OTC 15366

Subsea Electrical Power Generation for Localised Subsea Applications

Michael Stavropoulos, Barry Shepheard, Mark Dixon and Daniel Jackson, DeepSea Engineering & Management Ltd.

This paper was prepared for presentation at the 2003 Offshore Technology Conference held in Houston, Texas, U.S.A., 5–8 May 2003.

Abstract

This paper introduces and examines the prospect of subsea power generation at seabed level using marine current turbines to facilitate remote subsea tiebacks. Important parameters for the assessment of the feasibility of the technology are identified. The system can use proven (“off the shelf”) technology for energy storage, power conditioning and switching, while turbine blade design issues are discussed.

Results from a simulation code, built for the assessment of the technical feasibility of the system, are presented and discussed for representative base cases of two single-well production systems (all-electric and electrohydraulic).

Introduction

The substantial depletion of exploitable deposits in shallow waters of the continental shelf has increased the interest of the petroleum industry towards reserves at increasing water depths. As a result, enabling technology for the exploitation of deepwater reserves is developing exponentially. The emerging technology has made the prospect of hydrocarbon production from satellite reserves, which may lie considerable distances from production infrastructure, more attractive, subject to long distance tiebacks becoming more economical. As advances into production technology (e.g. subsea boosting, processing) make the exploitation of marginal fields technically feasible, the principal factors governing the use of subsea tiebacks become predominantly economic.

Localised power generation offers the possibility of reducing the costs associated with the production from subsea tiebacks by:

- Reducing the required umbilical functionality, with associated reduction in power transmission costs.
- Reducing or removing power generation systems at the surface platforms, with associated increase of their payload capacity.

Umbilicals, who together with flowlines, respresent the largest cost items in the post drilling phase of the production system installation, are used for the transmission of hydraulic and electrical power required for the production system operation, as well as control, data monitoring and chemical injection. From the above duties, the high-pressure power transmission lines (hydraulic power and chemical injection) are the most costly, followed by the electrical power lines, control and data monitoring. The removal of these operations will yield the corresponding cost savings to the system.

Indicative of the potential economic benefits offered by the removal of hydraulic lines is the current trend in the deepwater arena to develop all-electric (hydraulics-free) subsea production systems, which eliminate the need for hydraulics lines in the umbilical.

Furthermore, especially for large stepout distances (>30km), a large proportion (over 50%) of the power supplied from the topsides is lost in umbilical losses. Consequently, as stepout distance increases, the power generation requirements from the surface platform increase accordingly. Reduction or removal of the umbilical power transmission will reduce the power generation requirements from the surface platform, increasing its payload and lowering costs.

Localised power generation has been approached in a variety of ways in different projects. Previous proposed solutions have included:

1. Buoys with power generation facilities (using wind or wave energy) located in proximity to the production well to provide the necessary power via shorter umbilicals. This solution is applicable to benign environments but is limited by increased maintenance needs (and thus operational cost) of the buoy.
2. Subsea power generation from turbine operating in the water injection flowline. This solution is apparently limited to the cases where water injection is employed.
3. Subsea power generation using Stirling cycle engines which exploit the temperature differential between the production fluids and the surrounding seawater.
4. Subsea power generation using oscillating hydroplanes (Stingray project) powered by tidal currents. This solution is limited to shallow water (<100 m. depth).
5. Use of removable batteries located in the vicinity of the production system for the provision of the required power. This solution is limited by the intervention/battery replacement costs and battery life.

This paper introduces the prospect of generating power for a subsea production system at seabed level, using marine current turbines. To date, marine turbines have been used to harness tidal (surface) current energy for predominantly large-scale power generation (grid connection). As a result, they are installed in shallow waters (mono-piled to the seabed), operating in water depth typically less than 100 m, and are generally designed for diver maintenance.

The design goals for a subsea power generation system differ from the present grid connected marine current turbines power generation. To minimise operational costs, it is essential to design the system to operate reliably, maintenance-free and efficiently to the entire well production life. Furthermore, the power requirements from the system are significantly lower (in the order of 1MW for large-scale turbines as opposed to 1-10 KW for subsea power generation). Other design differences involve the high water depth of operation (1,000 – 2,000 m.), and different marine current regimes at seabed level (both in magnitude and direction). Due to the high water depth operation, installation and structural issues arise but the design of the system is such that current technology will suffice.

A more detailed description of the system and its design philosophy, as well as its operational characteristics, is presented in the next sections, followed by results from an in-house code for the simulation of the system behaviour for two base cases.

The idea of subsea power generation using marine current turbines was originally presented by DeepSea Engineering & Management at a Facilities Engineering Association (FEA) meeting (Novemeber 8th 2001). During the meeting intense interest was shown by operators, who also indicated the need for a feasibility study.

As a result, the present paper is part of a feasibility study sponsored the Department of Trade & Industry in the form of a SMART grant, due for completion in March 2003.

Subsea Power System

Figure A-1 in Appendix A illustrates a schematic of the proposed Subsea Power System. It is a classic design of a source - battery system, with two main components, the Power Generation Unit and an Energy Storage Unit, which are monitored and controlled by the System Control Unit.

The Power Generation Unit is the main power source of the system while the Energy Storage System serves mostly as supplementary power source to cover the power deficiency in siruations where the power generation does not meet the load power demands, and partly as main power source during system startup or shutdown.

In the following description it is assumed that the system is used as the only power source for an electrohydraulic subsea production system. The hydraulic system is assumed to be closed loop. It was decided to illustrate the system in this context because it includes all the possible scenarios of use. In addition to the system presentation a brief description of the Subsea Electronic Module, which is not part of the Subsea Power System, is included for clarity followed by a small section on the characteristics of the loads on the system during its operation.

Power Generation Unit

The Power Generation Unit (PGU) consists of a turbine (or bank of turbines), which extracts energy from the marine undercurrents, connected to an induction or synchronous generator, directly or via a gearbox respectively. A clutch/break mechanism is also incorporated at the mechanical link of the turbine to the generator, which allows the decoupling of the two components when required during the lifetime of the system (e.g. for maintenance work, excessive currents, production downtime).

The electrical power signal exiting from the generator is usually of low quality with high harmonic content. To rectify this problem, the signal passes through the Electrical Power Unit (EPU), which also incorporates an AC-DC converter (rectifier). The EPU has two outputs: one DC busbar and one AC line. The Energy Storage Units are tapped to the DC busbar while the AC output is connected to the Subsea Electronics Module (SEM), which is described later in this section.

Energy Storage Unit

The Energy Storage Units (ESU) comprises of 4 batteries; one main battery, one backup battery (dual redundancy) and two batteries devoted exclusively to powering the DC motors (HP line and LP line) of the Hydraulic Power Unit (HPU).

Each battery unit is equipped with DC-DC converters and charging circuits, as well as battery protection systems and charging/discharging control and is tapped to the DC busbar of the EPU for charging (when the system is on power excess mode).

The output of the main and backup battery is connected to the two SEM busbars (see SEM section) while the output of each HPU-devoted battery is a separate DC busbar which has tapings for the DC motors (and corresponding controllers), which drive the HP and LP pumps respectively. It should be noted here that the operation of the hydraulic motors is intermittent. Their duty is to charge the accumulators once the pressure falls below a specified level. The hydraulic power is delivered from the accumulators via two hydraulic lines (HP and LP) for the operation of the hydraulic valves in the production system.

System Control Unit

The System Control Unit (SCU) strategy is built with three main points in mind:

1. Power consuming equipment must not be deprived of power in the event of power source failures or when the total power demands exceeds the available supply.
2. Faults on the distribution system should have the minimum effect on system functioning
3. Power consuming equipment failure should not endanger the supply of power to other equipment.

System Operation

The system operation can be described by three modes. Normal operarion is characterized by the two following modes based on the instantaneous balance of power demands from the loads and supply from the PGU:

- ***Power Generation Excess (Battery Charge Mode):*** In this mode the control unit will connect the EPU output to the Subsea Electronics Module and operate the batteries into charging mode (if not fully charged).

- ***Insufficient Power Generation (Battery Discharge Mode):*** In this case the batteries are used to supplement the power needed for the operation of the production system. A special case of this mode is when there is a Subsea Power System failure, but the production is not shut down. The batteries should be rated such that autonomy in these cases is ensured for a specified period.

The other two modes of operation that the system may work on correspond to two special cases which involve:

- ***System Start-up:*** All the necessary power for the start-up of the system (and even for turbine start-up) is drawn from the batteries
- ***System Shutdown:*** The hydraulic circuit of the system is shut down, and the main battery provides enough power to shut the production system down safely.

The System Control Unit is also equipped with emergency systems, which should be able to disengage a faulty component safely and use its reserve (if dual redundant), ensure uninterrupted operation (if the problem can be overcome), or shutdown safely if the problem is fatal.

The System Control Unit will “report” to the production system Master Control Station (MCS), which is located at the topsides via the Communications box, and allows override for topsides or ROV intervention.

Subsea Electronics Module

The Subsea Electronics Module (SEM) is part of the Subsea Production System rather than the Subsea Power System, but details of its operation are essential. The main and backup batteries of the Subsea Power System are connected to the outputs of the SEM to ensure operation in case of insufficient power generation.

The SEM, as mentioned above, is fed with AC power directly from the EPU. It incorporates two AC-DC converters and outputs to two DC busbars (typically 24V and 5V). The solenoids used for the actuation of the electro-hydraulic valves are tapped into the 24V busbar, as is the Communications box of the system, while the sensors are tapped into the 5V busbar.

Subsea Power System Loads

The loads during the operation of the system can be categorized into two main groups; continuous and momentary loads.

The continuous loads are associated with power consumption which remains constant during the lifetime of the system regardless of the operation taking place at any one time. Such consumers would include for example the communications box, the monitoring sensors and the SCU. For the definition of continuous loads, the power requirement suffices.

Momentary loads are considered the loads which depend on the operational state of the system. A typical example would be a load due to valve actuation, or the HPU system activation. For the duration of each operation the power requirement from the system increases to accommodate the operation. For the definition of the momentary loads, apart from the corresponding power requirement, it is essential to identify the duration and frequency of operations as well as a statistical description of operation occurrences in a specified time period.

It should be noted that at no point during its lifetime the does the subsea power system run idle (without load), except for the case of temporary production shutdown when the system works to charge the ESU solely.

Tables 1 and 2 present typical values of momentary and continuous loads during the operation of electro-hydraulic and all-electric production systems respectively. The data is presented in terms of electrical loads, as the design of the hydraulic system falls beyond the scope of the present study. The table was compiled using information acquired from operators during the course of the present feasibility study.

Operation	Type	Power requirement	Freq. (/day)	duration
HPU	Momentary	11 kW / pump	2	2 min
Single valve actuation	Momentary	10 W	1-3	2 sec.
Choke valve actuation	Momentary or continuous	10 W (mom)	n/a	2 sec (mom)
SEM	Continuous	Max of 80 W	-	-
Sensors	Continuous	Max of 50 W	-	-

Table 1. Loads for electro-hydraulic tree operation

Operation	Type	Power requirement	Freq. (/day)	duration
single valve actuation	Momentary	3-5 kW	1-3	45-60 sec.
single valve normal operation	Continuous	20-50 W	-	-
choke valve actuation	Momentary or continuous	1-2 kW (mom) 60 W (cont)	n/a	45-60 sec (mom)
SEM	Continuous	Max of 80 W	-	-
Sensors	Continuous	Max of 50 W	-	-

Table 2. Loads for all-electric tree operation

It should be noted that the use of the choke valve can be either continuous or intermittent, depending on the field requirements and the topology of the production system.

In an electro-hydraulic tree the “normal” operation of a valve (kept in open position) is the responsibility of the hydraulic system which has to sustain the required pressure on either side of the valve to keep it open. Consequently, it does not impose any additional power requirement directly on the electrical system. On the other hand, during actuation (which normally lasts approximately one minute), a 10W two-second pulse is used to trigger the actuator to produce the desired pressure differential. After that pulse, the required power is provided as a whole by the hydraulic system. Data on the frequency of operation of the HPU is not definite, largely due to the fact that it depends on accumulator size and ratings, which is case- and hydraulic-system design dependent.

In an all-electric tree all of the above are the responsibility of the electrical power system, hence the significantly increased power demands from the system for actuation/operation of the valves. It should be remembered though, that there is no power consumption for generation of hydraulic power in this instance.

Technical Feasibility

Table 3 presents the potential of using existing technology for the purposes of the Subsea Power System. The table has been compiled after discussions with suppliers of the corresponding components who ensured the transferability of their technology for seabed operation in all cases, with the exception of turbines, the suppliers of which were confident that the technology was transferrable, subject to further development.

Since current turbines are used as the main power source of the system, in order to size the main power components (batteries and turbines) it is essential to acquire metocean data from the production well location. This should include a statistical representation of the marine current velocity direction and magnitude, which will provide essential information for the turbine blade design.

Blade design is a very crucial part of the overall system design as it can significantly increase the efficiency of the turbine, Power Generation Unit and the overall system.

A description of the turbine selection process follows in the next section.

Component/Technology	Function	Seabed Operation
EPU	Power Conditioning	Yes
Rectifiers	AC to DC conversion	Yes
Inverters	DC to AC conversion	Yes
HPU	Hydraulic Power Generation	Yes
Generators	Electro-mechanical Conversion	Yes
Batteries / Charging and Discharging Systems	Energy Storage	Yes
Turbines	Power extraction from marine currents	Further Development required
System Installation		Mature technology

Table 3. Existing technology and potential for transfer to seabed level

Marine Current Turbines

Marine current turbine power generation is based on the extraction of energy "carried" by seawater masses during their movement (currents). The power that can be extracted by N turbines from a seawater current which flows with speed V through an area A is given by

$$P = N C_p \frac{1}{2} \rho A \ V_0^3 \qquad (1)$$

where P is the marine current turbine power ρ the seawater density and C_P the hydrodynamic efficiency of the turbine. For a turbine with blade radius R the area is given by $A=\pi R^2$.

The hydrodynamic efficiency of the turbine respresents the fact that not all marine current energy can be extracted for power generation. During turbine operation the seawater is not contained or brought to a standstill, thus water "escapes" the turbine with residual power. It has been theoretically proven that a maximum of 59% of the total current power can be extracted by a turbine ($C_{p,max} = 0.59$). The value of the theoretical maximum was made neglecting the effect of swirl losses at the turbine tips, which is valid for turbines of high tip speed ratio ($\lambda > 3$) as a marine current turbine is expected to be.

Tip speed ratio is defined as:

$$\lambda = \frac{V_{tip}}{V_{current}} = \frac{\omega R}{V_0} \qquad (2)$$

where R is the turbine blade radius, ω the turbine rotational speed and V_0 the current speed.

For turbines with low tip speed ratio ($\lambda \approx 1$) the maximum power coefficient is approximately 42%.

The tip speed ratio, λ, is a very important design parameter for the selection of the operation characteristics. The variation of the efficiency C_p of the turbine with λ determines the operating current velocity range of the turbine, as well as its self-starting capability. It is self explanatory that the targeted operational velocity range is as wide as posible. For self-starting capability, the turbine will have to exhibit efficiency levels at low rotational speeds, which are high enough to ensure that mechanical friction and inertial forces will be overcome. To this end, minimization of friction is also targetted. The requirement for low weight for startup purposes is contradicted by a requirement for large inertia during operation. Hence, the weight selection comes as a result of a compromise of the two contradicting requirements.

Turbines can be divided into two types, depending on which component of the hydrodynamic force they use:

- Hydrodynamic drag devices
- Hydrodynamic lift devices

Due to the very low maximum power coefficient ($C_{p,max} \approx 16\%$) of drag devices, turbine power generation is based on lift devices, since performance is one of the main design targets. A different way to categorize turbines is according to the orientation of the spin axis. In terms of this, turbines are of two types:

- Vertical Axis Turbines (VAT) – drag and lift devices
- Horizontal Axis Turbines (HAT) – lift devices

HATs exhibit higher efficiency than VATs, but power extraction depends on current direction as opposed to various curent direction independent designs of VATs.

For the purposes of this project a Vertical Axis Turbine will be used because power generation is independent of the current velocity direction, and because a yaw mechanism in the turbine module would add to the complexity and reduce the reliability of the system. In addition to this, the VATs have the advantage that the generating machinery (gearbox and generator) can be installed at ground level as opposed to housing it into a nacelle at the top of a tower, which adds structural concerns, as in HATs.

Since the available power generation levels are directly related to the marine current velocity, it is essential to describe statistically the marine current velocity distributions. It is likely that the metocean sample collection has to span a long period of time (maybe in the order of 1 year or more) in order to be capable of describing seasonal variations of current characteristics statistically. The description of the current characteristics will yield the energy content of the currents on a given site and their energy distribution. The energy content determines whether it is worthwhile installing a turbine on the site and the energy distribution provides us with information about the prevalent current speeds to help with the turbine design.

The selection and design of a turbine power generation unit and its operational characteristics which includes size, control, generation machinery selection, rotational speed characteristics (variable or constant) and design point selection is a well-established process mostly due to the advances in wind turbine generators technology.

In the next section, a simplified selection process based on average power requirements only is presented.

Design Methodology - Simulation Code runs

In this section three typical case studies are examined using an in-house built code simulation, which simulates a subsea power system as described in the previous sections. The code performs power calculations on the system, based on which size selection is made. The cases examined are illustrated in Table 4.

Case No.	Production System	Hydraulic power production included
1	Electro-hydraulic	No
2	Electro-hydraulic	Yes
3	All-electric	Yes

Table 4. Simulation code cases

Cases 2 and 3 correspond to a subsea power system which provides complete autonomy on the production system, while Case 1 corresponds to a system which powers a subsea tree which receives hydraulic power via an umbilical.

The subsea tree is assumed to have an "average" configuration of 1 Choke Valve and 6 tree Gate Valves and 1 DownHole Safety Valve controlled by one SEM. The definition of an "everage" tree is certainly generic as tree configuration varies from well to well, but a generic tree description was considered more useful for the purposes of this paper.

The loads on the system for individual operation of the electrohydraulic and all-electric trees are presented in Tables 5 and 6 respectively. The occurrences of momentary operations are random.

The marine current was considered sinusoidal with an average of 0.5 m/sec, period of 2 days and amplitude of 0.3m/sec. It should be noted here that the program has the capability of using probability distributions (e.g. Weibull distribution which is a common distribution to describe wind distribution for wind turbine applications) for the description of the current velocity. It should also be noted that if the average veolity is $\overline{V}$, then the average power $\overline{P}$ is given by:

$$\overline{P} = N \, \frac{1}{2} C_p \, \rho \overline{V^3} A \tag{3}$$

The velocity and power (based on a 1m diameter turbine) distribution for two periods is presented in Figure 1.

Operation	Type	Power requirement	Freq. (/day)	duration
HPU (case2)	Momentary	11 kW / pump	2	2 min
Single valve actuation	Momentary	10 W	3	2 sec.
Choke valve actuation	continuous	-	-	-
SEM	Continuous	Max of 80 W	-	-
Sensors	Continuous	Max of 50 W	-	-

Table 5. Loads for electrohydraulic tree operation (Cases 1-2)

Operation	Type	Power requirement	Freq. (/day)	duration
single valve actuation	Momentary	5 kW	3	60 sec.
single valve normal operation	Continuous	50 W	-	-
choke valve actuation	continuous	60 W	-	-
SEM	Continuous	Max of 80 W	-	-
Sensors	Continuous	Max of 50 W	-	-

Table 6. Loads for all-electric tree operation (Case 3)

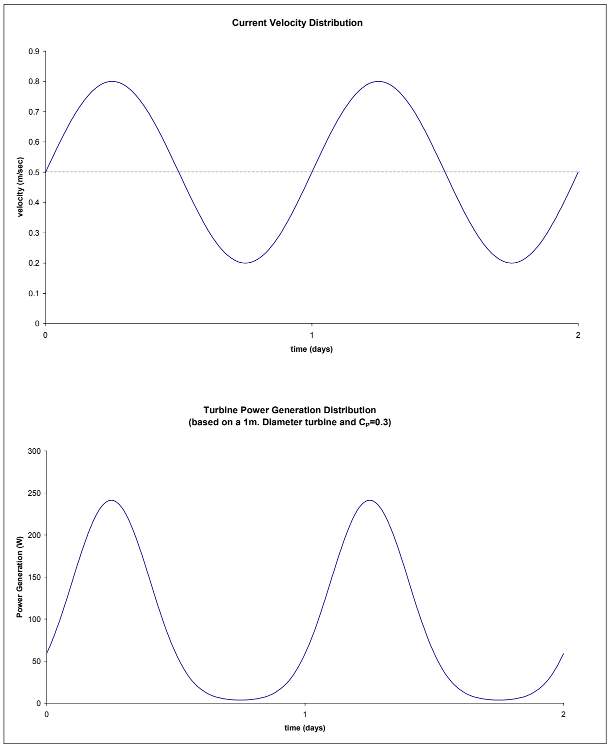

Figure 1. Velocity and Power Generation Distribution

The average power demands for each case are presented in Table 7.

Case Study	Average Load (W)
1	130.1
2	160.6
3	500.41

Table 7. Average Loads for the run cases

Since the code performs a power calculation for the system all the components are represented in the calculation by an efficiency factor. The efficiencies used for the runs are presented in Table 8.

Component	Efficiency (%)
EPU	70
Rectifiers	90
Inverters	90
Batteries Charging and Discharging Systems	70
Turbine	30
Gearbox	90
Generator	85

Table 8. Component Efficiencies

As a first aapproach, the number of turbines and their size is chosen such that they provide 120% (arbitrarily) of the mean power demand taking into account the efficiency of the Power Generation Unit. This approach can be revisited, if the power demands from the battery are not acceptable.

From equation 3 and taking the area A=πR^2:

$$R = \sqrt{\frac{2\,\overline{P}\,(x\;1.2)}{\overline{V^3}\,\pi\,N\,\rho\,(n_{EPU}\,C_P\,n_{generator}\,n_{gearbox})}} \tag{4}$$

The resulting radius of the turbine (for various N) for each case is given in Table 9.

Case Study	Turbine Radius (N=1)	Turbine Radius (N=2)	Turbine Radius (N=3)
1	3.26 m.	2.31 m.	1.89 m.
2	3.63 m.	2.56 m.	2.09 m.
3	6.4 m.	4.52 m.	3.7 m.

Table 9. Average Loads for the run cases

For the runs presented in this study N=1 was chosen. However, it is obvious that it is possible to produce the same amount of power using diffent number of turbines. The manufacturing and installation costs are going to play the most important role in this decision.

The calculation runtimes are set to 10 days. The code has a capabiity of simulating turbine or production system shutdown, but it is not presented in this paper.

The results of the runs (Figures 2,3 and 4) yield the overall power requirement from the ESU during production. These results are used for the selection and sizing of the batteries within the ESU. The results can also provide information on available charging time and power, as well as discharge times and maximum energy depletion during operation. The selection process of the battery is not presented in this paper.

For the presented cases, the batteries were simply rated such that they provide enough energy for all operations for two days. As mentioned previously in this paper, excess energy availability for shutdown and startup should be taken into account, should be taken into account, but for simplicity, this has not been included. The battery ratings are presented in Table 10.

Case Study	Battery rating at 24V
1	260 Ah
2	320 Ah
3	1000 Ah

Table 10. Battery ratings for each case

After battery selection, the system operation is simulated for the specified runtime (10 days) and the results are presented in terms of battery state of charge. As expected from the selected marine current energy distribution, at the end of each day (1440 mins), the power generation is not sufficient for the operation of the production, and the ESU operazates as an auxilliary power source at all cases.

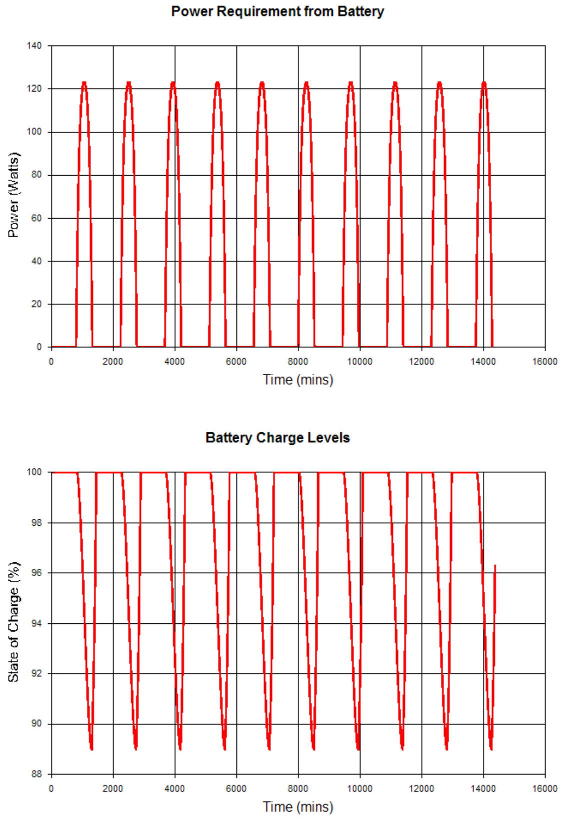

Figure 2. Case 1 Results – Power Requirements ("Battery Design" Mode) and Batery Charge Level)

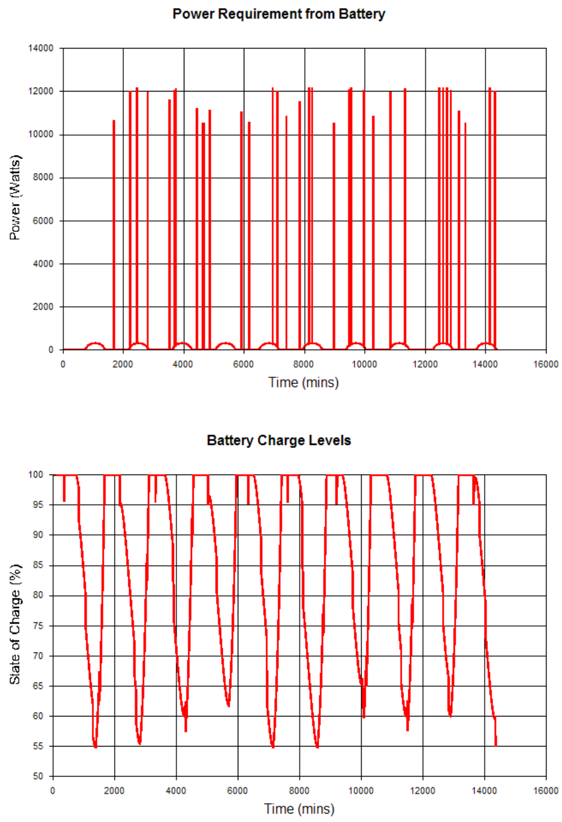

Figure 3. Case 2 Results – Power Requirements (“Battery Design” Mode) and Batery Charge Level)

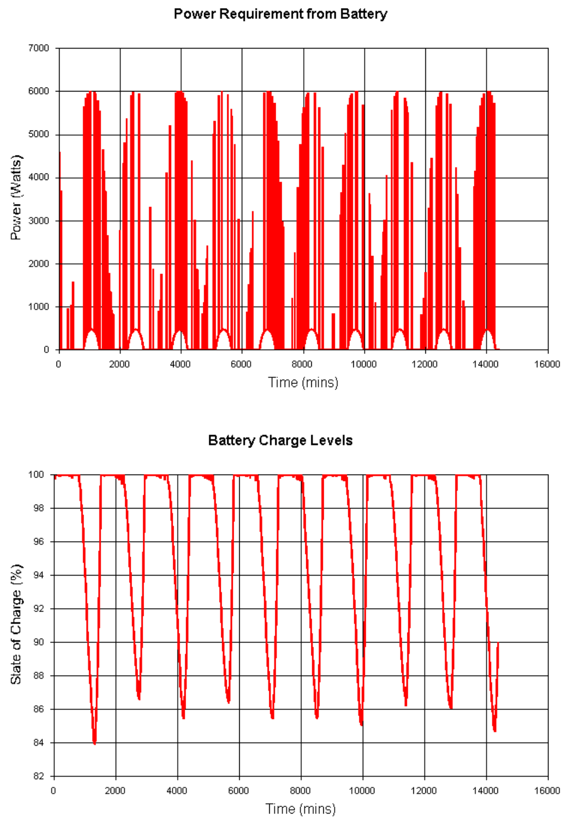

Figure 4. Case 3 Results – Power Requirements (“Battery Design” Mode) and Batery Charge Level)

From the results it is observed that in all-electric trees the operation of the production system is very apparent on the power requirement graphs of the ESU. In these cases the main power source for the actuations is the ESU, because the power consumption for each actuation is a multiple of the power generation levels. Energy sufficiency is ensured due to the much smaller duration of actuation comparatively to power generation (which is continuous). The same observation can be made in case of electrohydraulic with hydraulic power production. On the other hand, in the electrohydraulic system without hydraulic power production the power requirement for operation is small in comparison to the power generation levels. As a result, changes in power requirements form the battery correspond to power generation deficiency, rather than increased valve activity.

Commercialisation

As mentioned before, the subsea power generation system has considerable potential economic advanatages to offer which stem from the possibility to:

- Reduce the required umbilical functionality
- Increase the topsides payload capacity

In addition to that, the operational cost is practically zero and development costs are limited to turbine development, as all other components can be used “off the shelf”.

Judging from the power generation requirements of the base cases examined in the present paper, it is expected that turbine size isn not going to beprohibitive. This of course depends on the marine currents regime at the vicinity of the profuction system, but turbine size can be balanced with the utilization of a bank of smaller turbines for power generation purposes.

The economic potential assessment and calculation of important parameters (e.g. break-even tieback distances) has not been completed to date.

Conclusions

In this paper the prospect of subsea power generation at seabed level using marine current turbines to facilitate remote subsea tiebacks is introduced and examined. It was found that existing technology suffices for the all aspects of this system, with the exception of turbines, for who existing technology may require further (but achievable) development for operation at seabed level.

An assessment of the marine current regimes at the vicinity of the system, which will ensure efficient turbine design, and system sizing.

Results from a simulation code, built for the assessment of the technical feasibility of the system, as well as the understanding of the interaction of the system components, were presented and discussed for representative base cases of two single-well production systems (all-electric and electrohydraulic).

The system provides significant potential ecomomic advantages, with limited development requirements. As decision making in subsea tieback use becomes increasingly based on economic parameters, the system offers a very attractive solution.

References

1. "Review of Electrromechnaical Conversion in Wind Turbines", M. Dubois - Report EPP00.R03, April 2000, TU Delft
2. "Analysis of a Battery Charging Sysem Powered by a Fuel Cell" Dr-Ing Uwe Knorr, Ansoft Corporation, Pittsburgh PA
3. "Generating Electrical Power Offshore" Neil Kitney, University College London, Oct. 2000
4. "A Discrete-Time Battery Model for High-Level Power Estimation" – L.Benini et al., Univ. di Bologna
5. "Super Capacitors for Peak-Power Demand in Fuel-Cell-Driven Cars" R. Kotz et al. Paul Scheller Institute, Switzerland
6. "An all-electric Subsea Control System", S. Sangnesland et al., Norwedian Institute od Technology
7. "Wind Energy Technology and Current Status: A Review", T. Ackermann and L.Soder, Renewable and Sustainable Energy Reviews, 4 (2000) pp.315-374
8. Long Distance Tiebacks Conference Proceedings, Amsterdam 26-27 November 2001
9. "Generator Topologies for Direct-Drive Wind Turbines" M.R. Dubois et al. TU Delft

Appendix A

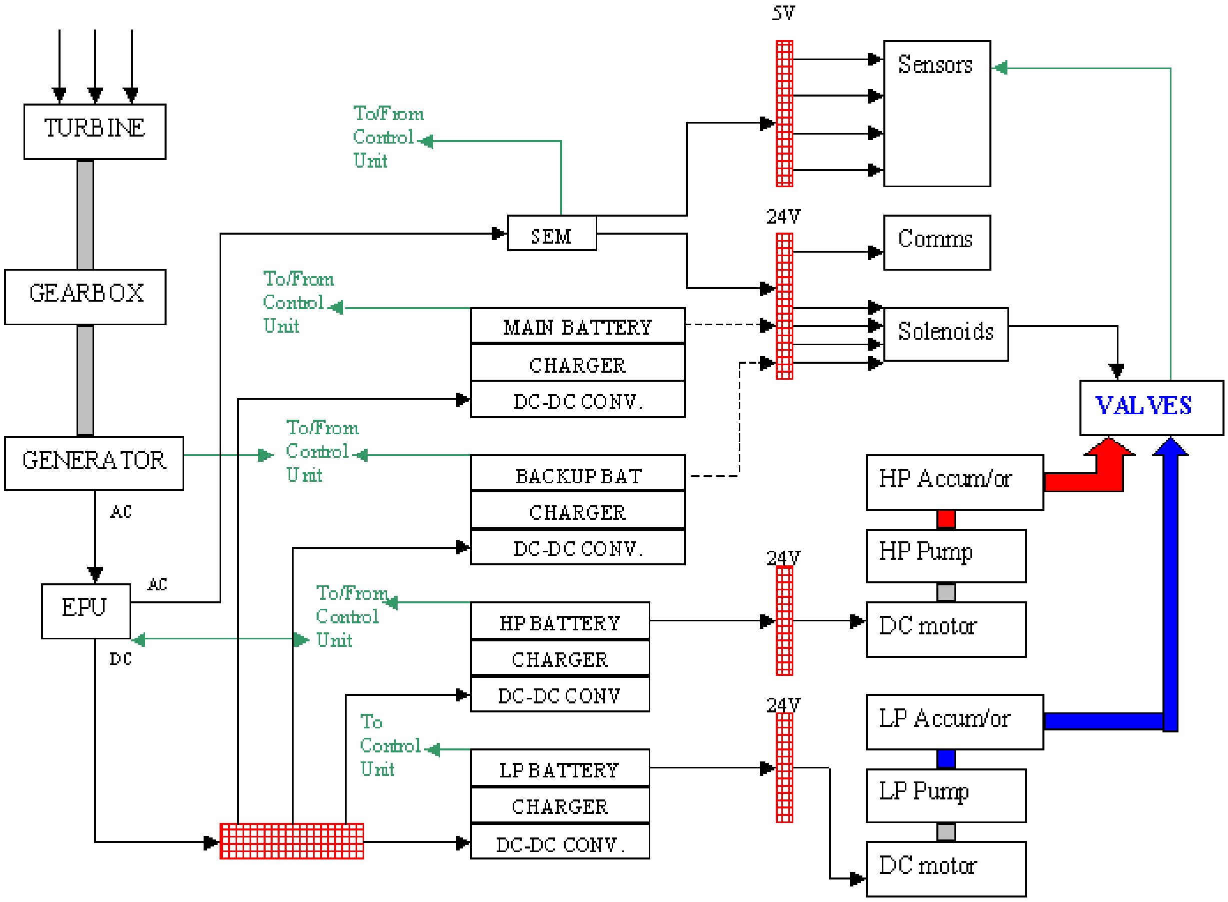

Figure A-1. Subsea Power System Illustration