Applied Ocean Research 43 (2013) 53–67

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Review

Review of challenges in reliable electric power delivery to remote deep water enhanced oil recovery systems

Vedachalam Narayanaswamy[*]

National Institute Of Ocean Technology

A R T I C L E I N F O

Article history:
Received 28 February 2013
Received in revised form 24 July 2013
Accepted 27 July 2013

Keywords:
Bio-fouling
EOR
ESD
FIT
IGBT
MTBF
PSD
VSDS
Wet mate

A B S T R A C T

This paper reviews the major challenges involved in reliable electric power delivery to remote deep water enhanced oil recovery (EOR) systems. As the oil well matures, top side based booster systems are not economical, and hence, subsea based booster systems are required. Such EOR processes require subsea systems to be operated at varying power and voltage levels, and this requires establishing subsea power stations with long tiebacks from the shore. Subsea stations carry out safe voltage step-down, distribution and conversion of electrical power in the order of mega watts. Breakdowns in subsea based EOR systems lead to huge production losses, and system retrieval for repair and maintenance is very costly and time consuming, and therefore systems need to be highly reliable. This paper describes the technical challenges involved in subsea variable speed motor drives, long step out power transmission, subsea energy storage requirements for safe start up and emergency shutdown, thermal and humidity management inside pressure rated enclosures, fault localization, pressure tolerant electronics and bio-fouling. Emerging advancements in electrical, power electronic, power transmission, energy storage and packaging technologies are reviewed, giving the confidence that the present technical maturity would be able to drive the development of reliable subsea based EOR systems.

1. Introduction

About 34% of today's energy requirements are met from oil and 21% from natural gas [5]. The demand for oil shows an uptrend with the global requirement forecast of 103 million barrels per day during the year 2020. From 1960 to 1970, 120 fields were discovered with recoverable reserves of 400 Giga barrels, whereas during the period from 2000 to 2010, only 10 fields were discovered whose recoverable reserves amounted to 30 Giga barrels [6]. Further, many offshore fields of Oil Producing and Exporting Countries (OPEC) are in the plateau region [5] and Norwegian offshore oil production which contributes to 10% of the global production has seen a 15% decline in production, during the years 1990 to 2005 [4].

To maintain the production plateau and to operate the remote located shallow water maturing oil fields on an economical basis, platform based EOR techniques [9,10] are adopted. With the increasing water depths, platform based EOR solutions are not efficient and economical, and hence, subsea based EOR processes are required [7]. Norwegian offshore deep water remote maturing fields are examples that require increased power at long step out distances for EOR. Tyrihans has been an operational field [4] since 2009 with subsea water injection pumps of 6 MW capacities and 35 km step out distance. In the near future, subsea compression and pumping is proposed for the Asgard [4] and Ormen Lange [1,2,4,9] fields. The Asgard field requires a power of 16 MW at 25 km step out, Ormen Lange field requires 50 MW at 120 km step out [8], and long tiebacks for artic fields are proposed after 2020.

These fields require subsea processing systems to be installed at deep waters with long tieback umbilical [9,26,61] from the ship/platform/shore facility. Subsea processes involve subsea motors, valves and other systems to be operated at varying power and voltage levels, and this requires establishing subsea power stations local to the well head, which receives power from the shore, using long step-out electro-optic umbilical cables [10] and carry out voltage step-down, safe distribution and power conversions in the order of tens of mega watts. Subsea breakdowns lead to huge production losses, and system retrieval for repair and maintenance is very costly and time consuming, and therefore, the subsea systems need to be highly reliable [3]. The recovery of the system to the top side sometimes costs more than the cost of the system itself [20].

Subsea booster production pumps and compressors need to be operated at variable speeds [8]. Variable speeds for electric motors are normally achieved by operating the motors at required frequencies, using variable speed drive systems (VSDS). A VSDS [12] is the linchpin of the booster station and involves multi MW power electronic converters, switchgears, transformers and motor. Applying the latest technological developments in power electronic control, circuit breaking techniques and insulation systems could help in attaining higher reliability.

---

[*] Tel.: +91 - 44 6678 3382.
E-mail address: veda1973@gmail.com (V. Narayanaswamy).

0141-1187/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2013.07.008

Subsea production processes are critical from the Health Safety and Environment (HSE) perspective [34] and require safe and reliable processes and emergency shutdown. Power supply for the valve control and actuator systems has to be highly reliable [39]. Moreover, a subsea system which is to be started after a prolonged stoppage, has to be energized only after getting the status of the subsea electrical condition. This requires safe electrical start-up methods. Methods for achieving these objectives with subsea based energy storage are detailed.

Due to high ambient hydrostatic pressure, power and control systems are enclosed in sealed enclosures [10] filled with inert gas. Power conversion processes produce thermal losses [9,20] and this leads to high ambient temperature inside closed enclosures, which is detrimental to the internal electronic systems. Deterioration of seals leads to water entry, resulting in increased humidity levels which may lead to condensation and associated damages. Methods for efficient thermal and humidity management are discussed.

Subsea systems are made modular [8,9] for ease of installation, intervention and retrieval. Electrical faults needs to be located precisely and quickly, so as to save cost and down time. Efficient fault localization techniques are discussed to enable to locate faulty modules for replacement.

The mass and weight of the subsea enclosures increase with depth [72,73], which poses challenges in the manufacturing, installation and operation phases. Pressure compensation techniques [77] offer enclosures whose thickness is independent of the water depth. But this exposes internal electronic systems to high ambient hydrostatic pressures. The need for development of reliable pressure tolerant electronics systems [72] and their potential advantages in the development of ultra-deep water systems are discussed.

Subsea power transmissions topologies [52,56,61] for long step out distances are decided based on capital investment, operating expenses and operational challenges such as reactive power control and fault management. Possible topologies, their reliabilities and involved costs are detailed.

Effective thermal management is done by evacuating the internally generated heat into the external sea water, using coiled heat exchangers exposed to sea water [8]. Various cooling strategies are discussed. Bio-fouling [79,80] on exchanger coils has an impact in the heat exchanger performance [81]. The factors accelerating bio-fouling and the control methods are explained.

2. Variable speed drive system

Based on the well head pressure and top side flow requirements, subsea production pumps and compressors need to be operated at variable speeds [8]. Variable speeds are achieved by operating the drive motors at required frequencies using a variable speed drive system (VSDS) [12]. A conventional VSDS string consists of a circuit breaker, transformer, water cooled frequency converter and the drive electric motor [8,9], adopted to subsea application inside pressure rated enclosures. Per Wikstrom et al. [12] have carried out reliability studies on a VSDS of similar capacity, whose failure-in-time (FIT) works out to 32,000 FIT with an mean time between failure (MTBF) of 3.6 Years. The probability of failure of the VSDS is thus 75.3% for a five year period, and the same can be seen from Fig. 1.

As deep water subsea compression stations demand a mean time between failure (MTBF) of more than 5 years [20], the probability of failures of the subsystems has to be reduced to as low as reasonably possible (ALARP), so as to attain a reasonably higher MTBF. The techniques followed currently in the industry to increase the MTBF are detailed below.

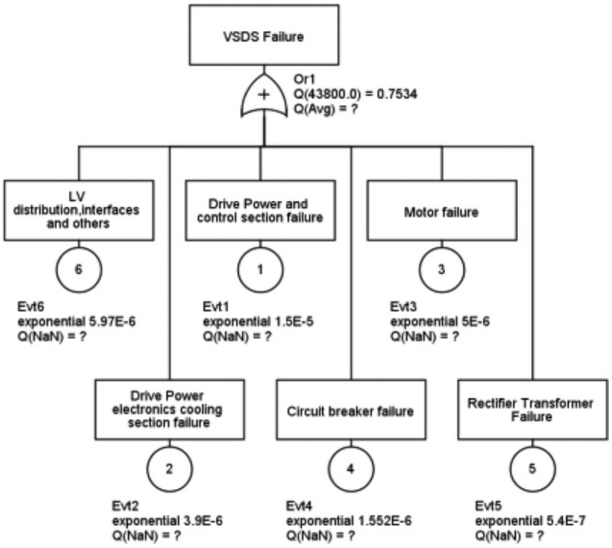

Fig. 1. Failure tree for calculating probability of failure for a VSDS [12].

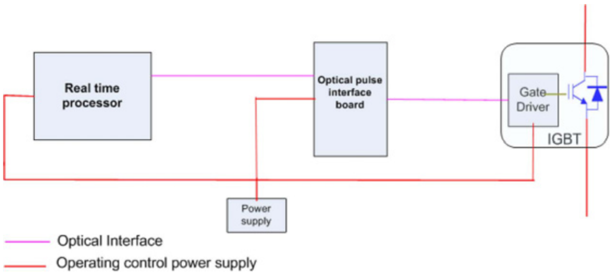

Fig. 2. Systems involved in IGBT switching operation.

2.1. *Drive power and control electronics*

Power electronic systems contribute 48% of the VSDS failure [12,17]. The failure rate of power and its associated control section contributes to 15,000 failure-in-time (FIT). The insulated gate bipolar transistors (IGBT) are the basic building block for the power electronic system. Rodriguez-Blanco et al. [14] have found that the failure rates of the IGBT hardware in a series connected configuration are mainly due to the loss of control command to the IGBT gate [15]. Fig. 2 describes the systems required for switching an IGBT [11,16]. The real time processor calculates the timing of the gate pulse and issues the switching signal to the optical pulse board, which in turn sends the gate switching pulse to the IGBT gate driver. Optical interfaces are used [13] for galvanically isolating the low voltage control electronics from a high power system.

IGBT are limited bymeans of voltage ratings. For handling increased voltage levels, IGBTs are grouped in series [11]. Fig. 2 indicates three IGBTs connected in series so that the applied voltage is shared.

Fig. 3 shows the string with three series connected IGBT sharing the applied voltage. Fig. 4 indicates the safe operating area (SOA) [19] for an IGBT, and this limits the power handled by a single IGBT module. In order to ensure that all the three series connected IGBT share the voltage equally, so that each IGBT is within the SOA, the simultaneous switching of all the three should be done. Failure of the gate command to one of the IGBTs in the string results in complete voltage being applied to the un-triggered IGBT and this forces the IGBT to fail [13] due to overvoltage. Bernet et al. [17] have experimentally determined that prolonged continuous switching delays of 10 μs to one of the series connected IGBT could damage the IGBT, and this could paralyze the complete VSDS power electronics. A solution to