TECHNIQUES TO IMPROVE MV CASCADED H BRIDGE INVERTER (CHBI) VFDs AVAILABILITY APPLIED TO DRIVE HIGH POWER ESP OIL WELLS

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Abstract – Artificial Lift systems are routinely employed in the petroleum industry in order to provide the energy needed for the fluid to be transferred from the reservoir to the surface. The ESP system is a method of artificial lift widely used in recovery, often applied in mature fields or fields with heavy oil (low API gravity), as well as high flow rate wells. The energy for ESP systems is supplied by a submerged motor pump set, often driven by a medium voltage adjustable speed drive on the surface.Electrical systems present in oil production units generally depend on redundancy of electrical equipment, primarily related to operational and production safety, in order to increase system reliability. However, in the case of offshore ESP systems, the power to each well is dependent on the operation of a dedicated frequency converter, and redundancy is practically impossible due to the dimensions of the equipment located on the production platforms.

Due to the high cost of interventions for replacement of the ESP equipment, the system requires the maximum availability possible. The reliability of applied frequency converters for ESP drives becomes essentially important to the operation of this system. A failure in the converter translates directly into lost production from that well, as well as high intervention costs.

The objective of this paper is to analyze the availability and reliability of frequency converters used in medium voltage multilevel CHDI drive topology for ESPs. A method to improve availability of MV frequency drives using the implementation of technical resources, focusing on increased system availability over the entire useful life of the ESP, is proposed. This will enable achievement of lower production losses and a better economic return on investment.

Index Terms – Electrical Submersible Pump, ESP, VFD, ASD, VSD, CHBI, Cascaded H Bridge Inverter, reliability, availability.

I. INTRODUCTION

Electrical Submersible Pump (ESP) installations have been widely used in the oil industry as an artificial lift method worldwide [1]. These systems are the lift method of choice for high volume wells, as well as those wells with heavy (low API gravity) oil. Throughout the lifetime of ESP technology, the systems have seen improvements in reliability and increased installed life. As intervention costs increase in higher technology wells, the reliability and run-time of the ESP systems becomes even more important.

In deep water applications, intervention costs run into the tens of millions of dollars (US$). At the same time, there is a tendency to build wells with high flow rates, and therefore require equipment with higher power. Currently there are installations with 1,600 HP/ 5 kV ESP motors.

In such applications, it is common for the ESP to be controlled by a variable speed drive (VSD). The drive provides operational flexibility as well as soft start / stop capability. The isolation from the platform electrical system inherent in drives provides some protection against transient events.

For high power equipment, a common choice is medium voltage (MV) drives. A large number of MV frequency converters used in deep waters ESP application have multilevel Cascaded H-Bridge Inverters (CHBI) topology.

The reliability and availability of CHBI frequency converters and its system applied for this purpose becomes essentially important to the operation of the ESP system. A failure in the converter translates directly into lost production and ESP equipment stoppage. Each unintended equipment stop inherently shortens the life of the ESP system either through startup failures or thermal cycling.

II. ESP APPLIED IN DEEP WATER

Some platforms are designed and built to use the ESP system as the main artificial lift way. In these units is normal to have a large number of frequency converters to drive ESPs. IN other locations, the platform is modified to allow application of the ESP system. There is also the possibility of applying the ESP system in existing and operating wells. In these cases, it is necessary to make changes on the surface and in the subsea.

An ESP consists of centrifugal multistage pumps driven by electrical motors. These pumps are design and constructed to be used in the harsh environment of a downhole hydrocarbon well in an underwater environment. The pumps are inserted downhole near the oil-producing zone, and provide the additional head necessary for transport of the well fluids to the surface at the desired flow rate. One or more seal protectors are installed between motors and the pumps, which allow internal pressure equalization with well pressure and provide protection against contamination of the dielectric oil inside the electric motors with fluid from the well.

The energy to power ESP is supplied through an electric power cable umbilical and goes through the path of the maritime platform through the production well. The existing electrical connections in this system depend on the application type. Conventional ESP system used in dry completion wells connect through a conventional wellhead configuration, commonly referred to as a Christmas tree. However, in deep sea applications, the ESP system to completion is the wet type, and specific underwater connections must be used. (13)

In most applications, the electrical power system, controls and fluid collection and processing systems are located on the platform at the surface. Each well has characteristics that require a careful specification of the ESP system for the specific application. As would be expected, wells with higher flow rates typically require bigger equipment in top side.

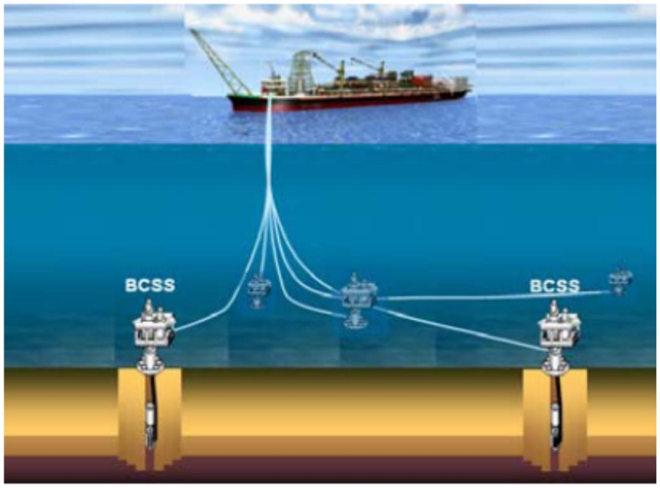


Fig. 1 ESP system in deep water application

III. ELECTRICAL SYSTEM AND VFD TOPOLOGY

The electrical distribution power supply system in oil platforms uses normally selective secondary topology. The power supply to the secondary equipment is redundant, and can be powered by both sides of bus bars. When a feeder or upstream equipment fails, there is another power option, maintaining the availability of the production platform systems The power for the MV VFD is supplied through a circuit breaker present in a medium voltage switchgear, and thus typically has redundant supply.

When evaluating the actual ESP equipment, however, this redundancy is often not physically possible. Not only is it impossible to install two pump sets in the well bore, the limitations of space and weight on the topside prevents duplicate drive equipment.

Frequency Drives applied to high power ESP systems (on the order of 1,600 HP) have rated power around 2,000 HP and rated output voltage up to 6,600 VAC. The inherent dimensions of such equipment make duplication on production platforms a near impossibility. In these applications, the application of techniques to increase the availability of VFD's employing built-in redundancy becomes especially important in order to maintain a high availability for the system.

A. VFD internal topology

The Cascaded H Bridge Inverter (CHBI) topology concept employs a multi-winding power transformer which creates angular displacement on the secondary side. Each secondary winding creates power output at a different phase angle. The number of transformer secondary windings depends on the number of pulses employed in the inverter, with each secondary winding side supplying power to only one cell, as shown in Fig. 2. Drive voltage output is obtained switching of the power cell outputs. In deep-water ESP applications, a sine wave filter is often employed in order to reduce the harmonics inherent in such a scheme.

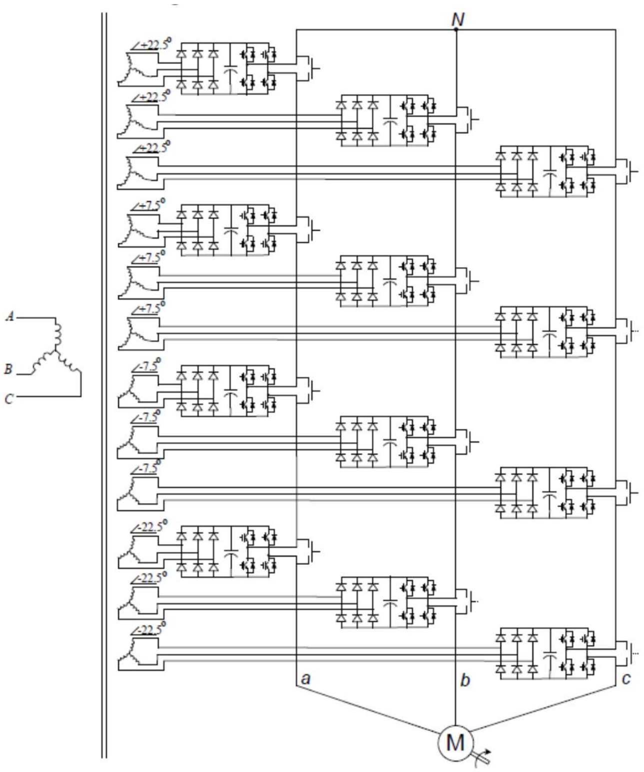


Fig. 2 MV CHDI drive Topology [7]

Each power cell consists of a three-phase bridge rectifier, DC link capacitor and the inverter IGBT's step. Overcurrent protection is provided through fuses. Each cell has an individual cell control board, responsible for receiving the switching signals by optical fiber and commanding the triggering of both the inverter bridge, and the IGBTs. Power Cells can be easily replaced in case of failure and are interchangeable.

The number of cells per phase depends of the output drive voltage. Normally, cell N+1 redundancy is applied in VFD design for the phase voltage necessary to supply the ESP. In deep water applications VSDs typically use 4, 5 or 6 cells per phase.

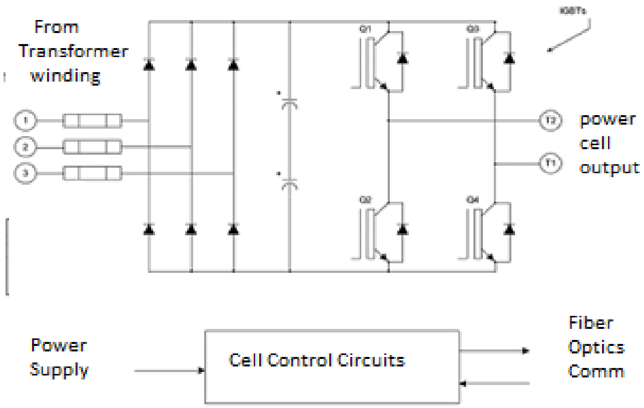


Fig. 3 Power cell electrical diagram

In addition, multiple sensors, circuit boards, power supplies and software compose the VFD control system. This equipment not only control the cells switching but also provide measurements, communications, signal conditioning, data processing, fiber modulation, remote monitoring and other functions. A failure of any of these components causes a shutdown of the ESP system, or at the very least reduced operational functionality.

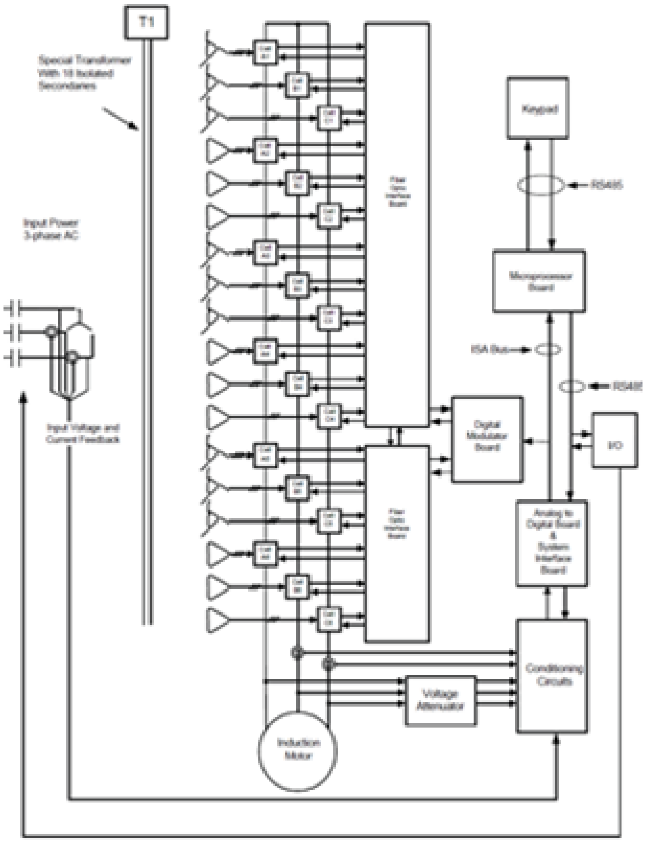


Fig. 4 MV CHDI Topology Control system schematic

Data communications between the VSD and the platform PLC and Central Control Room (CCR) are necessary. These data are used for monitoring but also for ESP protection. Start / stop commands, operating parameters for the drive and downhole equipment, power consumption and similar data are commonly communicated. A loss of data or data corruption can create inadvertent shutdowns of the ESP.

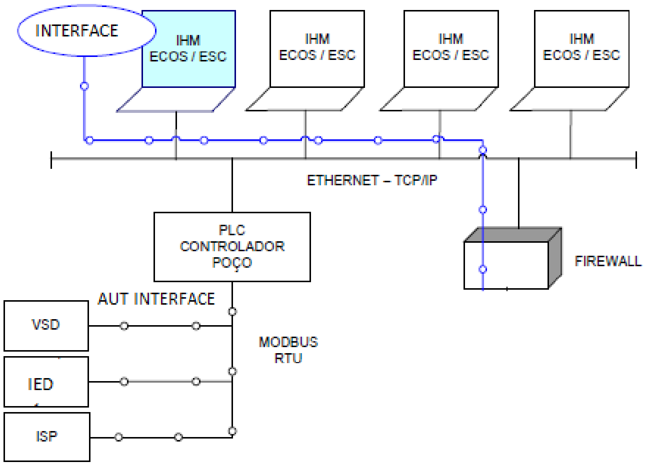


Fig. 5 Network and Automation Interface diagram

B. *Reliability analysis*

The reliability of a cell system composed of an 18 cell CHDI VSD (no cell bypass) can be calculated using equation (1) [7]:

$$R(t) = (e^{-\lambda_1 t})^{18}.(e^{-\lambda_2 t})^{36}.(e^{-\lambda_3 t})^{54}.(e^{-\lambda_4 t})^{18} \tag{1}$$

where

λ_n: Failure Rate (FR) of Component (MTBF^{-1})λ_1: FR Diode Bridge
λ_2: FR IGBT leg
λ_3: FR DC link Capacitors
λ_4: FR Cell Control Board

As expected, the complexity of the control system for multilevel CHBI inverters is very high. A failure in any one of these components can cause the drive to fail, resulting in inadvertent shutdown of the ESP, and the resultant costs and loss of life. Despite its importance, the reliability of all parts becomes very difficult to calculate.

In order to calculate a total drive reliability function, including power systems, control system, power components and interfaces, a large amount of dependable reliability data would need to be available. As a theoretical analysis is unlikely to provide meaningful data, an empirical analysis based on experienced failures was undertaken. This allows identification of areas where improvements would have the greatest positive impact on reliability.

IV. FAILURE ANALYSIS

To begin an understanding of the reliability of MV CHBI drives for deep-water applications, data and reports from offshore ESP wells installed in Espirito Santo, Campos and Santos Basins were obtained. These fields consist of 38 ESP wells with associated MV CHBI drives, distributed between several platforms and production areas. Power systems for each location were unique, and thus did not directly affect reliability.

The most serious failure registered was a 13.8 kV short circuit in the drive input power supply resulting in a downtime of several days. This event happened approximately 18 months after drive commissioning. The failure was identified as a catastrophic flaw in the equipment manufacturing, and was considered very rare. This time to repair was not considered in this first analysis.

Similarly, multiple failures were determined to have been caused by external sources, e.g. unstable and loss of auxiliary power and were not considered in this first downtime analysis.

Those failures identified for analysis could be segregated into three main groups: power cell failures, control systems failures and automation interface failures.

Most failures occurred in the automation interface, with failures in the control system a strong second. Additionally, one registered failure in an automation interface was identified as imminent. Failures in the power cells comprised only 14% of the identified events.

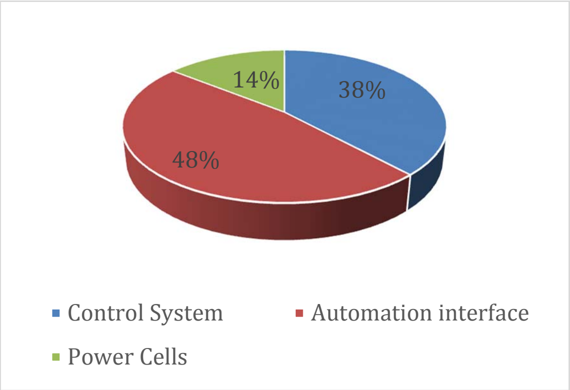


Fig. 6 Failures registered by failure mode

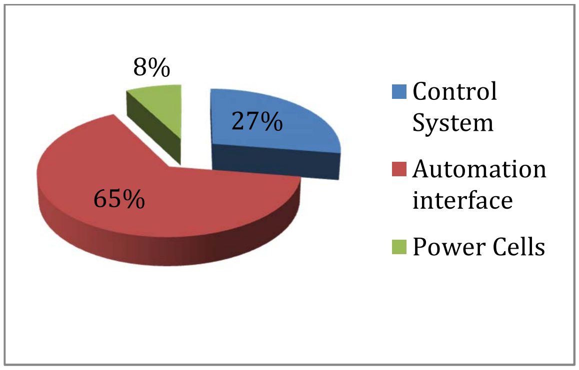


Fig. 7 Downtime registered by failure mode

When downtime was included in the analysis, failures of the automation interface comprised 65% of the recorded downtime, despite only containing 48% of the total failures.

Overall, a total of 998.98 hours of downtime due to VSDs and automation systems failures was identified. The calculated availability of these CHBI drive systems was 99.881%. The mean time to repair (MTTR) for these three failure modes were calculated:

Table 1 - MTTR by Failure Mode

Failure Group	MTTR (hours)
Power Cells	25,82 h
Control System	34,18 h
Automation Interface	64,70 h

The total time to repair (TTR) of a drive failure on an oil platform or remote area is the sum of several times and can be determined from Eq. (2):

$$TTR = T_{fi} + T_{rt} + T_{sp} + T_{rp} \qquad (2)$$

where

T_{fi}: Time for failure identification;

T_{rt}: effective repair and test;

T_{sp}: Service paperwork;

T_{rp}: Restart oil production;

Empirically, failures in the control system are more difficult to identify than faults in the power system. The control system in modern VSDs is sophisticated enough to identify faults occurring in the power system, and display data relating to the failure in the HMI or through software. This fact makes the failure identification time for most power electronics failures minimal. Moreover, if well specified for the application, frequency converters use redundancy techniques to reduce equipment downtime in the power circuits, such as bypass of a damaged cell. In addition, in many cases, power cells are modular circuits that can be easily and quickly changed if needed.

In the case of a failure in the control system or automation interface, there is often no reliable indication of the fault location. The time for failure identification in these cases can take several hours or days, because the maintenance team typically follows a replace and retest technique, rather than a root cause analysis. In most cases, there is no drive specialist on the platform to make the necessary test. This necessitates specialized personnel traveling to the platform location before repairs can begin, further increasing downtime.

To summarize this analysis, MV CHBI VFDs for ESPs in the field locations analyzed have generally good availability, particularly in the power electronics systems. Failures in these systems represent a small fraction of the downtime experienced by CHBI drives. Conversely, failures involving drives control system and automation interfaces, particularly in remotes areas like oil platforms, can result in considerable downtimes and production loss.

V. TECHNIQUES TO IMPROVE VFD AVAILABILITY

Some design techniques can be applied to minimize field problems in these systems and improve VSD availability in ESP applications. ESP systems normally runs 24h x 7 days week, so basic maintenance only can happen during a scheduled production stop. Specially designed equipment can be chosen to improve the return on investment for these systems.

A. Improve reliability of control voltage

The medium voltage VSD needs to receive auxiliary supplies of power from external sources apart from the main supply voltage. Normally, there are two required external power supplies:

- External power supply for internal fans (normally 380 Vac to 480 Vac) ;
- External power supply for control voltage and control (normally 115 Vac to 240 Vac) ;

A loss of any of the three power supplies will cause a loss of the VSD and uncontrolled shutdown of the ESP system. Therefore, this power must be provided from very reliable sources. One way to make power control voltage more reliable is by implementing a redundant system uninterruptible power supply (UPS) and transfer switch.

Very reliable systems can be developed if the control voltages could be provided directly in DC voltage to the appropriate DC busses. Battery banks used in platforms are more reliable than UPS Systems, and provide more constant and dependable voltage support.

B. Total Drive Redundancy

If the failure of the main transformer or catastrophic failure such as power electronics would result in a very high TTR, total drive redundancy is an important option to be considered. The failure analysis showed a failure in a transformer or short circuit is very rare, but it can happen.

Other important design considerations such as physical limitation, weight and equipment cost, normally do not allow redundancy to be applied to every well.

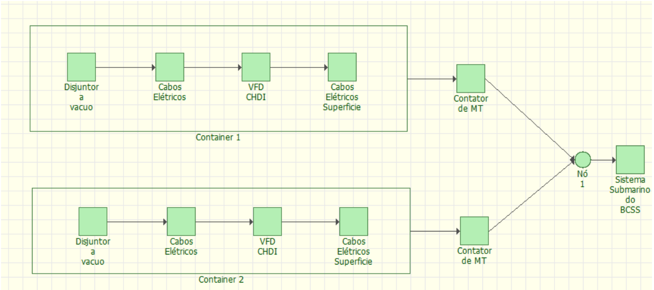


Fig. 8 Drive redundant simulation

This option becomes very interesting in platforms with many equivalent drives for ESPs. Simulations can demonstrate that one complete VFD spare per five ESP drives can improve the system reliability significantly with acceptable tradeoffs for cost, weight and dimensions.

C. Control and automation interface Redundancy

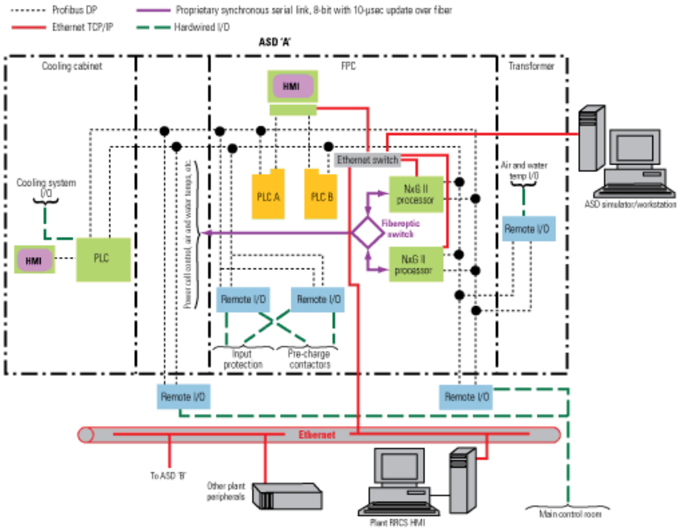
The measurement, control and automation system is at least as important as the power system components in availability analysis. The occurrence of faults in components of the control circuit boards and commands causes an immediate shutdown of the VFD. As discussed above, failures in these systems have the greatest impact on system downtime.

When the fault occurs in the control system, identification of the failure is not trivial. Depending on the extent of the problem, there can be no indication by the equipment, be false alarms, intermittent failures and spurious shutdowns, hindering or even making impossible the identification by the maintenance staff. In some cases, it may be resolved by changing boards and some components. Empirically, the fault identification time is inversely proportional to the experience and expertise of professional who is performing the failure analysis.

This fact contributes to increasing the TTR and for ESP application turns directly into production loss and reduced revenue.

Other problem that occurs in ESP applications is that the drive needs to run 24h x 7 days week, so basic maintenance only can happen in a scheduled production stop.

There are CHBI frequency converters with control redundancy applied in the cooling water recirculation pumps reactors or boiler water reactor (BWR) in the nuclear industry, as a technique for increasing the general reliability due to the enhanced safety requirements. As the control and automation equipment is the smallest and lightest of the drive components, these techniques can be applied to ESP applications with minimal costs in equipment dimension or weight.



Notes: ASD = adjustable-speed drive, FPC = fuse/pre-charge/control cabinet, HMI = human/machine interface, I/O = input/output, PLC = programmable logic controller, RRCS = reactor recirculation flow control system.

Fig. 9 Control redundancy system schematic of a MV CHBI Drive applied in nuclear power plants to increase reliability of BWR pumps [15]

Control redundant is not hot standby, it means that drive will shut-down before it can be started again. Regardless, if control redundant is applied and some component failure of the control system occurs, the drive can be operated through the redundant control system until repairs can be mad.

The TTR will be time to recognize failure, switch the control and start the production again, greatly reducing system downtime. Investigation and repair of the failures could be performed in an orderly manner without the pressure associated with lost production. Proper root-cause analysis could be performed and only damaged components repaired, further reducing costs of failures.

Additionally, Increase modularity of control devices also can bring good results reducing time to replace a damaged component [16].

VI. ECONOMIC ANALISYS AND IMPACT IN OIL PRODUCTION

The impact in oil production and return on investment for redundant control equipment can be measured in terms of the availability increase due to employment of more reliable equipment. This is accomplished for a specific production well by estimating the production loss in time, and comparing with and without redundant control equipment.

Simplified example of calculation for a deep sea well:

Estimated drive system useful life: 10 years (conservative);
Production well gross flow: 12,000 bpd (average);
BSW: 35% (Average);
Common system availability average: 99,881%
Redundant system availability: 99,99%

Difference between production losses = (0.9999 – 0.99881) x 360 x 10 x 12,000 x (1-0,35) = 30,607 bbl.

At an estimated price of US$50/bbl, this simplified analysis shows increase in revenue of over US$150,000 per year on average. The production loss optimization can be very profitable and the payback time very short. Financial evaluation needs to be done for each well and need be consistent, taking adjusting for variations in revenue per bbl.

This analysis does not consider increased life of the downhole equipment due to reduced thermal cycling and lower startup mortality. The ROI for these factors is difficult to determine, but could be much greater than that in increased production.

VII. CONCLUSIONS

Reliability and availability increase of ESP systems has been a very important subject and restless chased by the oil industry. This occurs because high costs involving the replacement of subsea equipment, rig intervention and the high loss of profit involved shutdowns of the system.

The overall reliability and availability of Medium voltages drive has an important aspect in industrial and production systems, and it means that drives manufacturers need to always to be improving new techniques and studies in this area. Aspects that can contribute to increase VFD availability directly contribute to an increase in ESP system availability. New techniques and equipment can be considered in the design stage and technical specification to minimize field problems.

MV Cascaded H Bridge Drives are in general reliable equipment and can be used in critical applications. For very special applications that require extreme reliable systems, e.g. high loss of profit, safety requirements or remote conditions, some design techniques can be adopted to increase reliability and availability even more.

The best techniques for increasing high power ESP power supply availability depends on several factors, since the availability of physical space on board, the number of ESPs wells in the platform as well the production well flow.

The redundancy of frequency converters for power ESP can be a good practice, since it implemented during the design phase and depending on the number of wells with ESP in a platform.

The use of VFDs with control redundancy are used in very high reliable applications and can add a significant availability to the ESP system, by being able for example to operate a well while investigating a failure in the control system and allow some preventive maintenance outside scheduled production stop.

For high flow production wells, the use of high reliability equipment and techniques can translate in very good results in comparison with conventional equipment.

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