

# A Force Sensitive Resistor Based Wireless Sensor Network for Pipeline Monitoring and Oil Spillage Control in Nigeria

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**Abstract** — This article, a force sensitive resistor (FSR) based wireless sensor network- an underground wireless monitoring system whose components are insulated against physical attacks from malicious intruders, proffers solution to abate the incidences of pipeline vandalisation, crude oil theft, and control oil pollution in the Niger Delta region of Nigeria. A force sensitive resistor based wireless sensor network was implemented in MATLAB /Simulink environment to find out leaks in an oil bearing pipeline. Two scenarios were studied. One in the absence of leak with four sensor nodes/four auxiliary sensor nodes, and the other when leak was present with four sensor nodes/four auxiliary sensor nodes. Results obtained indicate that the sensed pressure of each of the sensor nodes/ auxiliary sensor nodes of scenario 1 are within the preset pressure threshold of 120-125 kPa at 120.2–120.6 kPa, while for the second scenario, the results found indicate that the sensed pressure of each of the sensor nodes/ auxiliary sensor nodes of scenario 2 are lower than the preset pressure threshold at 114.2–105.6 kPa. The reduced pressure in any segment indicates the presence of leak in that segment. Thus, leaks are detected whenever the sensed pressure within any of the segments of the pipeline being monitored drops below the preset pressure threshold upon comparison by the microcontroller of the designed system. The node/auxiliary node within the segment where the leakage is found out then sends a pre-installed leak report containing node/auxiliary node location with time stamp to designated office(s) and personnel for necessary action(s) to be taken.

**Keywords** — FSR, MATLAB/Simulink, Microcontroller, Pipeline, WSN.

## I. INTRODUCTION

The production and growth of the oil and natural gas sector have for long been fraught with several threats and pressure which can be categorized as planned, and unplanned. While planned threats are associated with the illegal activities of oil thieves/vandals that are also called ‘bunkerers’ who attack pipelines carrying petroleum product to steal the product, unplanned threats contrastingly result from natural disaster, corrosion, cracking of petroleum pipeline, and process upsets leading to pipeline leakages. Both cases lead to oil spillage into the environment with the resultant effect that a large

portion of arable land is polluted, soil organisms are destroyed, plant nutrient is destroyed, and the fish stock which is the main stay of most Niger Delta communities is depleted. In addition to these consequences of oil spillage, so much revenue is lost from the stolen oil product and clean-up operations to remediate the polluted environment(s).

Between 2001 and 2010, Nigeria lost USD 7billion per year to the stealing of crude oil and no fewer than 2,550 people lost their lives due to fire incidences resulting from illegal oil bunkering activities, while over 35,000 barrels of crude oil have been spilled into the environment within this period [1]. In a bid to assure efficient surveillance, discovering, and reportage of oil leaks into the environment, petroleum enterprises all over the world are now using latest technologies to monitor pipeline to ensure environmental safety and economic growth [2].

One of these technologies is the wireless sensor networks. Wireless sensor networks are IEEE 802.15.4 enabled devices capable of robust and reliable multi-hop communication [3], [4]. Wireless sensors can be stationed in deserted area and can facilitate gathering of data from that area to faraway base stations and then control room [5], [6]. Wireless sensors have become very useful in varieties of civil and militaristic applications owing to their low-cost and simplicity of deployment [2], [7], [8]. Because of these inherent advantages wireless sensor networks have also found useful application in environmental monitoring and control applications especially in oil and gas exploration sector.

Utilizing this technology, wireless sensor networks, notwithstanding, the rate at which pipelines are vandalised has remained unabated because the constituent parts of the WSNs are easily targeted by vandals and destroyed since they are visible, thus rendering the monitoring system ineffective. For example, Nigeria lost \$1.35 bn worth of crude oil from the losing barrels of crude amounting to 22.6million to thieves and the vandalization of pipeline in quarter one of 2019 [9].

This work focuses on simulating a force sensitive resistor-based wireless monitoring system whose components shall be covert, and thus insulated from attacks by vandals in MATLAB/Simulink environment. It is a non-intrusive

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technology that could be fitted/retro-fitted to new/existing pipelines for effective monitoring of oil pipelines and control oil pollution in the Niger Delta Region of the Federal Republic of Nigeria.

The communication aspect of this work is assumed in this paper.

## II. LITERATURE REVIEW

Many research paper/works have been published in many countries of the world on the use of wireless sensor networks in pipeline monitoring, environmental monitoring, and uncovering of oil spillage. However, the implementation and deployment of many of these works have not expectedly abated the issues of oil spillage and oil pollution as of date in the Niger Delta. The authors in [10] aim to allow continuous surveillance of the steam flood and waterflood systems (SWATS) using wireless sensor network with low cost, short delay and fine granularity coverage while providing high accuracy and reliability. The shortfall of this work is that the monitoring by a singular node will not capture the topological impact on the transitory qualities of steam and water fluid to determine comparable issues and needless alarms. A network that has efficient and flexible key distribution scheme secured enough to prevent algorithmic complexity and denial of service attack with the network being able to conserve energy was developed in [7]; however, the issue of the possibilities of pilfering the physical constituent parts of the network was not thought about; actual monitoring of pipeline was also not contemplated in the work. Fault Tolerant Wired and Wireless Sensor Network Architecture for monitoring pipeline infrastructure was researched in [11]; however, there was no clear architecture illustrating how the individual sensor nodes will be deployed and what parameters are to be measured for a specified fluid. Also, the security of using the Wired and Wireless sensors was not considered in the work. The author in [12] suggested a system architecture for oil pipeline surveillance and security using WSN with the simulation of the proposed system. However, there was no clear and detailed explanation on what parameters are to be measured along the pipeline infrastructure. There was also no clear illustration regarding the sensor node.

## III. METHODOLOGY

The system essentially comprises a communication module, IRIS Mote, a 2.4 GHz IEEE 802.15.4 wireless module which houses the power supply unit, microcontroller unit, memory unit, and the RF transceiver which is the communication unit of the mote as depicted in the general block diagram (Fig. 1). The communication module is interfaced with pressure sensors- force sensitive resistors to realize the intension of the design. The designed system is powered through the power supply unit which is made up various components and two AA. The power supply functions to produce a constant voltage from 2.7-3.6 VDC.

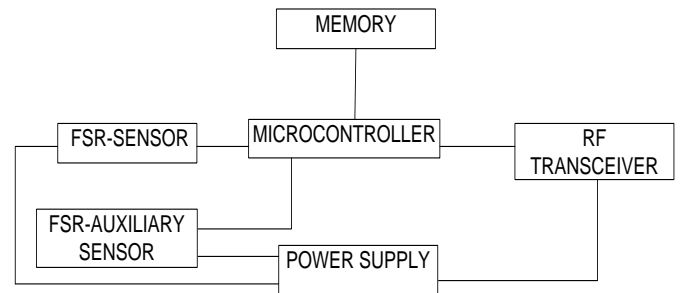


Fig. 1. Block diagram of an FSR-based Wireless Sensor Monitoring System.

### A. System Structure Theory of Operation

This work is composed of both nodes and auxiliary nodes (Fig. 1) that shall carry out monitoring and transmit data independently. Nodes and auxiliary nodes are designed to function in sending real-time status report of leaks via the cloud server/internet, using provided Wi-Fi. But the architecture of the auxiliary node is slightly at variance with the node's in that an auxiliary node, unlike a node which is made comprises a pressure sensor (FSR) and its associated communication module, is made-up of a cluster consisting of four pressure sensors (FSR) integrated with a cluster head (which in this case is the communication module of the auxiliary node) such that in monitoring operation, an auxiliary node covers four nodes; thus, a cluster (auxiliary node) is required for four nodes. Each sensor of an auxiliary node is attached in close proximity to the sensor of a node in the portion of the pipeline being monitored so that the variation in pressure that will be observed by the sensor of the node in that segment is also observed by that sensor of the cluster. The inclusion of the auxiliary nodes in this work is a measure to assure that real-time data are always transmitted in case a node is temporarily down.

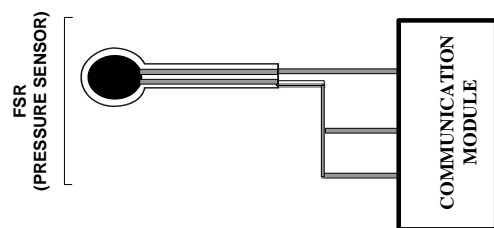


Fig. 2. Schematic of a Node.

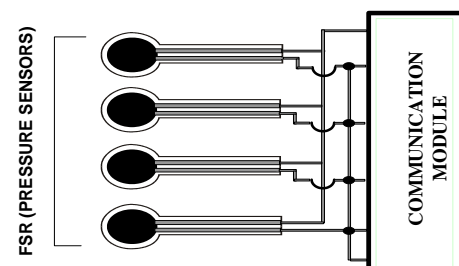


Fig. 3. Schematic of an Auxiliary Node.

The overall architecture this design (FSR-WSN) can be hierarchically broken into four:

- ✓ FSR-Sensor nodes (including FSR-auxiliary sensor nodes);
- ✓ Gateway;
- ✓ Cloud server (internet);

✓ End user.

Nodes (including auxiliary nodes) sense the operational parameter- pipeline internal pressure, as change in resistance within their location from where the sensor units of the nodes are attached to the pipe. The sensed pipe's internal pressure which is first seen as a change in resistance is then processed. The microcontroller then reads from its memory unit and compares the sensed pressure with the preset pressure threshold. If upon comparison, the sensed pressure is found to be lower than the preset pressure threshold, the microcontroller triggers the RF transceiver which is the communication unit of the sensor node/auxiliary sensor node to send a pre-installed leak report (containing sensor node identifier, location, and time stamp) through the gateway to the internet server (cloud). At the internet server stage, the received leak report is transmitted to the SMS gateway for onward transmission to designated personnel's mobile unit. The same report is transmitted to the Security and Data Acquisition Unit (SCADA), and database for update, data logging and for further necessary action(s) to be taken.

### B. Model of Oil Pipeline

Piping systems or pipelines are analysed in a steady state provided the process variables namely pressure and flow rate that describe the features of the pipeline are time invariant [13]. With the steady-state representing the transient state, mathematical equations, which correspond to the hydraulic dynamics, are gotten from the steady-state parameters [13]. Assumptions were taken as reported in [13] and [14].

A simplified transfer function that relates the change in output pressure with change in input pressure and change in output flow rate is given by [13].

### C. Design of Controller

The first approach to implementing Proportional-Integral-Derivative (PID) controller is to obtain the transfer function representing the dynamics of the system whose steady state variable characteristics is to be measured or detected. Then the parameters of the PID are determined using the MATLAB PID tuner. After that, a preset pressure threshold (reference value for the variable to be measured) is introduced, and the difference between the desired value (preset pressure threshold) and the real value (the current value of the variable being detected), which is in form of error analysed by the controller and causes communication to be initiated if it is below the preset pressure threshold. The mathematical representation of PID controller is given by [15], [16]:

$$u(t) = k_p e(t) + \frac{1}{T_i} \int_0^t e(\sigma) d\sigma + T_d \frac{de(t)}{dt} \quad (1)$$

Equation (1) shows that PID represents the sum of three terms that are governed by three key parameters: the proportional gain,  $k_p$ , the integral gain  $k_i$ , and the derivative gain  $k_d$ . The integral and derivative gains can be expressed in terms of  $T_i$  and  $T_d$  respectively. Such that:

The proportional term is:  $k_p \times e(t)$ .

The integral term is:  $\frac{k_p}{T_i} \int e(\sigma) d\sigma = k_i \int e(\sigma) d\sigma$ .

The derivative term is:  $k_p \times T_d \frac{de(t)}{dt} = k_d \frac{de(t)}{dt}$ .

However, in the implementation of controller, continuous time domain is converted to complex frequency (s-domain) by Laplace transform. Hence, (2) could be expressed as:

$$U(s) = k_p E(s) + \frac{k_i}{s} E(s) + k_d s E(s) \quad (2)$$

where  $e(t)$  is the difference between the preset pressure threshold and the sensed pressure in the pipeline in time domain while  $E(s)$  is the equivalent value in s-domain.  $U(s)$  is the output or command signal of the controller in s-domain while  $u(t)$  is the equivalent time domain value.

### D. Force Sensor Model

The dynamics of the force sensor which serves to communicate between the pipeline system and the controller is represented by the following transfer function given by [17]:

$$H(\omega) = \frac{V_{out}(\omega)}{i\omega\rho_1 A_1(\omega)} \quad (3)$$

where  $V_{out}(\omega)$  is the associated electrical output signal,  $i\omega\rho_1 A_1(\omega)$  is the input signal and it is equal to  $P(z, t)$ , which is the input pressure pulse,  $z$  is the normal axis to the system. The expression  $A_1(\omega)$  is the Fourier transformation of the incident pulse at  $z=0$  in the velocity potential representation, and the pressure to voltage transfer function (PVTF) applies to the N-layer system [17]. Since the FlexiForce A401 FSR is a two-layer system [18], equation (3) could be used to represent its pressure to voltage dynamics. Hence, representing equation (3) in s-domain gives:

$$H(s) = \frac{V_{out}(s)}{sP(s)}, \quad s = i\omega \quad (4)$$

## IV. RESULTS AND ANALYSIS

This section presents the results obtained from simulation test carried out in MATLAB/Simulink environment for leak detection in pipeline based on relative change in pressure profile or level. The output responses due to data sensed or measured by sensors connected to pipeline system are as presented in the following subsections.

### A. Simulation in the Absence of Leak

In this scenario, the pressure level of the pipeline system with four nodes ( $N_1, N_2, N_3$ , and  $N_4$ ) and an auxiliary node, a cluster of four FSR sensors (interfaced with their cluster head),  $S_1, S_2, S_3$ , and  $S_4$ , which are separately connected in close proximity to  $N_1, N_2, N_3$ , and  $N_4$  was considered. The performance of the system was evaluated through simulation conducted in Simulink environment. The simulation time was set at 200 seconds. The outputs obtained as displayed by scope attached to display graphical reports are shown in Fig. 4 in terms of detected pressure level in the pipeline. A 3-

dimension (3D) plot of the pressure of the measured pressure by the sensors is shown in Fig. 5.

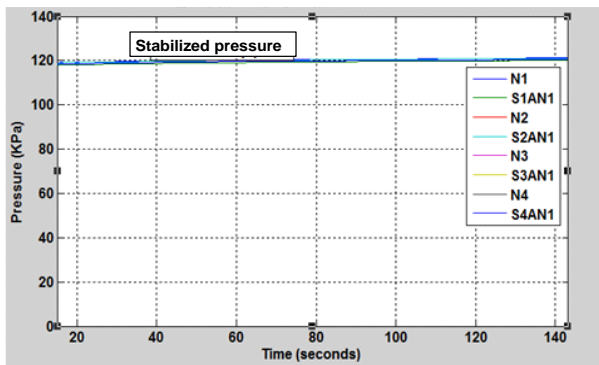


Fig. 4. Measured pressure level (no leak).

In Fig. 4, the simulation result of the output signals due to information gathered by the nodes and the sensors of the auxiliary node about the pipeline system indicates that no leak exists in the pipe since stabilized pressure of values ( $N_1 = 120.2$  kPa,  $S_{1AN_1} = 120.1$  kPa), ( $N_2 = 120.6$  kPa,  $S_{2AN_1} = 120.6$  kPa), ( $N_3 = 120.6$  kPa,  $S_{3AN_1} = 120.6$  kPa), and ( $N_4 = 120.6$  kPa,  $S_{4AN_1} = 120.6$  kPa), were registered. These values registered by the sensors are within the preset pressure threshold (120–125 kPa), that is, the pressure threshold required to be maintained in the pipeline by the oil which the controller compares with the sensed (actual) pressure at any point in time, processes and sends to the transceiver of the WSN module for onward transmission to personnel/SCADA whenever the sensed pressure falls below the preset pressure threshold. The transient and steady state analysis of the pressure dynamics in the pipeline in time domain as registered by the sensors are presented in Table I.

TABLE I: TRANSIENT AND STEADY STATE TIME DOMAIN CHARACTERISTICS OF PRESSURE IN PIPELINE

Sensor	DT (s)	SPT (s)	$M_p$ (kPa)	$P_d$ (kPa)
$N_1$	6.12	15.23	120.2	0
$S_{1AN_1}$	6.12	15.23	120.1	0
$N_2$	6.12	15.23	120.6	0
$S_{2AN_1}$	6.12	15.23	120.6	0
$N_3$	6.12	15.23	120.6	0
$S_{3AN_1}$	6.12	15.23	120.6	0
$N_4$	6.12	15.23	120.6	0
$S_{4AN_1}$	6.12	15.23	120.6	0

DT = Detection Time, SPT = Stabilized Pressure Time,  $M_p$  = Measured Pressure,  $P_d$  = Pressure Deviation.

Fig. 5 is a 3D plot called surface viewer that shows the features of the pressure in the oil pipeline considering the number of sensors, time, and pressure. Deduction may be made looking at the surface that no leak was detected as the surface showed levelled dark covered platform; therefore, the pressure in the pipeline is stabilized.

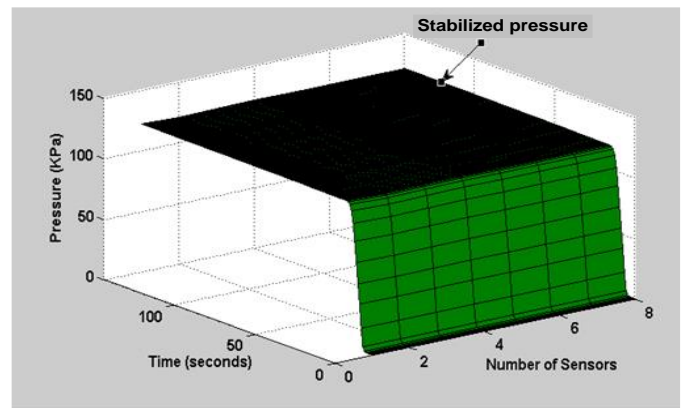


Fig. 5. Three-dimensional plot of pressure in pipeline (no leak).

### B. Simulation in the Presence of Leak

The simulation study was conducted in this case by introducing step disturbances as part of the pipeline dynamics at different time. The pressure level gotten from the simulation is shown in Fig. 6.

Fig. 6 shows the pressure level in pipeline system with presence of leak detected by each node and auxiliary node. The nodes are marked  $N_1, N_2, N_3$  and  $N_4$ , while the auxiliary node ( $AN_i$ ) is a cluster of sensors marked  $S_1, S_2, S_3$  and  $S_4$ . Each sensor of the auxiliary node is attached in close proximity to a node to serve as a subordinate. Initially, the pressure was stabilized at a value of  $N_1 = 119.59$  kPa,  $S_{1AN_1} = 119.58$  kPa,  $N_2 = 119.37$  kPa,  $S_{2AN_1} = 119.31$  kPa,  $N_3 = 119.60$  kPa,  $S_{3AN_1} = 119.61$  kPa,  $N_4 = 119.70$  kPa,  $S_{4AN_1} = 119.70$  kPa detected by the nodes and the corresponding sensors of the auxiliary node respectively. An introduction of step input signals of different magnitudes representing leak at different locations of the pipeline was carried out.

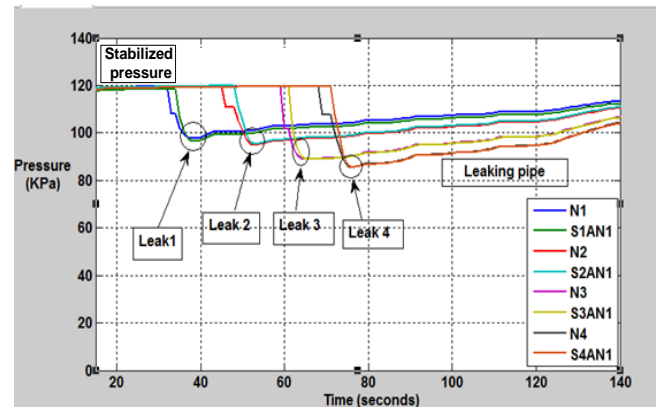


Fig. 6. Measured pressure level using four nodes and one auxiliary node.

Simulation plot as shown in Fig. 6 indicates that each sensor detected leak across the pipeline at different point in time.

Fig. 7 is a three-dimensional plot of the pressure of the oil in the pipe. Table II summarises the transient and steady state performance characteristics of the pressure in the pipeline system.



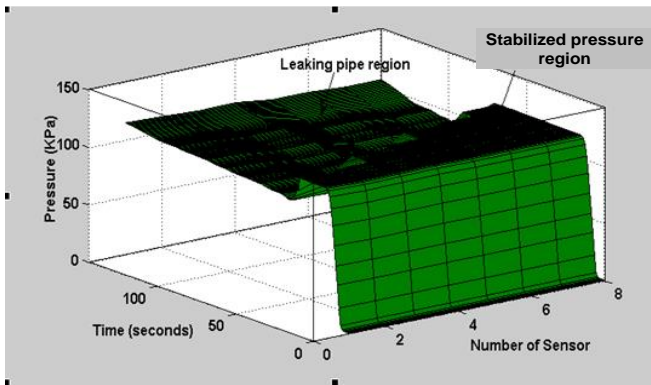


Fig. 7. 3D plot of leak in pipe for 4 nodes and one auxiliary node.

TABLE II: TRANSIENT AND STEADY STATE CHARACTERISTICS OF PRESSURE FOR 4 NODES/ONE AUXILIARY NODE

Sensor	DT (s)	SPT (s)	$L_p$ (kPa)	$P_d$ (kPa)	LDT (s)	$MF_p$ (kPa)
$N_1$	5.53	132.40	97.71	5.90	50.8	114.2
$S_1AN_1$	5.52	132.55	96.69	5.94	51.5	113.0
$N_2$	5.39	134.90	95.02	8.08	71.5	111.4
$S_2AN_1$	5.39	134.89	95.00	8.11	71.9	111.4
$N_3$	5.19	136.96	89.14	11.68	85.1	107.6
$S_3AN_1$	5.18	136.99	89.14	11.77	85.9	107.3
$N_4$	5.06	137.91	85.57	13.88	90.8	105.6
$S_4AN_1$	5.06	137.92	85.55	13.93	91.2	105.6

DT = Detection Time, SPT = Stabilized Pressure Time,  $L_p$  = leak pressure,  $P_d$  = Pressure Deviation, LDT = Leak Detection Time,  $MF_p$  = Measured Final Pressure (in pipe by sensor).

From Table II one can deduce that the presence of leak increases the stabilising pressure time (SPT). When there was no leak, the detected pressure level stabilised at 15.23 s, as depicted in Table I and was the same for all the measurements registered by the sensors. However, with leak setting in, the transitory stability of the detected pressure in pipeline was altered such that the stabilizing pressure time varies for each sensor depending on the magnitude of the leak with the least stabilisation time in the pipeline registered by  $N_4/S_4AN_1$  (137.91/137.92 s). It is clear that  $N_4/S_4AN_1$  detected the least leak pressure (85.57/85.55 kPa) in the pipeline when leak occurred at 90.8/91.2 s, while  $N_1/S_1AN_1$  registered the highest leak pressure (97.71/96.69 kPa) when leak occurred at 50.8/51.5 s. The leak pressure is the pressure at the locus of leak in pipeline. The surface plot (3D graph) in Fig. 7 indicates that leaks occurred across the pipe as the top surface which was completely levelled as depicted in Fig. 5 when there was no leak, now has surface depression indicating leak across pipe surfaces.

## V. DISCUSSION

The detected pressure levels by the nodes and the auxiliary node in the first scenario simulation were within the preset pressure threshold (120–125 kPa). To demonstrate the ability of the designed system to detect leak, a 2<sup>nd</sup> scenario simulation wherein a step disturbance signals of different magnitudes were introduced at different times was carried out. The result obtained showed leak pressure of different magnitudes, while the pressure levels in the leaking pipe found by the 4 nodes and one auxiliary node dropped from 114.2 kPa to 105.6 kPa. Looking at Tables II it is apparent that with leak occurring in the pipeline, the time it takes to detect pressure of the transient and steady state of the oil in

the pipeline reduces. This time represents the time it takes to detect and process data sensed from the pipeline with respect to the state of the pressure of oil and can be called the response time. The drop in the detection time can be attributed to the fact that as the pipeline leaks, the pressure in the pipeline is reduced.

This reduces the expansion of the pipeline, thus leading to a correlative reduction in the contact force on the FSR with a consequent increase in the resistance of the FSR-sensor which is decreased when the contact force on it is high. This increased resistance of the FSR on account of the reduction in contact force on it occasioned by the leaks which the system sees as a decrease in pressure makes for easy sensing of transient and steady state behaviour of pressure in the pipeline by the nodes and the auxiliary nodes. Hence, when there was no leak in the pipe, the detection time was 6.12 s, but reduces to 5.06 s with 4 nodes and one auxiliary node. It could be deduced too that leak causes the time for stabilization of the pressure in the pipeline to increase. When there was no leak, the pressure stabilised at 15.23 s and remained at that level throughout the duration of the simulation. However, with leak setting in, the transient stability of the detected pressure in pipeline was altered such that stabilization is achieved after leak was detected at different time frame depending on the size of leak as detected by the nodes. The surface plots show a more practical view of the pipeline system. When there was no leak, no deep was seen on the top of 3D surface plot in Fig. 5 as all the edges were at the same level. Nevertheless, when leaks occurred, deep was seen on the 3D surface plot as shown in Fig. 7. Generally, the results obtained indicate that leak in pipeline can be detected by the proposed system and that leak reduces pressure in pipeline.

## VI. CONCLUSION

Wireless sensor networks are a promising scheme for monitoring the state, specifically the pressure level in which leaks in buried oil pipeline can be located and established by the variations in pressure in the pipeline. This work has presented a force sensitive resistor based Wireless Sensor Network for oil pipeline monitoring against leakages based on pressure variation detected by pressure sensors (FSR). The monitoring unit comprises two types of sensor device: the node which is the main sensor, and an auxiliary node which is a subordinate. The detected pressure levels from the sensors are sent to a microcontroller that processes the acquired data from the sensors and compares it with a preset pressure threshold stored in memory expected in the pipeline. The outcome of the comparison if below the preset pressure threshold triggers the transceiver of the node/auxiliary node within the segment where the leak is detected to send a pre-installed leak report containing node/auxiliary node location with time stamp to designated office(s), personnel, SCADA, and the company's data base for necessary action(s) to be taken. The results of the simulation study carried out in MATLAB/Simulink environment revealed that a leak occurs when there is drop or reduction in pressure level in the pipeline. Hence, this work has demonstrated that the proposed system can be used to monitor pipeline/sense

pressure, detect leaks in oil pipeline and eventually control the spillage of oil into the environment.

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