactor Starting Method**

A reactor is inserted in the circuit during starting of the motor reducing the start current and the voltage drop in the network. Figure 5 shows the impedance diagram. The start current will be reduced linearly with the voltage left across the motor. The motor torque will be reduced by the square of the voltage remaining across the motor during starting. The reactor may be inserted in the line to the motor or between the motor and its neutral point. In the latter case the short circuit withstand capability of the reactor can be reduced to approximately:

\[
S_r = \frac{1.1 \times V^2}{X_m + X_n} \quad \text{[kVA]} \quad (6)
\]

The reactor can obviously be left permanently in circuit after starting the motor. The voltage drop over the reactor for induction and under excited synchronous motors in the case is:

\[
V_{rn} = I_n \times \sin \theta_n \times X_r \times \sqrt{3} \quad (7)
\]

The reactor usually is furnished with 50, 65 and 80% taps.

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Figure 5: Reactor Starting Single Line Diagram.

\[
X_r = \text{Reactance of the reactor [Ohms/Phase]}
\]

\[
V_r = \text{Voltage drop over the reactor [Volts]}
\]

\[
S_r = \text{Short circuit withstand capability of the reactor [kVA]}
\]

\[
V_{rn} = \text{Voltage drop in volts across the reactor if left in circuit}
\]
\[ \sin \theta_n = \text{sin of phase angle of motor} \]

\( T_r = \text{Reduced starting torque during motor start} \)

\( T_s = \text{Starting torque available with nominal voltage at the motor terminals} \)

\( I_r = \text{Starting current in Amps with nominal supply voltage at the motor terminals} \)

\( I_n = \text{Starting current in the circuit in Amps of the motor during motor starting} \)

The voltage at the motor in percent is:

\[ V_m = \frac{x_m}{x_m + x_r + x_n} \times 100 \quad (8) \]

The voltage drop in percent in the network is:

\[ V_{dn} = \frac{x_n}{x_m + x_r + x_n} \times 100 \quad (9) \]

The voltage drop in percent across the reactor is:

\[ V_r = \frac{x_r}{x_m + x_r + x_n} \times 100 \quad (10) \]

The starting current in Amp becomes:

\[ I_n = \left( \frac{V_n}{x_m + x_r + x_n} \right) \times \sqrt{3} \quad (11) \]

The reduced starting torque verses the full voltage starting torque becomes:

\[ T_r = T_s \times \left( \frac{x_m}{x_m + x_r + x_n} \right)^2 \quad (12) \]

Compared to the DOL start method an extra contactor or circuit breaker is required to short out the reactor after starting of the motor, adding additional cost. The reactor can also be left in the line at the expense of the voltage drop and losses across the reactor. The reactor is usually located next to the starter cubicle.

One advantage of the reactor method is that the distribution of the voltage drop over the reactor and the motor will vary during acceleration. The power factor of the motor increases with its speed and consequently also the motor voltage. This has a boost effect on the motor torque, specifically for synchronous motors where the motor torque drops off at the end of the acceleration.
The torque/speed curves of Figure 6 shows the difference in motor acceleration torque between a reactor and an auto-transformer start to be discussed later. The graph shows that the auto-transformer start method gives increased starting torque over the reactor start.

![Figure 6: Comparison of Torque vs. Speed Curve for Reactor starting and Auto-Transformer Starting.](image)

C. Captive Transformer Method

The same formulas for captive start as for the reactor start apply. A captive transformer is introduced in the circuit to the motor. Correct dimensioning of the impedance will keep the voltage drop in the utility network within acceptable limits.

The captive transformer is often closely located near the motor. The sizing and construction of the captive transformer has to take into account the frequency of motor starts as well as the thermal and current pulse effect of starting the motor.

Voltage is usually applied to the motor by closing a circuit breaker on the primary side of the captive transformer. A disadvantage is the fact that the captive transformer stays in the line after starting. This means that its losses are reducing the overall efficiency of the motor drive circuit.

A step down transformer will in many cases be used as the captive transformer making this method attractive in case of very large motors. A captive transformer start is often recommendable where only a single motor needs to be accelerated and the breakaway torque required is low. In such cases, by manipulating the step down transformer impedance and the allowable voltage drop at the motor, a solution causing minimum network disturbance can often be found.

Voltage drops of up to 25% at the motor may be acceptable as long as the motor delivers sufficient torque. Some manufacturers are willing to adapt shape and materials of the motor rotor cage to cope with special acceleration requirements.

D. Auto Transformer Start
An auto transformer is inserted in the line to the motor reducing the voltage to the motor terminals depending on the tap selected. After starting the motor, the transformer is bypassed. Figure 7 shows the impedance diagram.

![Auto-Transformer Starting Single Line Diagram](image)

**Figure 7: Auto-Transformer Starting Single Line Diagram.**

The motor voltage is:

\[ V_m = K \times V_n \]  \hspace{1cm} (13)

The voltage drop in the network is:

\[ V_{dn} = K \times \frac{x_m}{x_m + x_r + x_n} \times 100 \]  \hspace{1cm} (14)

The reduced starting torque versus the full voltage starting torque becomes:

\[ T_r = T_s \times K^2 \times \left( \frac{x_m}{x_m + x_r + x_n} \right)^2 \]  \hspace{1cm} (15)

The starting current in Amps becomes:

\[ I_n = I_s \times K^2 \times \left( \frac{x_m}{x_m + x_r + x_n} \right)^2 + I_{trm} \]  \hspace{1cm} (16)

\[ I_{trm} = \text{Magnetising current of the auto transformer [A]} \]

Auto transformers are very similar to reactors and in some cases are readily interchangeable. The standard voltage taps provided are usually 80, 65 and 50 percent. A reduction of the terminal voltage to the motor, by selecting a certain voltage tap, translates into proportional reduction of the starting current in the
motor. The starting current as reflected in the network is reduced by the square of the transformer ratio and magnetising current of the auto transformer.

Depending on the motor size, three contactors or circuit breakers are required in addition to the autotransformer. Therefore this method is more expensive than a reactor start.

The starting current as reflected in the network and the motor torque are reduced with the transformer ratio. Therefore transformer taps permit an optimal adjustment of the motor terminal voltage to a required minimum motor torque or starting current as seen in the network. To aid in optimising starting, tap settings could be custom made with tap settings to suit the driven application and network conditions.

**E. Capacitor Starting Method**

Capacitor starting involves a capacitor being energised at the time the motor is started, thereby providing the reactive current drawn by the motor and to support the network. Upon reaching motor rated speed the capacitor is switched out of circuit. Capacitors are usually selected to compensate for as much as half the voltage drop which can be expected in a DOL start. Naturally capacitors can also be used in combination with any of the reduced voltage starting methods described earlier.

A similar effect of generating reactive power can also be obtained by boosting the excitation of synchronous motors on the bus during the start of the motor. This starting method is used primarily in a weak network.

The following equations give the current and voltage drop in the network as well as approximately the reduced starting torque available at the motor.

Figure 8 shows the impedance diagram for the capacitor starting method.

![Figure 8: Capacitor Starting Single Line Diagram.](image)

The starting current in Amps becomes:

\[
I_n = \frac{V_m}{\sqrt{3} \times (X_n + \frac{X_c \times X_m}{X_c + X_m})}
\]  

(17)
The voltage drop in percent in the network is:

\[(18)\]

The reduced starting torque versus the full voltage starting torque becomes:

\[(19)\]

Besides a correctly sized capacitor, a contactor or fast switching circuit breaker is required as well as some means to sense when the motor has accelerated and the capacitor needs to be switched out of circuit. The voltage profile with and without capacitor start are shown in the following graphs of figure 9.

![Figure 9: Voltage vs. Time Graph for Capacitor starting.](image)

If more than one motor is required to be started, then only one bank of capacitors is required. The cost of capacitors can be further reduced by over stressing the capacitors, e.g. using 2400V capacitors at 4160V. This reduces the capacitance required by:

\[(20)\]

Capacitors add to the risk of transient over voltages and harmonic resonance, on the other hand they may provide some savings if penalties for peak power demand are implemented.
F. Frequency Starting

To provide a smooth and soft start, the motor is accelerated by a frequency converter and upon reaching the network frequency the motor is transferred to the network after synchronisation.

The same frequency converter can be used to start a number of motors in sequence, reducing costs. This involves having additional motor DOL contactors or starters as well as synchronising control gear.

Frequency starting can be applied to both induction motors and synchronous motors. The advantage of a frequency start is smooth acceleration, almost linear power draw, and negligible voltage drop in the network and no high transient motor currents and torques.

Advantages are that variable frequency and voltage starting offers the highest torque development due to inherent induction motor characteristics and ability of the drive to provide a voltage/frequency ratio that develops full flux in the motor, and hence full torque at standstill.

The disadvantages are high cost, complexity and large dimensions of the starter. Other disadvantages are voltage level as well as network harmonics. The cost of the starter is a function of the operating voltage, pulse number, filter circuits and the current capacity. These starters become attractive where variable speed and energy savings go hand in hand.

V Starting Methods Typical Concerns

A. How do network conditions influence the method of starting selection?

Generally the utility company or IPP will set restrictions on the allowable voltage drop at the power supply point of connection, regardless of projected load and plant conditions to safeguard the quality of power delivered in the distribution network and to minimise complaints and outages. The selection of starting will be influenced by the condition of the network and if large motors are required to be brought online.

Large motors require significant amounts of reactive power that is enough generally to affect the supply network. Reactor, captive transformer and auto transformer methods do not support the network. If a stiff network is available then the DOL start method can be used, unless the driven equipment cannot tolerate a hard start. A stiff network should have at least six times the motor inrush kVA available to minimise effects.

For week networks, these will need to have some form of reactive support. The capacitor starting method will provide such support. Other methods are to use a lower amount of reactive power upon starting the motor. If sacrificing motor torque is unable to be achieved due to the driven equipment, then jacking motor, wound rotor motor or frequency starting methods can be used.
A reduced voltage starting method is certainly not a solution if a direct on line start already causes excessive voltage drop at the motor with insufficient motor torque available to break-away the load.

**B. How does the type of driven equipment influence the method of starting selection?**

Driven equipment with high breakaway torque, a large amount of inertia or both, present the toughest problem. A high breakaway torque requires a high motor torque to be available, which in turn is only possible if the voltage at the motor terminals during starting remains high. Such loads require stiff utility supplies or if this is not possible, other methods such as jacking motor start and frequency start.

A high amount of equipment inertia will lengthen the run up time which means the thermal characteristics of the motor will become an important factor. Other starting methods such as auto transformer and reactor start should be considered, but may not be solutions. It is obvious that large machinery should, if at all possible, be started in an unloaded condition. This will reflect in an easier to accelerate speed torque curve. Centrifugal equipment with low break away torques therefore allow more flexibility in the selections of the starting method versus equipment with practically constant load torque characteristics such as reciprocating equipment and conveyors.

Running synchronous motors already on-line do supply reactive power to help a starting motor on line. Slow speed synchronous motors can be manufactured with low inrush down to 3.6x full load current reducing inrush reactive power required.

In some instances the driven equipment does not allow high torsional stresses and cannot be accelerated too fast. A reduced voltage starting method or soft starting methods will be required regardless of the network conditions.

Table II at the end of paper, gives recommended reduced voltage starting methods to be used for differing scenarios.

**VI Capacitor Starting System Design**

**A. System Components**

The components for the capacitor and captive transformer starting method used on the site consisted of 11/3.3kV transformers, one transformer per motor, four banks of 2.73MVAR capacitors, dedicated PLC system and tachometers attached to each motor for speed detection. Four banks of capacitors connected to a separate switchboard are available; however only three banks are required for the largest 2238kW motor, the fourth bank being a redundant spare.
Note that the motor voltages are 3.3kV and that 11kV motors had not been used, the transformers as well as stepping down the voltage are used to introduce impedance into the motor circuit to assist with reducing the motor voltage and hence current on start up. The transformers are of a cast resin dry type design, that are used primary for structural strength of the windings as they are shocked loaded during each motor start.

The duty and standby arrangement of the capacitor banks are rotated after each motor start operation so that each bank shares being switched. Depending on the size of motor, a differing number of banks are required, for the 2238kW motor three banks are used, for the 1305kW motor two banks are used, and for each of the smaller motors, 700kW and 900kW only one bank is used.

The simplified single line diagram of the site network given in Figure 1 shows the existing LNG bus. The ASU bus had been added to service the new ASU loads, as well as the capacitor bank switchboard which had to get moved across due to there being no spare feeders.

Dedicated PLCs are used for the control of the starting. One each for the LNG plant motors and the ASU plant motors. This was due mainly to the chosen PLC unit only having available two off high speed counter inputs to accept the tachometer signals, otherwise a single PLC system could have been used.

B. Sequence of Operation

In order to start one of the large motors the following sequence is performed, once enough generation is available. A request from the plant PLC system asks the dedicated motor control PLC to start the motor.

The sequence first switches in one capacitor bank, then after a very short delay closes the motor circuit breaker and switches in the next capacitor bank or banks depending on the motor size. After the motor starts and begins to accelerate the first bank switches out, then as the motor speed increases further the next bank is switched out. The stages for capacitor banks being switched out are selected based on motor speed and the voltage rise in the network.

C. ASU Plant System Integration

The design for the ASU plant system involved firstly to check that the existing capacitor banks were not too large or too small in size to correctly afford the capacitor assist starting method. Being suitable the smaller MAC motor was able to be started with one bank only as per the existing LNG plant’s 700kW ARC motor. The RAC motor however required the use of two capacitor banks for starting.
VII Capacitor Starting Theoretical Analysis

Theoretical analysis had been performed as well as dynamic simulation for the motor starting to determine that both existing capacitor bank sizes were suitable and to confirm network voltages were within specifications during starting.

The software used was a proprietary software package developed by a third party engaged by the IPP. However any good power systems analysis software package with dynamic simulation capability such as ERACS could be used to perform such simulations.

The following figures show the simulated output results for the starting of the Large MRC motor of the LNG plant, and the two motors, MAC and RAC of the ASU plant.

![Figure 10: 2238kW MRC Starting Power vs. Time Plot.](image1)

![Figure 11: MRC Starting Voltage vs. Time Plot.](image2)

The following figures are the 900kW MAC motor starts without the use of capacitors for support whilst starting the motor.
The following are 900kW MAC motor starts with the use of one 2.73kVA capacitor bank for support whilst starting the motor. The capacitor is brought online just prior to motor energisation.
The following are the 1305kW RAC motor starts without the use of capacitors for support whilst starting the motor.
The following are the 1305kW RAC motor starts with the support of one 2.73kVA capacitor bank whilst starting the motor. The capacitor is switched out of circuit at four seconds.

Figure 18: RAC Starting Power vs. Time Plot, with 1 Cap Bank.

Figure 19: RAC Starting Voltage vs. Time Plot, with 1 Cap Bank.

Figure 20: RAC Starting Power vs. Time Plot, with 2 Cap Banks.
The plots shown in Figures 20 and 21 show the 1305kW RAC motor starts with the support of two 2.73kVA capacitor banks whilst starting the motor. One capacitor bank is switched just prior to the motor circuit breaker closing, and the second is switched in at the same time the motor is energised. The capacitors are then switched out of circuit during acceleration of the motor.

With the use of two capacitor banks it can be seen that the overvoltage is more than 10 percent, as both banks are brought online just prior to motor energisation. Note that the voltage sag is much reduced compared with the case of only one capacitor bank in use.

VIII Testing & Commissioning

A. Case A – System Pre commissioning

The pre-commissioning of the system is fairly straightforward, with the normal inspection and testing requirements for HV switchgear, protection relays, LV wiring and PLC IO to confirm correct installation and functional operation. Additional specific testing is required for the motor speed tachometer prior to energisation to confirm correct operation. To simulate the motors full speed operation, an electric hand drill was used with a magnetic disk held up to the sensor unit that had been dismounted from the motors normal mounting position. Checking for the correct motor speed is critical to the functional operation of the capacitor starting method.

B. Case A – Capacitor Start Commissioning

Commissioning of the ASU plant motor starting was done during a LNG plant planned maintenance shutdown. This was done primarily due to the known
possibility of a potential blackout which would have adverse consequences on
restarting the LNG plant should a blackout occur.

Commissioning the starting method involved using a Power Analyser
connected to the 11kV bus to record system data during the motor starting
events. The analyser had been set to continuously record voltages and
currents.

With each motor start the performance of the start was checked by reviewing
the network voltage data recorded from the power analyser. The timing of the
switched capacitor circuits was then modified in the PLC program so that
capacitor switching could be optimised to give the best performance.

During the commissioning phase numerous plant blackouts were experienced
generally due to over or under voltages on the system caused by incorrect
timing. This lead to an increased commissioning time due to delays in black
starting the plant power system after such events occurred.

C. Case A – Power System Measured Data

During starting of the HV motors flicker was observed as would be expected,
the reduced voltage levels remained within tolerable limits, however over
voltages were experienced. The main issue causing these over voltages was
due to incorrect timing of switching the capacitors out of circuit.

The following plots obtained from the Dranetz power meter shows the system
voltage levels for the MAC and RAC motor starts after successfully
commissioning the starters. At the time of the motor starts all three LNG plant
generators are online, and the LNG plant is running near full production.

From the recorded data, Figures 22 and 24, the voltage increase at the time of
starting had risen to 1.05% and 1.06% for the MAC and the RAC motors
respectively. Also it is noticed that the bus voltage did not sag during the
starts. The actual performance being less than that of the simulated theoretical
results that had indicated rises of 10% or more.
From the sine wave plots shown, during the MAC motor start a \( \frac{1}{2} \) wave frequency displacement is observed. For the RAC motor start a similar event occurs with a half wave phase shift recorded by the power analyser.
TABLE III
MULTILIN RELAY MOTOR STARTING DATA

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>MAC</th>
<th>RAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC</td>
<td>182A</td>
<td>259A</td>
</tr>
<tr>
<td>Unloaded Start Current</td>
<td>404A</td>
<td>1121A</td>
</tr>
<tr>
<td>Unloaded Acceleration Time</td>
<td>1.6 sec</td>
<td>1.6 sec</td>
</tr>
<tr>
<td>Loaded Start Current</td>
<td>835A</td>
<td>1863A</td>
</tr>
<tr>
<td>Loaded Acceleration Time</td>
<td>8.0 sec</td>
<td>4.5 sec</td>
</tr>
</tbody>
</table>

From the Table III data, the starting current for the MAC motor is determined as 4.6 times the motor full load current. For the RAC motor the starting current is determined as 7.2 times the motor full load current.

Due to the process configuration the MAC feeds the system that presents positive air pressure to the RAC, also the RAC motor is a multiple stage compressor that has more inertia which would cause more start-up power required. The unloaded values represent motor starts without the compressors connected to the motors. During the starting of the compressors, the inlet guide vanes on the units are closed to reduce compressor loading.

D. Case B – 600kW Mill

The mill motor is able to be started with either 2 x 1250kVA generators or at a minimum of 1 x 1250kVA and 1 x 500kVA generators sets running. Prior to starting the mill the existing load on the system is between 150 and 200kW.

The mill motor start gives an observable voltage sag being most significant at the instant voltage is applied and at the end of the acceleration period of the LRS. The duration of the starting period is approximately twelve seconds. Figure 26 shows the voltage vs. time plot for one of the mill starts.

It can be observed that the average voltage drop on the 415V network is approximately 10 Volts or 0.95pu. Whilst watching the office lighting in the admin building nearby, the flicker in the lights is very noticeable to the naked eye, even though the average voltage drop is within specifications during starting. However the voltage drop on one of the phases is more pronounced having a voltage drop 0.93pu.
Using the rule of thumb for diesel generation required for motor starting, of the 600kW mill motor, the required kVA in generation would be 1500kVA for motor starting by reduced voltage of soft starting means. With one of the larger sets and the smaller generator set, the minimum amount of kVA available is 1750kVA. There is a small overhead available which is managed by the sequencing of the plant start-up and other service loads to minimise the reduced amount of spinning reserve and reactive power support.

IX Case A System Risks

During motor starting commissioning the greatest risk is a power system blackout. If the system is isolated and does not supply other customers then this risk could be disregarded. However system blackouts in getting the starting sequence correct are real, as happened numerous times during our experience. The main issues causing blackouts are with the timing of the capacitor banks. With either too much or too little reactive VARs switched in or out at the wrong times would cause the generator controllers to trip, with either just disconnecting the generator’s main breaker or completely shutting down. Further delays then occur in requiring a black start generator to get the system up and running again to continue with the commissioning.

The main issue for the generating sets tripping is having too much positive VARs in the network, leading to instability and over voltages. Initially when the LNG plant was first commissioned, it took the commissioning engineers on site approximately one week to effectively commission the MRC motor start
sequence due to the size and number of capacitor steps. Even though this length of time was experienced and maybe it could be thought of as not being such a good method to be used, once commissioned the capacitor starting method works very well.

The introduction of capacitors into the network could lead to system resonance. A study needs to be performed to check the resonant frequency and ensure that it does not correspond to the power system frequency or any harmonic frequencies. If required damping reactors can be added into the capacitor circuits to avoid any possibility of occurrence.

Another risk although less significant is ensuring that pre-packaged or off the shelf equipment is fit for purpose. The issues with the MAC and RAC skids was that orders for the equipment had been placed by the client prior to knowing the requirements for starting such motors. This had occurred due to the project being fast tracked with a push to order equipment early to meet the anticipated plant start-up date. Therefore it is important to ensure before making purchases on equipment that the design criteria requirements for the system are known so that construction and commissioning efforts are not impeded.

X System Improvements

The design for starting of the ASU plant motors was required to be the same as per the original installation which was a requirement of the IPP. After designing and commissioning the ASU system and reviewing the issues associated with such a system the following are given as possible improvements that would aid in reducing costs and commissioning time.

- Removing from the system the use of a tachometer on the motor, as this proved difficult to install due to the pre-packaged compressor skid motors not being designed to have sensor disks or rings fitted to the motor shafts. This later lead to the failure of the shaft magnetic ring on the RAC motor which then lead to plant downtime for remedial repairs and then later the replacement with new parts.

- Programming the PLC logic to automatically switch the capacitors out of circuit based on motor power factor or system voltage rather than speed to reduce commissioning time and possibility of plant blackouts would advantageous, as the timing had to be commissioned by completing various starts. The motor starts also had caused further delays due to the 20 minute restart interlocking.

- Due to distance between the motor and PLC, cable selection for the speed sensor became important due to the high frequency signal. The use of an analogue 4-20mA signal would allow standard instrument cable to be used if another method for controlling the capacitor switching is used based on either power factor, reactive power or voltage level.
Using a motor protection relay or power meter with an analogue output signal of power factor could be used to provide a 4-20mA signal that could then be used for switching the capacitors out of circuit during motor start up. This method however would require the PLC to have very fast analogue input processing capabilities.

Use of 11kV motors with bypassed reactors could be used instead of using 11/3.3kV captive transformers. Volt drop would still be achieved during the starting stage but without the ongoing transformer losses in circuit. However the potential cost savings of a reactor may be offset by the costs of an additional HV panel.

XI Conclusions

There are many ways to start large motors, selecting the best method is primarily a coordination problem between the overall power system, motor manufacture, driven equipment manufacturer, and equipment costs.

For weak power systems it is possible to find a suitable starting method for large motors. Also as shown it is possible to combine different methods to achieve a suitable and economical outcome.

The capacitor starting method works well to maintain the network voltage and to reduce power quality effects, compared with case B where voltage sag is both noticeable and prolonged.

Dynamic modeling of the preferred motor starting method will provide confidence and reveal limitations in the chosen design during the initial stages of project design. Practical results will generally always be different to that compared with theoretical results due to inaccurate or assumed input data entered into the simulation model. As shown by case study A with the practical results giving better than expected results.

Performing a system study is important to determine appropriate settings and sizing of equipment; however it should not be overlooked that the need to commission the system may take some time due to the nature of the week network, and/or the starting method chosen.

Solid state starters offer advantages such as a smooth start over traditional methods; however the costs and efficiencies need to be considered.

Providing the customer that has their own power generation system as in case B and is content with having power quality issues during motor starting, then less costly and complex starting methods can be employed.

Acknowledgements

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The author notes that sections III through V are copyrighted material from [1], with permission from IEEE.

References


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<tr>
<th>Table: II: Selection Chart Cost Basis, 5000HP (3730kW) 4 Pole 4.16kV Synchronous Motor Driving Centrifugal Compressor.</th>
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<tbody>
<tr>
<td><strong>STARTING METHOD AVAILABLE</strong></td>
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<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>DOL</td>
</tr>
<tr>
<td>Reactor Start</td>
</tr>
<tr>
<td>Auto Transformer Start</td>
</tr>
<tr>
<td>Captive Transformer</td>
</tr>
<tr>
<td>Frequency Start</td>
</tr>
<tr>
<td>Capacitor Start</td>
</tr>
<tr>
<td>Wound Rotor Start</td>
</tr>
<tr>
<td>Jacking Motor Start</td>
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</tbody>
</table>

Cool Down Period Between Starts is Long