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Improving the Design Approach to Developing Through-Metal Communications for Use in Subsea Pipeline Robots

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***Abstract*—Vital inspection and repair operations on subsea pipelines usually involve pipe-bore robots, which must be controlled and monitored from outside the pipe. In many situations cables cannot be connected to the in-pipe robot and duplex wireless communication through pipe-wall is the only solution. Wireless power transmission (WPT) through pipe-wall has been considered to facilitate the required duplex communication. In WPT through subsea pipe-walls the conductive media (i.e.: stainless steel and seawater.) will significantly reduce the power transfer efficiency (PTE) of the system. This paper proposes a coil geometry optimisation methodology to boost PTE of these wireless communication systems. The proposed technique, in addition to increasing the PTE improves the overall system's signal to noise ratio by reducing the coil antenna's internal resistance.**

***Index Terms*—Resonant magnetic induction, power transfer efficiency, inductive power transfer, power transfer through-metal .**

Fig. 1. A pipeline inspection gauge (PIG) is being inserted into a pipe.

I. Introduction

The ubiquitous use of subsea pipelines in the transport of oil and gas products over long distances is inevitable as they are more reliable, energy-efficient and cost-effective compared with other methods such as maritime transportation [1]. To transport oil and gas products, subsea pipelines are spread over thousands of miles, located beneath or over the seabed, crossing mudbaths, shallows or deep oceans while carrying highly inflammable and explosive materials. The extreme conditions of surrounding medium expose oil and gas pipelines to many different hazards. The environmental effects such as temperature, humidity and erosion can rust external pipe-wall away. Maritime activities around the pipeline and accidental strike by a ship's anchor may cause deformation or dent in pipe. In addition to the external defects, there are many internal challenges associated with maintaining an integrated and safe product stream inside subsea pipelines. For instance, streaming product chemistry can lead to corrosion of the pipe's internal surface. Accumulation of sedimentary deposits, left from product impurity, and rust deposits, caused by pipeline corrosion, can also internally obstruct the pipeline [1]. Both external and internal defects can result in pipe-wall damage, rupture and product leakage which eventually lead to oil spillage and environmental pollution. In addition to endangering the sea-life, oil spillages, such as Deepwater Horizon catastrophe in 2010 in the Gulf of Mexico [2], may cause human casualties and impose financial losses. To forestall such disasters, international safety case regulations require the oil and gas providers to routinely monitor, identify and control all potential internal/external pipeline hazards beforehand [3]. A low cost, periodic pipeline evaluation inspirits development of non-destructive testing (NDT) [4].

In the oil and gas industry, and drinking water/sewer transportation system minimal structural, non-destructive evaluation (NDE) of pipes is widely undertaken using Pipeline Inspection Gauges (PIGs) [1]. In essence, a PIG, as shown in Fig. 1, is an electromechanical pipe-bore robot, inserted into a pipe, which supports structural health monitoring and maintenance of pipelines concurrent with fluid stream inside the line. The pipe inspection robot moves through the pipeline either pushed by the fluid or self-propelled. Early PIGs were mostly used for removing pipe blockages and cleaning purposes. However, with technological advancements PIG performance can be classified as three main categories: utility, plugging and in-line inspection (ILI) PIGs [3]. Utility PIGs are suitable for pipeline cleaning and dewatering purposes. Plugging PIGs are used, during maintenance or pipe replacement process, to isolate the affected section of line from the product stream. The ILI PIGs, also called smart PIGs, are commonly utilised for non-destructive internal/external fault detection and localisation purposes. Based on the required NDE technique, the smart PIG will be equipped with different accessory units (e.g.: sensors, detectors, etc.) which can assist a precise structural health inspection. Some of the NDE units mounted on the inspection robots can be mentioned as magnetic flux leakage (MFL) detector [5], electromagnetic acoustic transducer (EMAT) [4], X-ray detector [4], Eddy current sensor [4], [5], ultrasonic transducer [4], [5], optical sensor array [6], and acoustic transducer [4]. Employing laser scanner or stereo camera for visual monitoring of the internal surface of pipeline can also boost damage inspection capabilities of the smart PIGs [7]. The suitability of the chosen NDE method should be determined with considering different factors such as the material and thickness of the pipe-wall under inspection [5], and the effect of method on the pipeline's surrounding environment [4].

Even though utilising PIGs is the most successful method of non-destructive pipe maintenance and structural health monitoring in the oil and gas industry, there are many challenges associated with inspecting/repairing pipelines using these robots. The pipe-bore robots are likely to stall inside the pipeline at any point during the PIG running such as PIG launcher and pipe's bends. Retrieving these robots can also be very dangerous; if the pipeline operator opens the PIG receiver before the robot has been fully reached there, it will be shoot out of the trapper with high speed. Such challenges potentially can damage the robot itself or result in human injuries; hence, PIGs must be tracked/localised while inside the pipeline [1]. One of the other challenges during PIG running is the inspection's lengthy data-processing time, which can significantly affect detecting defects in their early stages. During an inspection run, the ILI PIG monitors and records the pipe condition (i.e.: extent and location of the defects.). However, the acquired data can be analysed only after retrieving the PIG from the pipeline. This process, depending on the length of the inspected line, might take some weeks. Enabling faster defect detection requires instantaneous transmission of the obtained data to the processing unit located outside the pipeline. Furthermore, a reliable pipeline isolation using plugging pipe-bore robots requires real-time transmission of duplex (i.e.: two-way.) control signals to the PIG for sealing/unsealing operations inside the pipe [3]. Therefore, live duplex signal communication between outside and inside the pipe is vital to enable both PIG control and task management. The PIG's conventional active data streaming relies on wired signal communication [9]. The tethered cables connecting the operator (i.e.: controller/processor unit outside the pipeline.) to in-pipe robot reduce the PIG's operation distance. In addition, tethered cables restrict the PIG mobility as they can easily tangle during the robot movement and lead to PIG stall inside the pipe [1], [8], [9]. Therefore, an effective PIG running demands duplex wireless signal communication with the in-pipe robots.

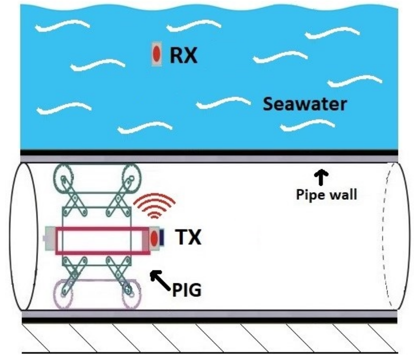

Fig. 2. An ELF signal detector, where the receiver (Rx) antenna precisely detects the transmitter's location.

Much work has been devoted to wireless data streaming between inside and outside the pipeline [1], [8], [9]. Extremely low frequency (ELF) magnetic field has been proposed as a wireless signal transfer technique to detect the PIG's location in [1] and [8]. The ELF detector system consists of a signal transmitter (Tx) mounted on the in-pipe robot and a receiver (Rx) outside the pipe, as shown in Fig. 2. In the proposed technique the receiver can only detect the PIG's location and the system lacks duplex signal communication between inside and outside the pipe. The authors in [9] have used the pipe interior space as the wireless propagation medium to transmit the signal back and forth between the operator and the in-pipe robot, as shown in Fig. 3. The signal transfer efficiency of this method highly depends on the pipeline's internal diameter and length. This is because the signal carrier is confined inside the pipe space, which results in signal reflection by the pipe's inner surface. As the propagation distance increases, the level of reflected signal raises, leading to higher signal attenuation levels. Hence, through pipe-space communication can only provide efficient wireless signal communication for short inspection distances. For example, the distance between the operator outside the pipe and the pipe-bore robot in the stainless steel pipe (i.e.: the material of most of oil and gas pipelines.) with a diameter between 0.2 m and 0.4 m can be maximum 100 m [9]. Such limited operation distance restricts

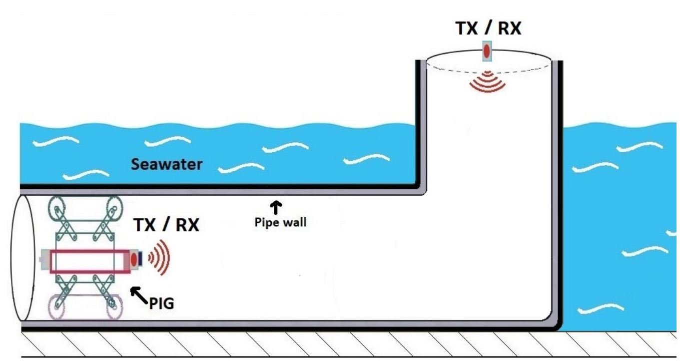

Fig. 3. Utilising the pipeline's interior space for duplex signal communication with a pipe-bore robot.

this duplex communication method and makes it ineffective for all sizes of pipeline including medium length or long pipes. To respond the duplex signal transfer requirement, through pipe-wall communication with PIGs will be investigated, for the first time, in this paper.

II. Through Pipe-wall Communication with PIGs

Through pipe-wall communication, as shown in Fig. 4, is impacted by three factors: the pipe-wall's ferromagnetic material (i.e.: mostly stainless steel.), thick coating inside and outside the pipeline (e.g.: epoxy and concrete.) and the medium surrounding the line (e.g.: seawater and clay.). In wireless communication through subsea pipe-wall the signal passes through three different transmission media with high electric conductivity (σ). This leads to a significant reduction of the signal's penetration depth (i.e.: skin depth.) in the overall medium. The skin depth (δ) is the thickness which the radio frequency signal can travel inside a medium until its amplitude reaches e^{-1} (i.e.: $\sim$37%.) of its original value [10]. The skin depth, based on [10], can be calculated as:

$$\delta = \frac{1}{\sqrt{\pi f_{\circ} \mu \sigma}} \tag{1}$$

where $f_{\circ}$ is the signal's frequency and μ is the medium's magnetic permeability. The most effective method to increase the signal penetration depth for real-time wireless communication through subsea pipe-walls is by use of magnetic coupling between transmitter (Tx) and receiver (Rx) at frequencies between 3 to 3000 Hz. This frequency range is known as extreme low frequency (ELF) band [11]. However, there are some limitations in using ELF signals. Firstly, ELF communication systems require physically large Tx/Rx antennas, due to the long wavelength involved. Secondly, large physical antennas have high internal resistance, which raises the amount of power required to drive the antennas. Thirdly, ELF systems have a small signal to noise ratio (SNR) leading to slow and erroneous signal communication. In a communication system SNR is the ratio of the received power to total noise power at the system's receiver [12]. A method to alleviate these limitations, to the best of the authors' knowledge, has not been covered to any significant detail in the literature.

In this paper, improving the power transfer efficiency (PTE) between a magnetically coupled Tx and Rx antenna pair is proposed to raise the power level of the received signal and improve the system SNR. Increasing the system's PTE requires utilisation of a wireless power transfer (WPT) method, which is suitable for penetrating through subsea pipe-wall. Wireless power transfer (WPT) can be classified as capacitive and inductive coupling systems.

Capacitive power transfer (CPT) employs electric field coupling between two pairs of capacitive, metallic plates. The PTE in CPT systems is constrained by the specific physical requirement for large coupling area to align the capacitive pair [13]. Hence it is not feasible to use the CPT for through pipe-wall wireless power transfer. Inductive WPT is based on magnetic coupling between a Tx and Rx coil pair. Due to the high leakage reactance in the signal transmission medium (i.e.: subsea pipeline.), the inductive power transfer (IPT) can not provide high level of PTE [13]. However, adding resonators (i.e.: compensation capacitors.) to the inductively coupled windings can effectively cancel out the leakage reactance of the system at the resonance frequency ($f_{\circ}$) and provide a reactance-free power transfer link [14]–[19]. Here, resonant inductive coupling is considered as the most suitable WPT technique for PIG communication through subsea pipe-wall.

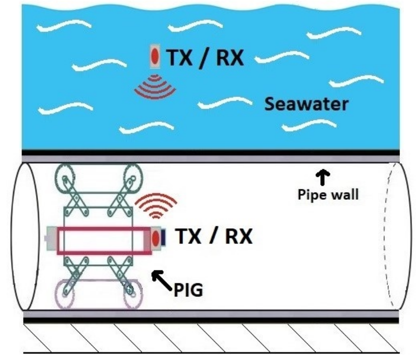

Fig. 4. Duplex communication with a PIG through subsea pipe-wall.

The operational principal of resonant inductive coupling necessitates that the Tx and Rx coils operate at the same resonant frequency; which requires a careful design approach to achieve. To ensure signal penetration through subsea pipes, the system's resonance frequency must be calculated from (1). For example, in a typical subsea, oil and gas, pipe with 100 mm distance between Tx and Rx coil pair, $f_{\circ}$ will be calculated as 15 Hz. The considered dominant pipe material and surrounding media are stainless steel 301 and seawater. Although operating the resonant system at such low frequency (i.e.: ELF band.) assures signal penetration through the subsea pipe-wall, achieving high power transfer efficiency remains challenging [11].

III. Maximising PTE for IPT through Subsea Pipe-wall

Over the last few decades, different methods have been proposed to maximise PTE in resonant inductive links [15]. Much work has been devoted to geometric optimisation of Tx/Rx coil pair as a method to improve the PTE in IPT systems with spatial limitations [14]–[19], such as subsea pipes. In all these techniques free-space is considered as the communication medium between the Tx/Rx coil pair. However, in communication through subsea pipe-walls the conductive media (i.e.: stainless steel and seawater.) will significantly reduce the PTE of the designed geometry. Building upon the coil optimisation technique in [15]–[17], this paper proposes a design methodology to boost PTE for wireless communication through subsea pipe-walls at ELF resonance frequency. The proposed technique, in addition to increasing the overall system's SNR by reducing the antenna's internal

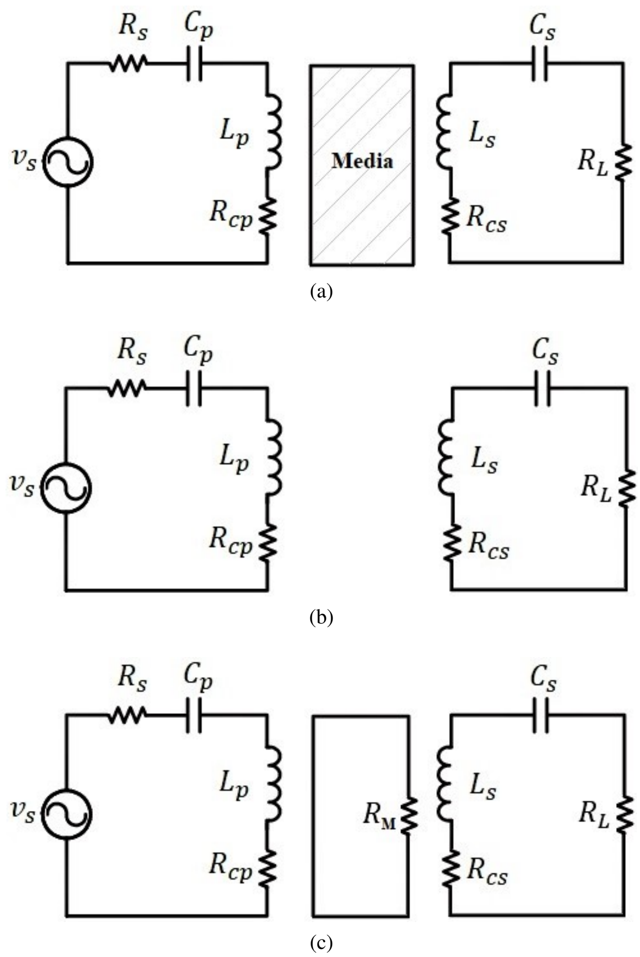

Fig. 5. (a) The general configuration of resonant inductive coupling for wireless communication through subsea pipes. (b) The equivalent circuit model for free-space as the transmission medium. (c) The equivalent circuit model for the subsea pipe as the transmission medium.

resistance, leads to a net reduction in the required power level needed to drive the communication system.

A general configuration of resonant inductive coupling for wireless communication through subsea pipes is shown in Fig. 5 (a). The first step in developing the optimum coil geometry which maximises PTE in these systems is to find the system's resonance frequency with considering the skin effect. Knowing $f_\circ$, the optimum geometry with considering free-space as the power transmission medium will be designed from the optimisation algorithm in [15]–[17]. In this paper, for a typical subsea pipe with 100 mm distance between Tx and Rx coil pair the resonant frequency has been calculated, from (1), as $f_\circ = 15\,\text{Hz}$. At this resonant frequency, a coil with radius of 0.3 m is designed for the IPT system shown in Fig. 5 (b). Using the designed coil geometry the PTE of the resonantly-coupled system with (i) free-space and (ii) subsea pipe as the medium is simulated using MATLAB. The simulated curves for the cases (i) and (ii) are depicted as A and B in Fig. 6, respectively. Comparing the curves A and B can provide the numerical value for power loss at the subsea pipe (i.e.: stainless steel and seawater.), which is shown as R_M in Fig. 5 (c). Having achieved R_M the coil geometry design technique in [15]–[17] will be again used to find the optimum coil geometry which maximises PTE in wireless communication through subsea pipe-walls. Maximising PTE, improves the SNR in wireless communication through subsea pipe-walls. As a result, subsea systems will have improved data rates and better physically optimised coil antennas leading to enhanced wireless communications with pipe-bore robots.

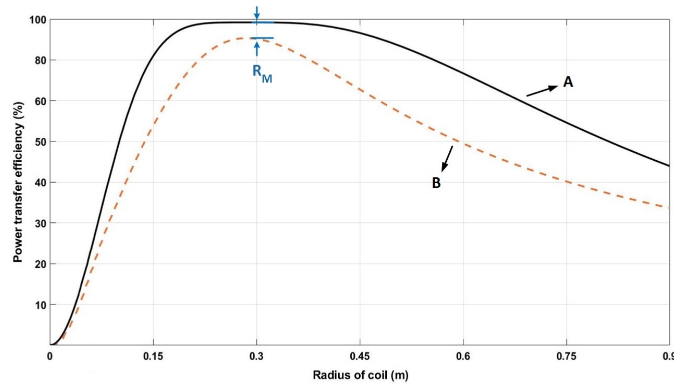

Fig. 6. Simulated PTE values for a resonantly-coupled inductive link at $f_\circ = 15\,\text{Hz}$. The PTE curve for the system with free-space as the signal transmission medium is shown by solid black line. The orange dashed line shows the PTE curve when the transmission media are stainless steel and seawater.

IV. Conclusion

The wireless power transmission through pipe-wall was considered to facilitate duplex communication with pipeline inspection gauges in subsea pipelines. A coil geometry optimisation technique was proposed to boost power transfer efficiency (PTE) of the duplex communication system. The proposed method, by increasing PTE, improves the signal to noise ratio in wireless communication through subsea pipe-walls. As a result, subsea systems will have improved data rates and better physically optimised coil antennas leading to enhanced wireless communications with pipe-bore robots. This work can be further developed to show the practical PTE measurements from the physical testbed prepared based on the proposed optimum coil geometry.

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