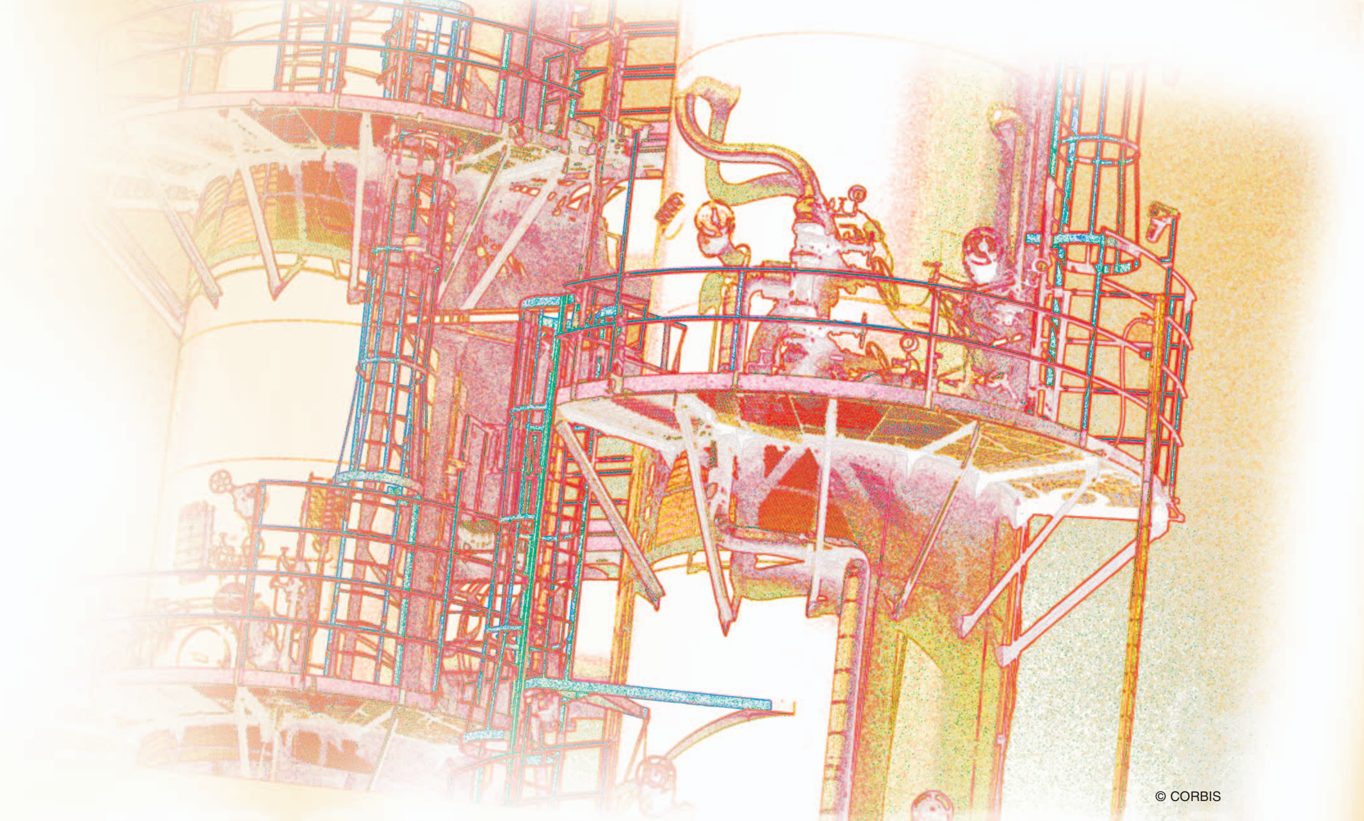
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THE SOFT STARTERS

Adjustable-speed systems for multiple megawatt rated motors

BY FRIEDER ENDREJAT
& PRAGASEN PILLAY

LARGE PUMPS AND COMPRESSORS IN THE MEGAwatt range are often required by the petrochemical industry. The associated motors are often large enough for soft starting or may also be so large to dictate the requirement of soft starting. Soft starting may also be required because of the nature of the process or the driven equipment. Direct online (DOL) starting results in the severe transients in the machine and associated power system, which can be avoided by soft starting. One or more large drives in a process plant can often benefit from the adjustable-speed operation for improved process control or energy savings. The reliability of the process is, however, extremely important because outages frequently result in major production or financial losses. Therefore, a reliable, flexible, safe, and cost-effective system is required.

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Conventional Techniques

DOL Starting

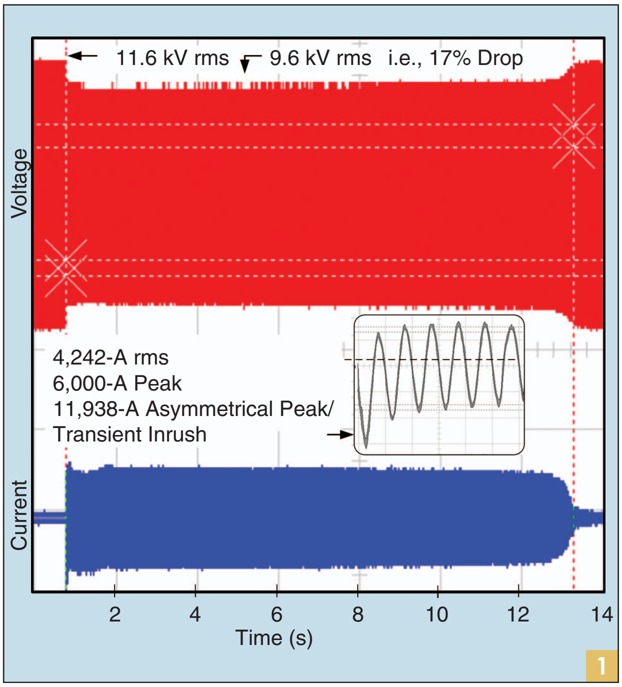
A medium-voltage (MV) motor startup current [1] is normally smaller in per unit than a low-voltage motor startup current [2]. The ratio of the transient inrush current to the locked rotor current is generally higher for large MV motors compared with low-voltage motors (the ratio increases with motor size because of the decreasing locked rotor power factor). It is difficult to manage the effects of the thermal and dynamic (transient inrush current) stresses during startup, especially for large motors in excess of 10 MW.

Failures during the startup can be prevented by protecting the motor properly [3]. A startup recording of a large MV motor (13.7 MW) is provided in Figure 1. There is a risk of stator end-winding failures (dynamic forces) associated with DOL starting for large older motors, especially those that are frequently started. These failures cannot be prevented by correct protection settings. These forces are proportional to the square of the current ($F\alpha I^2$), and only a decrease in the starting current can result in a significant reduction of the dynamic forces. Figure 1 shows a significant voltage drop (17%) even with a stiff network (411 MVA fault level based on the source impedance at 11 kV).

LARGE PUMPS AND COMPRESSORS IN THE MEGAWATT RANGE ARE OFTEN REQUIRED BY THE PETROCHEMICAL INDUSTRY.

Conventional Alternative Technologies

Alternative technologies used for starting MV motors include the insertion of reactance, using Korndorfer reduced voltage autotransformer, using autotransformer with capacitor assist, and reducing voltage power electronic starters [1], [4]. The starters can also be used when the driven equipment requires a lower starting torque. The starting current is approximately proportional to the supply voltage, and the torque is proportional to the square of the current; therefore, a reduction in voltage will significantly bring down the torque imposed on the driven equipment.



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DOL startup recording of a 13.7-MW IM.

Adjustable Voltage and Frequency Applications

Large motors (e.g., >15 MW) cannot be started effectively by any of the previously mentioned methods. A less stressful and a more controllable soft-start system is required, e.g., adjustable voltage and frequency starting methods. Traditionally, motor generator (MG) sets were used. However, static frequency converters (SFCs) have become far more popular because of the elimination of rotating parts and the maintenance-intensive mechanical equipment (e.g., the fluid coupling and the associated auxiliaries). Soft-start technology is often defined as a technology that provides adjustable voltage to the motor via power electronic devices [normally silicon-controlled rectifiers (SCRs)]. SFC adjustable-speed drive (ASD) technology is used for optimal soft starting [1]. The load commutated inverter (LCI) technology has been used exclusively for large motor applications (soft starters and ASDs). An example of an 11-kV, 55-MW motor LCI startup recording with low starting current (below rated current) is given in [6].

It has been stated that the LCI technology is the obvious choice for large adjustable-speed systems, although the power ratings of the alternative technologies are increasing [5]. SFCs, also used as ASDs, will now be discussed in details. The LCI technology has been proven as a mature and a reliable solution for many applications, but it has several disadvantages, which are outlined in [6]. These disadvantages can be overcome only by a very comprehensive and a rather complicated system engineering. Normally, an application-specific special design of motors was required. Furthermore, additional harmonic reduction and power factor compensation techniques were required (for ASDs). These were associated with costly additional equipment, which required space and affected the efficiency and the reliability of the system [7], [8].

Modern Techniques

Technology Overview

Several newer MV technologies have been developed to compete with the LCI technology. These include the following [9]: pulse-width modulated current source inverter, three-level voltage source inverter (VSI; neutral point clamped), multilevel voltage source, floating symmetrical capacitors inverter, and VSI with a multilevel cascaded H bridge (VSI-H) having a multisecondary transformer.

Each of these technologies has certain advantages and disadvantages [9] and not all address all the disadvantages of the LCI alternative. Disadvantages [6], where applicable, can be effectively addressed by front-end alternatives or improvements (e.g., active front-end or high rectifier pulse number or filters) or load side additions (filters), depending on the topology and application. Many additional variations of the multilevel VSI technology have recently been investigated, and control and modulation strategies were improved to minimize the harmonic content of the voltage output waveforms. This removed the requirement for any additional front-end or load side modifications or additions [10], [11]. Nevertheless, new multilevel VSI technologies are available to address all the disadvantages and, most importantly, to obtain high-output voltages (≥11 kV) without a step-up transformer, e.g., the VSI-H type with a detailed comparison with the LCI technology in [12].

SEVERAL NEWER MV TECHNOLOGIES HAVE BEEN DEVELOPED TO COMPETE WITH THE LCI TECHNOLOGY.

Advantages of the Application

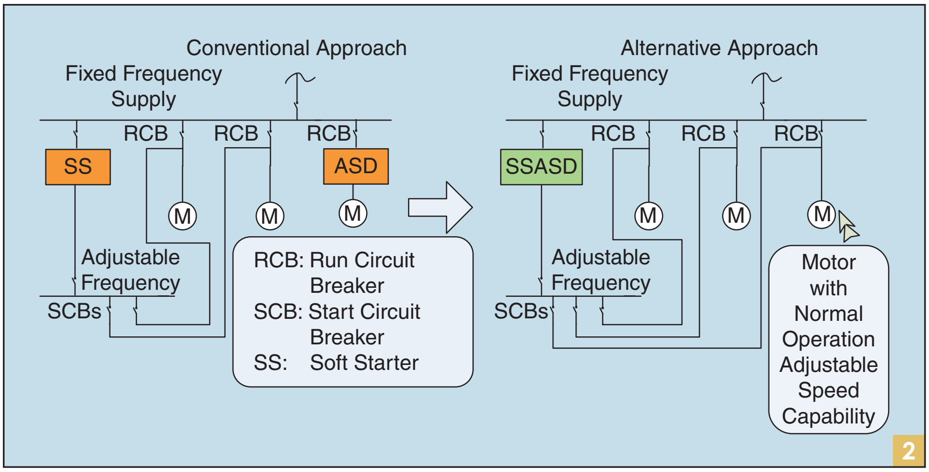
Some of the new technologies can be used for existing motor applications (no special motor design required). Specific advantages associated with some multilevel technologies (e.g., VSI-H) are the minimization of du/dt output wave change rates, common mode voltages, and electromagnetic interference (in addition to the near sinusoidal voltages) [13]. Therefore, stator winding and bearing failures are reduced [13]. Furthermore, this technology is also associated with high efficiency (no step-up transformer losses) and high power factor [13].

Multiple Motor Soft Starting with the Capability to Operate One Motor at the Adjustable Speed Using a Single SFC

Introduction and Potential Existing Applications

Energy savings (based on the affinity law principle [14]) can often be applied where multiple motors are driving compressors or pumps. Instead of driving all the motors at rated speed with dissipative process control methods (e.g., inlet valves), one motor can be driven at an adjustable speed according to the load demand of varying process. The other loads can then be driven at their optimal efficiency (it may be necessary to switch off one or more motors in accordance to the demand of the process). Quantification of the losses of typical applications associated with flow valves and other dissipative flow control methods is given in [14] and in the "Case Studies" section.

Large motors identified for energy savings were being operated for many years. DOL-started large motors have often experienced failures. Other electrical system components, e.g., driven equipment, switchgear, incoming transformers, are also negatively affected [14].



2 **Single SFC applied as an SSASD.**

A single SFC used as a multiple motor soft-starter ASD (SSASD) addresses all the aforementioned problems. When a motor needs to be started, the SSASD is ramped up and synchronized with a fixed frequency supply. The SSASD is then isolated from the fixed frequency supply, after which any of the other motors can be soft started. Thereafter, the SSASD is synchronized again with the fixed frequency supply and ramps down the adjustable-speed motor according to the process demand. The necessary process control is implemented during the ramped up and ramped down conditions to meet the required process flow and pressures and to minimize process upsets. A graphical illustration of the conventional approach versus the proposed alternative approach is shown in Figure 2.

In summary, instead of applying two different units for different loads (i.e., the adjustable-speed load and loads requiring soft starting), only one unit is used alternatively by both types of loads.

The benefit of this concept is recognized by some industries, but the motivation was mainly based on economic flow or pressure control where multiple motors are used for a specific application (e.g., pipeline or compressor station applications).

The failure of a dedicated ASD may cause significant production losses. This risk may be reduced by including redundancy in the ASD, but added capital cost and a subsequent failure can result in expensive production losses. The shutdown periods of some petrochemical plants can typically be every four to six years. Some of the new SFC technologies have not been applied long enough in the industry to prove that this availability requirement will be met.

One major advantage is that the concept of an SSASD system can address the availability requirements when at least $N - 1$ redundancy is built into the important system components with the highest risk of failure that may result in production loss. As soon as a component in the SSASD system fails, the SSASD can still be ramped up and synchronized with the fixed frequency supply. The SSASD is then removed, and the faulty component can be repaired without any production loss.

Applying the SSASD Concept to New Projects

An SFC may be required for the following reasons (soft starting):

1) very large motor starting (e.g., 55 MW) [6]
2) compressors often need to be ramped up in a controlled manner within a specified time margin
3) large compressors may have to be slow rolled initially for an extended operating time
4) the electrical network may not be able to support DOL starting of large motors, or it may be uneconomical to design a network to support the DOL starting (low transformer impedance and switchgear with a very high fault level).

An SFC may also be required to drive one or more motors at adjustable speed for the following reasons:

1) energy savings by applying adjustable speed instead of dissipative flow control methods
2) adjustable-speed operation may be required for extended operation periods during the initial startup.

An SSASD can eliminate the cost associated with an additional dedicated SFC for soft starting.

Additional Important Benefits of the SSASD Concept

Hazardous Area Considerations

Most petrochemical motors must be suitable for application in zone 2 [International Electrotechnical Commission (IEC)] hazardous areas. DOL-started MV motors may cause sparking during startup, which may ignite the potential explosive environment. A purging system or a prestart ventilation system may be required to avoid the presence of the gas during starting [3]. The application of an SSASD to soft start the applicable motors can minimize the risk of sparking, and the startup current can be limited below the rated current. This may remove the requirement of a purging or prestart system. New reduced certification requirements may be applicable for certain MV technologies because of more sinusoidal output waveforms [15]. Some important factors that must still be evaluated are given in [12], [15], and [16].

Motor Rotor Design and Protection

DOL-started large motors may have longer startup times than the maximum allowable locked rotor withstand time [1]. A speed monitoring system may then be required in conjunction with the motor protection relay [1]. An alternative is to design the rotor for a locked rotor withstand time that is longer than the startup time. An SSASD eliminates these requirements.

Motor Stator Winding Insulation Damage and Protection

DOL-started motors are occasionally switched (interrupted) during startup (e.g., locked rotor condition, emergency stop, or process trip). It may result in overvoltages because of multiple reignitions and virtual current chopping, which may be significant depending on the system's reactances and capacitances [17], [18], resulting in insulation damage. The situation is more significant during startup because of the poor power factor. An SSASD system (high power factor and power electronic soft switching) can avoid these overvoltages during startup and switching; therefore, the life of the motor may be prolonged. Motors with a high voltage (e.g., 10 kV versus 6 kV), high power (e.g., 3 MW versus 200 kW), and fairly long cable distance (e.g., 800 m) may present a dangerous combination for overvoltages [19]. This combination is also typical for an ideal SSASD application, which increases its feasibility. It is shown in [19] that larger motors (typically above 1 MW) do not experience significant overvoltages following interruptions in the running mode. Surge arrestors or suppressors are, therefore, not required.

Motor Condition Monitoring

In many cases, the reference frequency used by condition monitoring equipment (e.g., partial discharge monitoring) analyzing software is limited to the supply frequency. A dedicated SFC needs to supply the frequency in accordance with the process demand; therefore, accurate measurements cannot be taken. Furthermore, motor side harmonics might also interfere with the measuring system. An SSASD provides the facility to perform periodical condition monitoring (after synchronization).

Some ASD topologies allow operation with an earth fault (until a second earth fault occurs) because the drive isolates the earth path [20] (correct system insulation coordination is important). It is also possible to detect an earth fault of any of the soft-started motors prior to startup and before the damage occurs. The following sections discuss the advantages associated with motors being soft-started optimally with the SSASD concept.

Power System Considerations and Process Stability

Most of the uses of ASD described in [14] hold good. No voltage dips associated with large motor startups will be experienced if these motors are started with the SSASD. Negative effects on associated low-voltage loads will be eliminated.

Process Availability

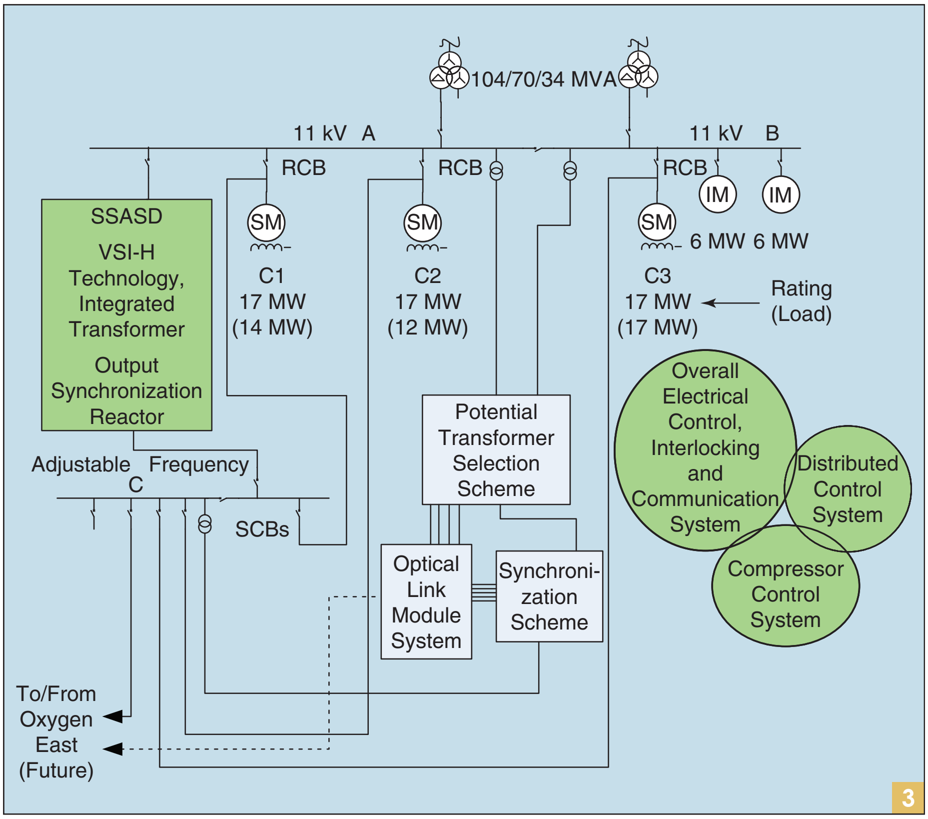
The SSASD concept allows the ASD to be synchronized with the supply (only for adjustable frequency motor) before a trip occurs, not only for components with $N - 1$ redundancy, as previously described, but also for many alarm conditions that would have eventually led to a trip. Components with $N - 1$ redundancy, depending on the project specification and the drive topology, can typically be power cells (e.g., in [21]), cooling pumps, cooling fans, and control processors.

Alarms that can prompt the process operator to synchronize the unit prior to the occurrence of a trip include converter transformer temperature alarm, power electronic device temperature alarm, coolant temperature alarm, cabinet temperature alarm, low water flow alarm, and water level low alarm (major leak).

Limitations and Associated Solutions

Most of the failure modes can be addressed by the SSASD concept as described earlier, but some extremely unlikely failures cannot be addressed. Single points of failure include the converter transformer and the power connections connecting the transformer secondary to the power cells.

When equipped with a cell fault bypass facility (VSI-H), the faulty cell is designed in such a way that it is bypassed before the fault progresses to other parts of the drive. This concept is well proven with voltages up to 7.2 kV. Higher voltages (e.g., 11 kV) follow the same topology but use new power cell and power connection designs. A fault might progress to the power connection area, which will result in a trip and can also result in a significant damage. Therefore, it is advisable to take additional design precautions to create a fault-free zone in the power connection area, i.e., to eliminate arcing and three-phase or phase-to-phase faults as far as possible. Hence, the power modules should be segregated from each other and especially from the power connection area as far as possible. One option is a busbar design that will not arc when exposed to air ionization. This can be achieved by busbar insulation or segregation. An alternative effective approach is to replace the busbars with cables. It is still recommended to have an alternative emergency startup backup for critical applications (e.g., DOL starting where possible or a backup soft-start system) to address single points of failure.



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Single-line diagram of NPP SSASD.

Case Studies

SSASD for a New Petrochemical Plant

Overview

Adjustable-speed operation of compressor 1 (C1) is required for initial startup, energy savings, and optimized process operation. Compressor 2 (C2) and compressor 3 (C3) motors need to be soft started. The partial plant single-line diagram is shown in Figure 3. The initial motivation for the SSASD system was based on the limitation of the switchgear fault level and busbar voltage drops associated with the DOL startup of the large motors. The only alternative to the SSASD concept would have been a dedicated starter of the adjustable frequency type and a dedicated ASD. This is due to the requirement of a very specific controlled soft start of the large motors and the requirement to slow roll them during initial startup. The startup torque speed curve of the C3 compressor dictates that a dedicated SFC for soft starting would have required a rating (12.75 MW peak) close to the rating of the ASD for C1 (maximum load 14 MW).

TABLE 1. COST EVALUATION OF A STANDARD VERSUS SSASD SYSTEM.

	Cost (p.u.)	
Description	SFC and ASD	SSASD
Soft starter (SFC type)	0.72	
SSASD		1.00
ASD (VSI)	0.92	
Switchgear (variable frequency bus)	0.28	0.32
Control system	0.10	0.13
Additional civil or room costs	0.10	
Total	2.11	1.45

Basic Economic Evaluation

The capital expenses are significantly less with the SSASD (Table 1). The p.u. cost for all cost evaluations is defined as the cost of a 15.5-MW SSASD unit (i.e., 1 p.u.).

System and Technology Overview

The VSI-H topology was selected with 11-kV output voltage capability when one cell had failed. An input transformer is used with multiple phase shifted secondary transformer windings, each feeding a power module. The proper phase shifting results in harmonic reduction, and a total of 15 modules (five per phase) are used, which results in a 30-pulse configuration. Each power module is based on a diode rectifier front end and a high-voltage insulated gate bipolar transistor (IGBT)-based single-phase inverter. Synchronization is possible after a module failure has occurred ($N - 1$ redundancy). The redundancy of all important related system components is at least $N - 1$, including the programmable logic controllers (PLCs) and the synchronous machine excitation panels. A compressor control system controls the process flow and the pressure during synchronization and fixed frequency operation.

Output Voltage, Insulation, and Hazardous Area Considerations

The near sinusoidal voltages at the terminals of the motor (with an output reactor and correctly selected carrier frequency) poses no risk to motor insulation [22], and a compliance with hazardous requirements [12] is achieved.

Synchronization

Previously, the internal synchronous transfer scheme of the ASD manufacturer allowed only the transfers to the same bus from where the ASD is fed. A proposal, however, was implemented to safely synchronize to and from remote busses [e.g., the B bus for a new petrochemical plant (NPP)] [12].

Startup Recordings

Figure 4 illustrates the characteristics, considerations, and a smooth startup recording (low starting current).

Wider Plant Systems Overview

Oxygen East

Figure 5(a) illustrates the electrical infrastructure. The 55- and 22-MW motors are presently soft started with an LCI system, as described in [6]. The diagram shows the future possibility to use the LCI to soft start the 36-MW motor (presently started by the MG sets). A future possibility for a modified interconnection to oxygen West via the existing power and communication cabling and a connection to NPP are shown.

Oxygen West

The plant consists of seven electrical trains, each with an 11-kV, 36-MW synchronous motor (SM) driving an air compressor and an 11-kV, 13.7-MW induction motor (IM) driving an oxygen compressor. Presently, the SMs are started with MG sets, whereas the IMs are started directly on line. Figure 5(b) indicates the single-line diagram of the system. Figure 5(c) provides a plot plan overview of the systems.

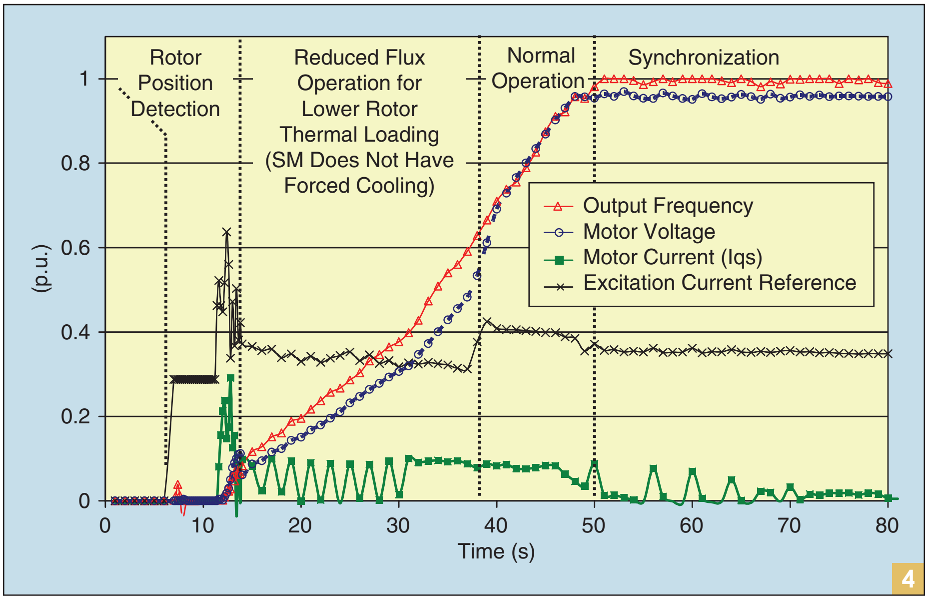
Oxygen Soft Start and Drive System Feasibility Study Components

IMs (13.7 MW)

IMs are old, and some of the motors have been rewound. The motors may have become more sensitive for DOL starting because of rewinds or upgrades. These rewinds or upgrades were associated with some modifications that could affect the mechanical rigidity of the windings, which are especially stressed during starting. An average of 1.6 failures per year is experienced (for eight motors), of which more than 90% can be attributed to the DOL starting method. The motor rewind cost is 0.053 p.u.; therefore, the average cost per year is $1.6 \times 0.9 \times 0.053 = 0.08$ p.u. (see the "Estimates Options, Integration, and Solutions" section). The average number of starts per year is nine per motor. The additional thermal and mechanical stresses associated with starting are completely eliminated when using the soft-starting capabilities of the SSASD.

MG Set-Started SMs (36 MW)

The first portion of the startup is associated with IM action before the motor reaches synchronism with the output of the fluid coupling-based MG set from where the generator is ramped up to the supply frequency (before synchronization with the electrical network occurs). It appears that the starting rotor cage (damper bars) is not designed very conservatively, and significant heating occurs during startup, which is aggravated by poor cooling due to a slow rotational speed. Rotor damper bar failures have occurred, and this resulted in a decision to perform significant refurbishment work on the motors (total project cost of 0.8 p.u.). Subsequently, maintenance and inspection intervals on the motors have been increased to limit the expenses. The yearly amount for related refurbishment and maintenance is estimated in the "Estimates, Options, Integration, and Solutions" section.



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NPP SSASD startup recording (no-load).

Energy Savings Study

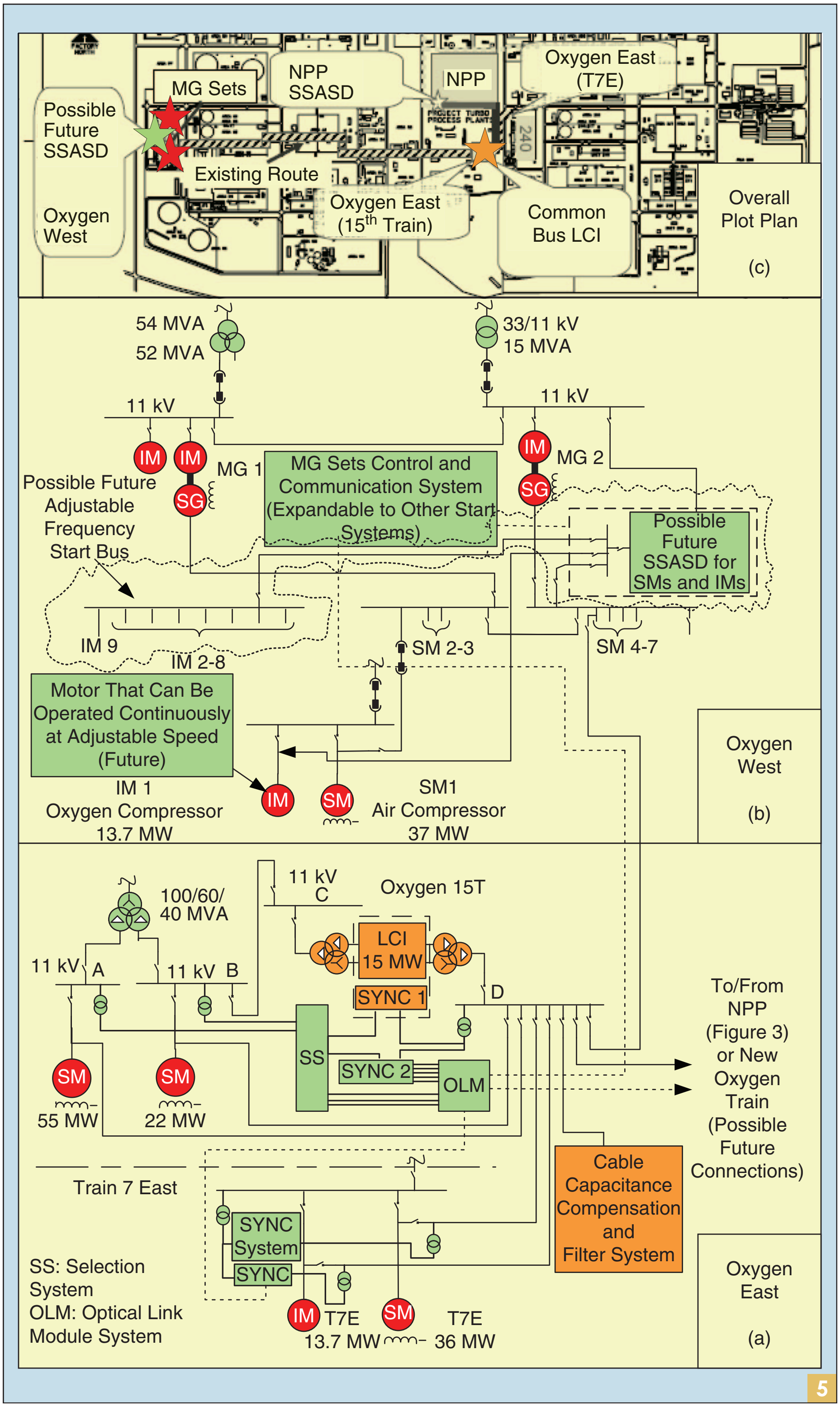
The newest oxygen train (15th) can be operated at full capacity and therefore benefit from the increased train efficiency. It is proposed not to share the loads between the other train compressors but to operate all oxygen compressors (13.7 MW motors) except one compressor at rated load (or the most efficient load point). The remaining compressor will then be used to regulate the flow efficiently by means of adjustable-speed operation. The advantage of this option is that energy is saved with adjustable-speed operation by avoiding the use throttling on all motors during normal operation. Energy saving principles and saving estimation techniques are described in [14]. Energy can also be saved by switching the motors on and off at optimal times with a soft-start system and avoiding the risks associated with DOL starting. The yearly energy savings amount was initially estimated to be between 0.14 and 0.18 p.u. The study was refined by the plant maintenance department, and it estimates the energy saving at 3 MW, with an associated yearly saving of 0.15 p.u. The electricity regulator and provider has introduced a funding scheme for energy savings or demand side management projects. The contribution of the possible funding is described in the "Estimates, Options, Integration, and Solutions" section.

MG Sets

Approximately 0.08 p.u. is required every five years to maintain fluid couplings. The oil coolers of the MG set (for the fluid coupling and the lube oil system) are reaching their end of life. It is estimated that the coolers will have to be replaced in the next five years, and this will cost approximately 0.08 p.u. A soft starter or SSASD with the required redundancy built in $(N-1)$ or with backup from another start system should eliminate the need of the MG sets. The estimated savings are shown in the "Estimates, Options, Integration, and Solutions" section.

LCI Used as a Backup for Other Systems

The LCI may possibly be used in the future as a backup for other start or drive systems, but only in emergency situations and only as a soft starter. Additional filtering is required to compensate for long cable distances (resonances). It was verified that no dangerous pulsating air-gap torques will be imposed to any of the SMs mentioned earlier. Furthermore, additional rotor position detectors may be required because of the long cable lengths. The LCI also has the capability of performing a flying start [6], and it can used to catch a remote motor after an SSASD trip has occurred and synchronize the unit with the fixed frequency supply before the process is disturbed.



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Oxygen and NPP single-line and plot plan diagrams.

Other Systems Used as a Backup for the LCI

Typical reliability figures of an LCI system is provided in [23]. The figures show that it is extremely unlikely that a fatal failure of a major item (LCI transformer or reactor) will occur. It must, however, be stated that a failure cannot be ruled out and that severe production losses can occur if a major item should fail catastrophically. The LCI reactor and transformers are specialized items, and an extensive period can pass before any of these items can be repaired or replaced. According to [24], it took a significant time to repair a dc link reactor failure compared with other typical drive failures. There are two options to avoid this production loss: to procure a transformer and reactor or to rely on a backup from another start system.

Estimates, Options, Integration, and Solutions

This section provides a summary of overall feasibility estimate items (Table 2), options (Table 3), benefits (Table 4), backup considerations (Table 5), and solutions capable of meeting the aforementioned objectives.

Energy Savings Solution

Energy can be saved by the adjustable-speed operation of one of the oxygen compressors. The simplest way to achieve

TABLE 2. FEASIBILITY COST ESTIMATE (ESTIMATE ITEMS).

Item	Description	Estimate (p.u.)
1	ASD unit (includes SSASD function): 11 kV, 15.5 MW (oxygen West)	1.00
2	Start bus and associated switchgear (oxygen West)	0.63
3	Automation equipment [PLC SCADA (supervisory control and data acquisition) extension and interface] (oxygen West)	
4	Cabling and junction boxes (oxygen West)	
5	Subtraction if only reduced specification start-duty switchgear is used (oxygen West)	−0.22
6	SSASD and switchgear room (oxygen West)	0.12
7	Interconnection cabling between NPP and 15th oxygen train (oxygen East)	0.13
8	Additional LCI equipment [resistance capacitance (RC) filter, RC switch, RC housing, software modification] for LCI to function as a backup for other systems (NPP and oxygen West)	0.23
9	Cable modifications to make 15th oxygen (oxygen East) train common hub [excluding Train 7 East (T7E) IM]	0.06
10	Additional switchgear at 15th oxygen train to accommodate T7E SM with common hub system	0.05
11	Modifications to 15th oxygen train PLC to interface with a remote starter	0.05
12	Additional switchgear at 15th oxygen train to interface with a remote starter (one breaker)	0.05
13	Additional cabling (and connection box) to accommodate soft starting of T7E IM	0.06
14	Additional switchgear to accommodate soft starting of T7E IM	0.05
15	Switchgear and switchgear modification only for ASD operation (assume bypass option)	0.10
16	LCI transformer and reactor	0.14
17	Backup NPP SFC only used for soft starting (excluding redundancy, module bypass functions); switchgear infrastructure is already in place	0.69
18	Additional engineering for NPP SSASD system to obtain a backup from LCI	0.18
19	Backup NPP SFC room	0.10
20	Additional engineering for NPP SSASD system to obtain a backup from the dedicated SFC (duplicate functionality of SSASD)	0.12

Note: Installation and commissioning costs are included. Prices are subject to the EURO, USD, and ZAR exchange rates.

TABLE 3. FEASIBILITY COST ESTIMATE (SUMMARY OF OPTIONS).

Option	Description	Applicable Items from Table 2	Estimate (p.u.)
A	Only ASD without capability to soft start other trains	1, 6, 15	1.21
B1	SSASD system starting IMs and SMs, driving one IM	1, 2, 3, 4, 6	1.75
B2	SSASD system starting IMs and SMs, driving one IM, with start duty switchgear	1, 2, 3, 4, 6, (−5)	1.53
C	Backup for LCI by extending option B (additional costs)	9, 10	0.11
D	Backup for LCI by using NPP SSASD	7, 11, 12	0.22
E	Backup for oxygen SSASD using LCI	8, 11, 12	0.32
F	Backup for NPP SSASD using LCI	7, 8, 11, 12, 21	0.63
G	Backup for NPP SSASD using oxygen SSASD system	7, 11, 12	0.22
H	Option B extended to start T7E IM as well	1, 2, 3, 5, 6, 9, 10, 11, 12, 13, 14	2.07
I	Dedicated SFC backup	17, 19, 20	0.91

this is by installing a dedicated ASD. This option (Table 3, A) is presently not economically viable.

Soft-Start Solution

A soft starter of the adjustable frequency type is the only technically acceptable soft-start solution to fulfill the requirements discussed in the previous section.

SSASD

An SSASD can address both the energy saving and soft-start requirements of all the compressor motors (Table 3, B). This is the most economical option to soft start the compressor motors because the adjustable-speed energy can also be saved. As per the present figures, this option is more economical than the option of a dedicated ASD (Table 4).

Integration of the Different Soft-Start and Drive Systems

Figures 3 and 5 show the potential interconnection of all the applicable starting and drive systems. The estimates show that the optimal and most economical backup for both the LCI and the NPP SSASD is by using an oxygen SSASD (Table 3, option G versus F, option C versus D, after the system has been installed). It is, however, a long-term project, and it will meet business figures only in future in terms of return on investment (ROI) and net present value (NPV) when electricity costs increase. It must be noted that electricity costs in South Africa are presently among the lowest in the world but are rapidly increasing. In the near future, cost may become high enough to validate further investigation involving all engineering disciplines to determine the feasibility of implementation. The application

TABLE 4. FEASIBILITY COST ESTIMATE (BENEFITS AND PAYBACK TIME).

Item	Benefit	Cost (p.u.)	
1	Estimated electricity supply company funding	0.50	Per year
2	Maintenance or repair cost on IMs (13.7 MW)	0.08	Per year
3	Maintenance or repair cost on SMs (36 MW)	0.005	Per year
4	Energy saving	0.14	Per year
5	MG set maintenance: fluid couplings (on one MG set)	0.01	Per year
6	MG set maintenance: oil coolers (one MG set)	0.01	Per year
7	Total yearly saving	0.24	Per year
8	Estimated savings by revising the 13.7-MW motor replacement strategy (considering fewer failures and longer life)	0.40	NPV
	Payback time	Years	
9	Dedicated oxygen ASD (Items 1 and 4 and Table 3 Option A)	4.94	
10	Oxygen SSASD (Items 1 and 7 and Table 3 Option B2)	4.26	
11	Oxygen SSASD and revised strategy (Items 1, 7, and 8 and Table 3 Option B2)	2.61	

concept may be even more feasible in countries with similar energy saving opportunities with higher electricity costs.

Therefore, the short-term solution is to use the oxygen 15th train soft-start (LCI based) and NPP SSASD systems as backup for each other. This is the best option but only if incorporated early in the design process and commissioned prior to the final plant startup. This is evident from a decision analysis that was performed based on the information in Table 5 and the cost estimate in Table 3. Table 5 also illustrates that a dedicated SFC should be considered as a backup if a shutdown is the only option to perform the commissioning.

A NEW TECHNOLOGY-BASED SSASD AS A BACKUP FOR OTHER SOFT-START SYSTEMS IS A VIABLE ALTERNATIVE.

Conclusions and Recommendations

New opportunities and possible benefits are identified and quantified when the multiple motor SSASD concept is applied in a unique manner with near sinusoidal high-output voltages with the capability to synchronize and desynchronize SMs safely to multiple utility sources. SSASD systems may allow new technology to be applied economically with a lower risk level to

TABLE 5. BACKUP CONSIDERATIONS TO PLANT MAIN SFC.

Number	Description	Using Existing LCI Backup	Using New SFC Backup
1	Design	Advanced design required	Simple
2	Main installation requirements	Filter Filter room Motor position encoders Extensive power and control cabling and trenching or racking Complex control and interfacing system Additional switchgear for filter and interconnection	SFC system New drive room
3	Precommissioning	Extensive testing of the control system logics, interfaces, and communication	Auxiliary systems commissioning and open loop tests
4	Commissioning: New plant	Achievable	Achievable
	Commissioning: Two-week shutdown	Extremely challenging	Achievable
	Multiple identical process trains	Achievable	Achievable
5	Flexibility	Only emergency startups	Full operational capabilities (including continuous variable speed operation)
6	Reliability or availability	LCI is a proven technology and may therefore improve the overall reliability or availability	Risk is higher with new SFC technology as backup, the risk can, however, be managed, especially if experience has already been obtained with the similar main plant SFC
7	Other considerations	The LCI can also obtain backup from the plant main SFC, which is especially important if no other backup options to the LCI are available	No backup for LCI (no cabling)

meet process and energy saving requirements for large drive systems. Additional availability and reliability benefits are introduced.

Special precautions are, however, still required until the new technology is proven in the field. Recommendations are provided to reduce the failure probability associated with single points of failure. Furthermore, it is recommended to provide a backup for the critical SSASDs, and it is shown that several solutions can exist in a large petrochemical facility.

One solution is to use older proven technology (e.g., LCI, if already installed) as an emergency backup, only for starting. It can also be economical and feasible to use the new technology as backup for the old technology, thereby significantly improving the overall availability of large drive applications in a petrochemical facility. Sufficient time allowance for commissioning is essential because of the increased system complexity. A new technology-based SSASD as a backup for other soft-start systems is a viable alternative compared with an LCI-based system when long cable distances are involved.

SSASD SYSTEMS MAY ALLOW NEW TECHNOLOGY TO BE APPLIED ECONOMICALLY WITH A LOWER RISK LEVEL TO MEET PROCESS AND ENERGY SAVING REQUIREMENTS.

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Frieder Endrejat (frieder.endrejat@sasol.com) is with Sasol Technology in Secunda, South Africa. Pragasen Pillay is with Concordia University in Montreal, Quebec, Canada, and the University of Cape Town in South Africa. Endrejat is a Member of the IEEE. Pillay is a Fellow of the IEEE. This article first appeared as "Soft Start/Adjustable Speed Systems for Multiple MW Rated Motors" at the 2006 Petroleum and Chemical Industry Conference.