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Published in:
2018 53rd International Universities Power Engineering Conference (UPEC)

DOI:
10.1109/UPEC.2018.8541946

Publication date:
2018

Document Version
Peer reviewed version

Modeling and Analysis of the Remaining Useful Life of MV XLPE Cable: Case study of Oman Oil and Gas Power Grid

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***Abstract*—Cables are one of the main assets in the power grid particularly for distribution network where the loads are widely spaced, this is a vital issue in oil and gas power grid. Monitoring cables on-line is an impossible task due to the cost and the excessive number of distributed cables. In most of oil and gas production countries the ambient temperature hits 56 degree Celsius that adds to the failures of power cables and shorten the cables lifecycle and the hour to hour capacity.**

This paper presents the results of estimating the maximum operating temperature of the cable during different operating load and under different ambient temperature, it is anticipating its impacts on the cables lifecycle. This is compared to the cable manufacturer design specification associated with the normal operating temperature. The results identify the factors contribute significantly to the degradation of the physical insulation property of the cables. In this paper the response time in the thermal transient model is used to identify the remaining useful life (RUL) of the cable. The model is used as a diagnostic procedure to detect the degree of aging, the results show that RUL of underground cables is7.5 years and for overhead cables is13.3 years under ambient temperature of 47°C and maximum load current.

Keywords—Analysis of Cable Lifetimes, Modeling, Ageing Failure, Maintenance, Condition Monitoring, Failure Process

I. INTRODUCTION

Oil and gas companies in Oman are the foremost exploration and production companies in the Sultanate of Oman, they account for more than 90% of the country's gas and oil production, which the production is providing a significant contribution to the most income of Sultanate economy. Critical oil and gas companies' electrical power system (power generation, distribution, and supply) are using MV XLPE cable to interconnect production stations, production facilities, and infrastructure facilities. The electrical power system is facing the challenge to provide reliable source and running the production and facilities continuously. The severe weather and hydrocarbon environment of the North of Sultanate of Oman adds extreme factors in stressing power cables and its insulations, consequently leading to shorten cables lifetime.

A study that is conducted in [1] has considered aging and high temperature are the main critical factors of cables' failure. A comprehensive study of thermal aging on medium voltage (MV) cable insulation materials in Dhahran, Saudi Arabia and identified the problem and leading to shorten the lifetime of XLPE MV and HV cables. The results show that the cable insulation will not operate satisfactorily at temperatures over 90° C, because it softens and melts near this temperature. However, for temperature above 107°C, XLPE gets soften somewhat and continues to provide good insulation at temperatures at up to about 150° C[2].The authors addressed the aging problem due to high voltage stress leading to high temperatures which cause the cable age acceleration [3]. The aging and degradation as a result of temperature has been highlighted by [4].The decline of electric strength is due to all the stresses acting on the insulation material which are the cause of its aging [5]. The analysis study was conducted on EPR and XLPE insulation of cables by using load cycling, thermal transients, and electro-thermal stress due to applied voltage and load cycles on the cable to identify the life estimation model while they are in service [6]. The analysis study of the dielectric properties of MV EPR cable insulation is using an experiment of applying electrical and thermal stresses on the cable that is designed for 15kV and 105° C. This determines the life time of the cable insulation and identified that the breakdown strength probability of cable insulation is 63.2 % with 15 minutes applied rated voltage from 70° C to 190° C and the time failed within 630 to 420 seconds [7]. Also the authors conducted a study in 2015 on 15kV XLPE cable insulation included EPR to identifying the age of the cable insulation by applying switching impulses to the cable and determining that at 10,000 switching impulses the cable insulation failed [8]. Authors of [9],[10] and [11] were conducted a study in the same subject. They analysed the life expectancy model of XLPE cable material property that is using thermal and mechanical applications, the research informing that the probability of melting range was 50% from 1 to 5 years of cable operation period for more than 40° C and for 10-years operation period, the probability of melting range is 89% [12]. Similar study was carried out in XLPE cable insulation that is using electrical and mechanical properties analysis [13].The experimental study application of thermal aging of XLPE and PVC cables are applying voltage and current on the cable to measure the current through the insulation and identify the total harmonic distortion. The author has applied hot air to the cable insulation for temperature simulation [14]. The challenge here in this technique, its accuracy to find the correct results, it was not a real case application to real time of the cable when it is in service. The mathematical model was developed to identify the effect of the soil and cable backfill thermal conductivity on the maximum temperature of the cable conductor, this has been achieved by using MATLAB software to calculate the two-dimensional temperature distribution on the underground cable including cable core, thermal backfill, and soil [15] and also conducted similar study using COMSOL software [16].

The temperature is a main problem related to cable failures and have raised concern over the condition of many of cables over the years and temperature is of interest in this study. The temperature range in Oman is between 24 – 56º C and the operating temperature of the cable is in average of70 – 104ºC. MV cables require adequate identifying the maximum operating temperature in order to stressing the cable insulation and optimise the life-cycle.

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II. Medium Voltage (MV) Cable Description

Medium Voltage cable designs vary widely to meet the diverse requirements of the users, but there are certain components, which are common to all constructions of cables. All types of electric cables consist essentially of a low resistance conductor (circular copper or aluminium conductor) to carry the current and insulation (XLPE, paper, or other high resistance insulation) to isolate the conductors from their surroundings. Other main components may include screening to obtain a radial electrostatic field, a metal sheath to keep out moisture or to retain a pressurising medium, armouring for mechanical protection, corrosion protection for the metallic components and a variety of additions extending, for example to internal and external pipes to remove the heat generated in the cable. The cable longitudinal and cross section are shown in Fig. 1. The XLPE cable can be applied with a conductor temperature of 130 ºC for emergency overload conditions for 10 seconds, it must be understood that erecting and laying conditions necessary to allow for temperatures must be accurately carried out and controlled during installation in order to restrict thermo-mechanical problems.

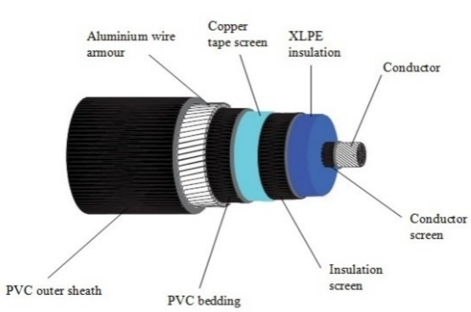

Fig. 1. MV cable structure.[Oman Cable Company Catalogue at PDO, 1998]

III. Cable Failures Analysis

Cable asset management has become increasingly important aspects of business strategies. A significant number of cable asset management has been developed in recent years on the basis of selecting the optimal replacement options. In Oman oil and gas fields, despite all possible options the cost of failures on cables continue to increase, as depicted in Fig. 2 the rate of failures is continuous particularly when the cable is coming to its middle age. It is recorded that most of the failures occurred due to high temperature associated with the load. There were495 failures due to overheating out of 555 failures in the period from 1995 to 2017 for 33kV cables failures data. Oil and gas companies expected the lifetime of the cable is 20 years according to Oman climate associated with maximum load, however manufacturer expectation lifetime of cable is 40 years at 40° C outdoor temperature calculated at maximum load current and underground temperature of 30° C associated with maximum load current as well as at maximum operating cable conductor temperature 90° C (cable design temperature). Since the 3-year maintenance routines are not very effective in reducing the cable failures, this paper addresses a framework for cable asset management, and proposes models that could be used to operate the cable on safe mode of lifetime and support decision on cost effective cable replacement.

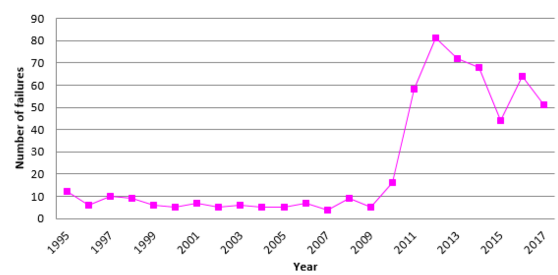

Fig. 2. Number of cable failures 1995 -2017 (33kV)

IV. 33kV Cable Temperature Data and Analysis

A. *The indoor and outdoor cables temperature data arecollected for the critical facilities feeders*

The temperature data are collected for analysis and monitoring the condition of the cables of the critical facilities feeders at critical climate, that is summer time associated with load, current, voltage, and power factor at North Region of Oman. This temperature data are measured by thermo-unit on cables at indoor and outdoor of the feeders for each phase. The data are collected in May, June, July, and August from 2000 to 2010 which these the critical months at North Oman during summer time, the average ambient temperature is 51° C. An example of the data collected is shown in Table I, information worksheet.

B. *Actual temperature data with manufacturer operating load and temperature for analysis*

As the manufacturers determined 40 years is the lifetime of both overhead cables operating at 40° C ambient temperature at the maximum designed load current, and UG cables operating at 30° C. The designated maximum operating cable conductor temperature is 90° C, however, the oil and gas companies are

TABLE I. 33kV CABLE AND TERMINATION TEMPERATURE SPOT POINTS AT DIFFERENT AREAS' FEEDERS

date	location Description	Feeder Description	Feeder Measuring Location	Temperature (°C) R-phase	Y-phase	B-phase	Load in (MW)	Ambient Temperature (°C)
May-00	Yib 33kV Substation	Main Ring Feeder - C100 CB	Switchgear	68.18	68.48	68.68	12	48
			Last pole	82.19	82.99	82.39		
May-00		Main Ring Feeder - C300 CB	Switchgear	66.87	66.97	67.27	8	48
			Last pole	81.85	81.65	82.55		
May-00		Main Ring Feeder - C400 CB	Switchgear	66.32	66.28	66.16	7	48
			Last pole	81.23	81.26	81.19		
May-00		Main Ring Feeder - C500 CB	Switchgear	68.18	68.31	68.13	11	48
			Last pole	82.17	82.62	82.12		
May-00		Main Ring Feeder - C300 CB	Switchgear	66.72	66.32	66.54	7	48
			Last pole	81.81	81.28	81.68		
May-00	Yib 33kV Substation1	Main Ring Feeder - C400 CB	Switchgear	67.06	67.09	67.11	9	48
			Last pole	81.83	81.62	81.88		
May-00		Main Ring Feeder - C500 CB	Switchgear	66.16	66.13	66.17	8	48
			Last pole	81.63	81.65	81.59		
May-00		Main Ring Feeder - C700 CB	Switchgear	69.33	69.34	69.14	14	48
			Last pole	84.04	83.98	84.00		
May-00		Main Ring Feeder - C800 CB	Switchgear	69.28	69.23	69.21	13	48
			Last pole	83.47	83.55	83.48		
May-00		Main Ring Feeder - C900 CB	Switchgear	70.18	70.16	70.12	15	48
			Last pole	84.23	84.21	84.17		
May-00		Main Ring Feeder - C1000 CB	Switchgear	69.04	69.02	69.00	13	48
			Last pole	83.21	83.20	83.18		

considering 20 years the lifetime of the cables, this is due to high average temperature in Oman, however the failures are still in process high continue failing as shown in Fig.2. The average actual temperatures of the three phases for the feeders at indoor and outdoor with the same load current and ambient temperature are presented in Tables II and III. The cable examined in this paper is 630 (mm^2) 33kV XLPE size.

TABLE II. INDOOR CABLE CONDUCTOR 630 (MM^2)

Load (MW) (P_L)	Load current (A)	Ambient Temperature (°C) T_A	40° C in Air current rate (A)	30° C in UG current rate (A)	load % at 40° C	Cable Actual Average Temperature (°C)
5	103	47	840	650	12	65.6
6	123	47	840	650	15	65.9
7	144	47	840	650	17	66.2
8	165	47	840	650	20	65.2
9	185	47	840	650	22	
10	206	47	840	650	25	67.3
11	226	47	840	650	27	67.6
12	247	47	840	650	29	68.3
13	268	47	840	650	32	69.0
14	288	47	840	650	34	69.4
15	309	47	840	650	37	80.5
16	329	47	840	650	39	71.0
17	350	47	840	650	42	71.1
18	370	47	840	650	44	72.6
19	391	47	840	650	47	
20	412	47	840	650	49	

TABLE III. OUTDOOR CABLE CONDUCTOR 630 (MM^2)

Load (MW) (P_L)	Load current (A)	Ambient Temperature (°C) T_A	40° C in Air current rate (A)	30° C in UG current rate (A)	load % at 40° C	Actual Average Temperature (°C)
5	103	47	840	650	12	80.7
6	123	47	840	650	15	80.9
7	144	47	840	650	17	81.1
8	165	47	840	650	20	81.3
9	185	47	840	650	22	
10	206	47	840	650	25	82.1
11	226	47	840	650	27	82.4
12	247	47	840	650	29	82.5
13	268	47	840	650	32	83.4
14	288	47	840	650	34	83.8
15	309	47	840	650	37	84.6
16	329	47	840	650	39	85.0
17	350	47	840	650	42	85.8
18	370	47	840	650	44	86.3
19	391	47	840	650	47	
20	412	47	840	650	49	

V. MODELING OF THE CABLE REMAINING USEFUL LIFE

The dynamic heat of the cable is depending no the thermal rating of the cable and is determined by the maximum operating temperatures attained by the cable components (e.g. conductor, insulation, termination, etc.) these components' operation is depending on operating temperature and load. The insulation material is the main component in the cable that is at high stress from the temperature. Normally, manufacturers are specified the ratings of the cable components in the user guide manual, however in general these are not applicable to all situations, because of variable operating conditions and other factors. It is necessary to be able to calculate the rating under different loading and a variety of other factors e.g. contaminating environment, high ambient temperature, etc.

The heat dissipation is the sum of the contributing dissipation coefficients to be determined the total heat loss at the maximum operating temperature by using heat transfer coefficient for surface area, surface area of heating, and differential temperature between maximum operating temperature and ambient temperature. Then the total heat

$$P = h.\ A.\ \Delta T \quad (W) \qquad (1)$$

dissipation is,

Where, P is the total dissipation (w), h is the heat transfer coefficient ($w/m^{2\circ}$ C), A is the surface area (m^2), and ΔT is the differential temperature between maximum operating temperature and ambient temperature (° C).

The transient thermal response of the cable is considered to be identified and analysed the steady state ratings while cyclic or emergency.

Let P (w) is the rate of power (loss) generation in the cable (including all contributing forms). As the temperature in the cable is rise above the ambient temperature, it causes dissipation to the generated heat to the surface area of the cable at the same time the temperature is rise in the cable that means the thermal capacity of the cable is also taking the generated heat and stored in the cable.

So, we assume s total heat transfer coefficient h ($w/m^{2\circ}$ C), so that knowing the surface area A (m^2) and ambient temperature T_o (° C) and the heat dissipated to the ambient can be calculated. In additional knowing the thermal capacity mc [m = mass of the cable (kg/km), and c = specific heat of conductor or insulation (Jk/kg ° C) and the temperature rise, the heat supplied to the thermal capacity storage can be calculated.

Thus, during the time increment differential time (dt) the power switched on at the cable within transient period as total power Pdt, is partly lost to ambient [$1/Rth\ (T-T_o)\ dt$] = [$hA\ (T-T_o)\ dt$] that is cable thermal resistance & surface area also known and is partly retained by the thermal capacity (mc dT) that is cable mass and specific heat both are known for the cable.

$$P = \frac{\Delta T}{Rth} \quad (W) \qquad (2)$$

$$\Delta T = (T - To) \quad (^\circ C) \qquad (3)$$

$$Rth = \frac{1}{h.\ A} \quad (°C\ /W) \qquad (4)$$

Substitute equation (3) and (4) at equation (2) as,

$$P = h.\ A.(T - To)\ \ (W) \qquad (5)$$

So, the heat balance yields the total heat generated P linear differential equation is,

$$m\ c\ \frac{dT}{dt} = h.\ A\ [T\ (t) - To\ ]\ dt = P\ dt \qquad (6)$$

Where, P is the total dissipation (w), h is the heat transfer coefficient (w/$m^{2°}$ C), A is the surface area (m^2), T(t) is the temperature at time and To is ambient temperature (˚ C), m is the mass of the cable (kg/km), and c is the specific heat of conductor or insulation (Jk/kg ˚ C).

A. The response time in the thermal transient of the cable model

The first-order lag is the transient exponential response in the thermal transient of the cable after the change at the load and ambient temperature. From equation (6) re-arrange gives,

$$\frac{m\ c}{h.\ A}\ \frac{dT}{dt} = [\ T\ (t) - To\ ]\ dt = P\ dt \qquad (7)$$

$$\frac{m\ c}{h.\ A} = [\ T\ (t) - To\ ] = P \qquad (8)$$

We consider, when the load constant (although this is not always a valid assumption as we will see later) and the changes in the temperature from it is reference position in which To is considered is To = 0 as the first-order tag to the final steady state temperature at which T(t) = Ts or we called Tf (first-order temperature) as percentage (0 - 100%). it gives

$$\frac{m\ c}{h.\ A}\ \frac{dT}{dt} = T\ (t) = P\ dt \qquad (9)$$

Hence, the thermal time constant τ is,

$$\tau = \frac{m.\ c}{h.\ A} = P \qquad (10)$$

Sine, the load is not constant as a characteristic feature of such an exponential response curve is that when τ is not equal to t that is the operating time (life time) in seconds, then T(t) its total change that is ΔTs = [T(t) – To] as shown in Fig. 6.

$$(T(t) - To) = \Delta Ts\ (1 - e^{-\frac{t}{\tau}}) \qquad (11)$$

From equation (8) Where, Ts is the steady state temperature rise,

$$\Delta Ts = [\ T\ (t) - To\ ] = \frac{P}{h.\ A} \qquad (12)$$

and the thermal time constant is,

$$\tau = \frac{m.\ c}{h.\ A} \qquad (13)$$

The temperature rise is thus exponential and time variation as a response of the first-order when power is switch on or change as shown in equation (11), (12), and (13).

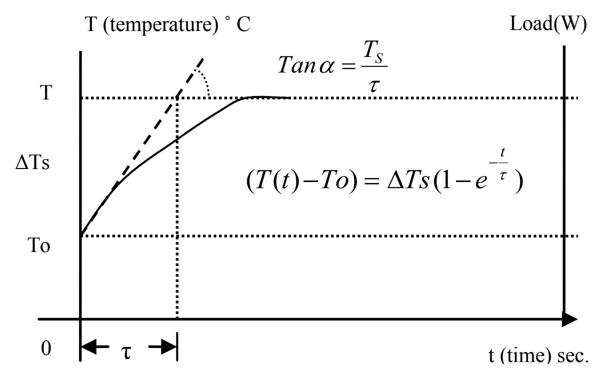

Fig. 6. Characteristics of a thermal time constant vs temperature and load

Again there is an exponential variation the same time constant on the cooling as for the heating when power switched on and off. If the heat transfer coefficient h is the same for the heating and the cooling, however this is not always the case when the cable has power switched on the conductor and other components aids dissipation, but it is not when the load is not running on it.

In all our cases when consider the wind is zero, because most of the cable is buried and inside the substation, just a small portion of the cable outside (on air) at the first pole of the feeder.

B. Example (1): applying the model

The XLPE cable with conductor class 2 and 5 has 630 mm^2. The maximum load current on air 40˚ C is 840A and underground 30˚ C is 650A for class 2 and on air at 30˚ C is 1039A and underground at 20˚ C is 689A.

It is operating at ambient temperature 47 ˚C and the maximum operating temperature is 90˚ C. The DC conductor resistance at 20˚ C is 0.0283 Ω/km and the AC resistance at 90˚

C is 0.0391 Ω/km for class 2 and the DC resistance at 20˚ C is 0.0287 Ω/km and the AC resistance at 90˚ C is 0.041 Ω/km for class 5.

The cable mass is 7715 kg/km and the specific heat of conductor is 385 J/kg ˚ C and the specific heat of insulation is 1900 J/kg ˚ C. The model is to determine the Remaining Useful Life (RUL) of the cable.

The cable data:

The class 2 conductor resistances:

The DC resistance at 47˚ C	R = 0.0000306 Ω/m
The AC resistance at 47˚ C	R = 0.0000516 Ω/m
On air maximum current	I = 840A
Underground maximum current	I = 650A

The class 5 conductor resistances:

The DC resistance at 47˚ C	R = 0.0000310 Ω/m
The AC resistance at 47˚ C	R = 0.0000542 Ω/m
On air maximum current	I = 1039A
Underground maximum current	I = 689A

For class 2 and 5:

The mass of the cable m = 7715 kg/km

The specific heat of conductor C = 385 J/kg ˚ C = 0.385 kJ/kg ˚ C

The specific heat of insulation C = 1900 J/kg ˚ C = 1.9 kJ/kg ˚ C

The maximum operating temperature T = 90˚ C

The ambient temperature T_o = 47˚ C

The class 5 power as the resistance of conductor under each condition:

R AC on air

P = (1039)2 x 0.0000542 = 58.5 W/m

R AC underground

P = (689)2 x 0.0000542 = 25.7 W/m

The thermal time constant under each condition:

$$\Delta Ts = (T - To) \ (°C)$$

ΔTs = 90 – 47 = 43˚ C

$$\Delta Ts = \frac{P}{h.A} (°C)$$

$$\therefore h.A = \frac{P}{\Delta Ts} \ (W/°C)$$

$$\tau = \frac{m.c}{h.A} = \frac{m.c\,\Delta Ts}{P} (S)$$

For conductor:

mcΔTs = 7715 x 0.385 x 43 = 127722 J/m

For insulation:

mcΔTs = 7715 x 1.9 x 43 = 630316 J/m

The thermal time constant of conductor class 5:

R AC on air

$$\tau = \frac{m.c\,\Delta Ts}{P} = \frac{127722}{58.5} \quad (S)$$

τ = 2183.3 S = 36.4 min. = 0.6 h

R AC underground

$$\tau = \frac{mc\Delta Ts}{P} = \frac{127722}{25.7} \quad (S)$$

τ = 4869.7 S = 82.8 min. = 1.4 h

The thermal time constant of insulation in class 5:

R AC on air

$$\tau = \frac{mc\Delta Ts}{P} = \frac{630316}{58.5} \quad (S)$$

τ = 10774.6 S = 179.6 min. = 3 h

R AC underground

$$\tau = \frac{mc\Delta Ts}{P} = \frac{630316}{25.7} \quad (S)$$

τ = 5858.8 S = 97.6 min. = 1.6 h

For example, if we considered one of the full load and constant ambient temperature is continuous loading on underground cable class 5 for 24 hours, we can determine (RUL) that is the remaining time of life of the cable insulation according to company life time (t) given that is 20 years at 20˚ C, but our calculation the load is at 47˚ C. in the example we consider the worst scenario in the cable insulation as below:

Class 5 cable insulation thermal time constant:

R AC on air cable

τ = 3 hours

R AC underground cable

τ = 1.6 hours

t = 20 years = 175200 hours

If the cable is running at ambient temperature 47˚ C and full load current. It is deteriorating before 20 years under that condition.

For underground τ = 1.6 hours

$$RUL = 20 - \frac{t}{\tau} \quad (year)$$

RUL = 20 - 12.5 = 7.5 years

For on air τ = 3 hours

$$RUL = 20 - \frac{t}{\tau} \quad (year)$$

RUL = 20 - 6.6 = 13.3 years

The results illustrated the cable will be in worst condition after seven and half years, if it is running under that load and ambient temperature.

However, that is not the reality, the load is varying as night demand and day demand is different with ambient temperature has minimum and maximum within 24 hours that is increasing and decreasing, even within an hour per day.

The result:

So, now we know the transient thermal time to rise the temperature at the conductor and insulation to the steady state temperature proportional to the load. Since the thermal time at maximum operating temperature is known and company and manufacturer are designated the life time (t) of the cable is 20 and 40 years, we can calculate the cyclic and emergency ratings with different load at variety of ambient temperature in daily, monthly or even yearly to predict the Remaining Useful Life (RUL) as the cyclic and emergency ratings (overloading) is calculated above the maximum load current is 6% that is increase due to skin effect and so the RUL depending on the duration of continuous operating load and operating temperature varying associated with ambient temperature.

VI. Conclusions

The maximum cable operating temperature analysis conducted on XLPE cable measured data included projected maximum cable operating temperature within manufacturer data.

The cable operating temperature model approach can be used to establish link with reliability analysis and compare different preventive maintenance (PM) methods.

The models can be performed and the resulting output can be used as real data input within a simulation framework to optimise cost effective PM strategies.

The models can be used to the existing condition monitoring system to optimise the operation of the grid.

Benefits to asset manager; a very good insight on the cable asset failure pattern and the outcome of study can be used to support decisions on preventive maintenance and aging policies.

Acknowledgment

The authors place on record the support and encouragement given by the authorities of Petroleum Development Oman during the course of this work.

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