Study of the effect of AC-Interference and AC-Mitigation on the Cathodic Protection of a Gas Pipeline

N.Kioupis*, N. Kouloumbi**, G. Batis** and P. Asteridis**

* Public Gas Corporation of Greece (DEPA) S.A.,
207, Messoyion Ave.,
115 25 Athens, Greece,
e-mail: n.kioupis@depa.gr

** National Technical University of Athens,
School of Chemical Engineering.,
Department of Materials Science and Engineering,
9, Iroon Polytechniou Str.,
157 80 Zografou Campus,
Athens, Greece
e-mail: koni@chemeng.ntua.gr

KEY WORDS: *Cathodic Protection, Buried Pipelines, AC Interference, Overvoltage Arresters.*

ABSTRACT

In the present work, an examination was undergone for the effects of the AC-interference and AC-mitigation on the function of the cathodic protection system of a natural gas buried pipeline subjected to 50Hz AC induced by high-voltage power lines. The role of the up-to-this-time operating overvoltage arresters was investigated since their operation disturbed cathodic protection and the AC-corrosion risk was barely eliminated. Thus, this study was directed towards the design as well as on the evaluation of their performance of new specific AC-mitigating electronic devices, named Alternating Voltage Arresters of Continuous Function (AVACF). The installation of AVACF aimed at the minimization of AC-interference and AC-corrosion of the pipeline without detrimental effects on cathodic protection system operation and maintenance, taking into account the very small values of the cathodic protection currents involved. The effectiveness of cathodic protection was assessed through in-situ monitoring of pipeline electrical characteristics before and after the installation of AVACF. The acquired data analysis provided encouraging results. The cathodic protection system function was improved as indicated by the significant decrease of the AC voltage of the pipeline minimizing thus AC-corrosion risk. Furthermore, the reduction of the total cathodic protection current as well as the important diminishing of any low frequency fluctuations and/or deviations of pipe-to-soil potential resulted in reduced general corrosion risk and better reliability of cathodic protection measurements.

INTRODUCTION

Economic reasons as well as crowding of various constructions usually force pipelines to follow routes in close proximity to high-tension power lines. Thus, the pipelines are exposed to AC-interference, which results in perturbation of cathodic protection and AC-corrosion risk. One of the most serious consequences of steady state induced AC is that corrosion can occur even if cathodic protection levels satisfy the standards and despite the induced AC has been reduced to less than 15V as required by other standards[1].

Theoretical studies of the AC-induced corrosion have been published[2,3]. Also, study of the AC-interference on the DC cathodic protection characteristics has been mainly carried out in the lab or in corrosion coupons/probes. Laboratory experiments on steel specimens have shown that AC causes an increase of the cathodic protection current density and a shift of the open-circuit potential[4-6]. In a pipeline case, the higher the AC probe current density the greater the amount of DC cathodic current density[7]. Moreover, on various corrosion probes DC potential oscillations of the same frequency of the AC voltage (e.g. 50Hz) have been observed and were related to the AC-corrosion susceptibility[8,9]. In-situ long-term monitoring and analysis of the electrical parameters of the cathodic protection of a buried pipeline, which was under AC-interference, has been recently reported[10]. However, further research is generally required for the clarification of the influence of the AC voltage on cathodic protection parameters, mainly in well-insulated pipelines.

The presence of alternating voltage and current on buried metallic pipelines can cause malfunctioning or even damage to the Transformer/Rectifier (T/R) units of impressed current cathodic protection. This is particularly valid for T/R units that are not equipped with suitable AC filter and surge protection[11,12].

The induced potentials can be controlled and attenuated by earthing measures. However, a direct earthing of the pipeline counteracts cathodic protection. Therefore, an AC mitigating and DC blocking system i.e. a unit that allows the free flow of AC but effectively impedes the DC discharge has to be installed between pipeline and earthing electrode. The well-coated pipeline under examination poses special requirements for the AC mitigating device. For this reason, such a device was the so-called “Alternating Voltage Arrester in Continuous Function (AVACF)”, which was designed in details, manufactured and installed in the pipeline in question for the goals of this experimental work.

There are various AC mitigation systems, such as zinc grounding cells[1], polarisation cells[1,13], AC compensation apparatus[14,15], solid-state DC-blocking devices (e.g. Isolation-Surge Protectors)[16,17], electrolytic capacitors[1] etc.

Each type of AC mitigation system should be selected and implemented with great care in order to be effective.

EXPERIMENTAL

The pipeline under study was a section of a transmission natural gas main line. At the time of the experiment, it had been already buried in the soil for 5 years. The depth of burial was 1 to 2m. The material of the pipe steel was API 5L grade X-52 up to X-60. The external diameter was 30in. The wall thickness was in the range between 9.52mm and 15.6mm. The pipeline was coated with fused bonded epoxy primer and three-layer extruded polyethylene. Heat-shrinkable polyethylene-compatible sleeves covered every girth weld (applied in the field) while a coal tar polyurethane coating was used for the valves.

The cathodic protection was supplied by one T/R unit operating potentiostatically with magnetite anodes. The T/R unit was equipped with a special low-pass AC filter, which diverted AC around rectifier diodes so that the T/R unit operation was not affected by AC. The pipeline under examination, 45km in length, was electrically separated from the rest line through buried insulating joints at both ends (at chainage 2.3km and 47.3km). The pipeline was never influenced by telluric or DC stray currents. In addition, no electric trains passed nearby. Steady state AC-interference on this pipeline, resulted from induction by the electromagnetic fields, originating from electric power transmission lines (eight 150kV and two 380kV lines). The high voltage lines and the pipeline routes are depicted in Figure 1.

The pipeline was equipped with cathodic protection measuring posts allowing measurements of potential and line current. There were 18 test posts, named “KG, which allowed measurements both on pipe and on grounding wires that had been installed at different sites along the pipeline. Since pipe installation, grounding wires made of hot-dipped galvanized steel, had been buried at selected locations in parallel to the pipeline at a minimum distance 0.2m from it (Figure 2). The outside diameter of the earthing wires was 12mm (minimum) and they were coated with 70μm zinc layer thickness corresponding to 500g/m^2. Table 1 shows the grounding locations chainage with the respective earthing wire length, the measured AC resistance, the calculated DC resistance of earth wire to remote earth and the corresponding average soil resistivity at every grounding site.

Semiconducting overvoltage arresters were connected between pipeline and earth in the 18 KG type test posts. In principle, those arresters consisted of a set of anti-parallel thyristors that were activated by an AC potential across pipe and ground wire. When the arrester was active, the alternating current was conducted by the arrester towards ground; consequently, the AC voltage dropped. The actual activation voltage of the arresters was measured in the range from 22 to 26V. During the low load time, i.e. below activation voltage, the arrester behaved like an open switch. Laboratory and field test results showed that the DC current flow through the energised arrester was in the order of few milliamperes and that it could not be effectively attenuated by adding more diodes in the positive current path.

The experience in the field indicated that the overvoltage arresters did not satisfy the desired functionality for the cathodic protection system, as it will be shown below. Hence, supplementary measures had to be taken in order to reduce the AC levels on the pipe but without degrading cathodic protection. To achieve this goal, electronic devices, named AVACF, capable of conducting AC yet blocking DC were designed, manufactured and installed in KG"type measuring posts. AVACF was connected in parallel with each overvoltage arrester i.e. across pipe and earthing wire (Figure 2). In the design of AVACF, special attention was paid to the very high insulating capability of the pipeline coating, which posed special requirements for the AC-mitigating apparatus. For example, minor DC leakage current must be achieved (few microamperes) and the AC-mitigating device has to be well protected against electric surges.

Thus, AVACF was designed to fulfill the following technical data:

- Max. steady state (long-term) AC voltage: 30Vrms
- Max. steady state DC voltage: 15V
- Max. steady state AC discharge current: 10A
- Steady state AC discharge current at 30VAC in a test circuit with a 20 Ohm resistor: 1,5A
- Steady state DC leakage current at 15VDC in a test circuit with a 20 Ohm resistor: 10microamperes
- Protection from overcurrent by means of a slow acting anti-surge high breaking capacity fuse: HBC 16A(T)
- Overall capacitance: 4700microfarad
- Operation temperature range: $-20^{O}C$ to $+80^{0}C$
- Waterproof and corrosion-resistant housing

The main advantages of AVACF relative to existing devices are the following:

- Extremely high DC blocking capability (DC leakage current in the order of few microamperes) so that DC flow to/from earth to be totally prevented. Consequently, the cathodic protection function, line current and DC potential measurements are not severely affected
- No increase of DC leakage current with increase of DC voltage
- No requirement for external power source (battery or AC mains)
- Mitigation of on-off CP potential recordings falsification from the AVACF capacitance discharging effect
- Execution of on-off potential measurements without having to disconnect AVACF from the protected pipe
- Continuous function starting from very low AC voltage values
- Permits the exploitation of the pre-existing overvoltage arresters in order to be protected from surge/lightning transients
- Suitable dimensions to fit inside the existing measuring post housing
- Easy installation and maintenance.

A beneficial property of AVACF was that the DC leakage current hardly increased with DC voltage. This feature largely facilitated investigating measurements for cathodic protection problems or coating defect surveys where the increase of T/R output is usually advantageous to rise the accuracy of the measurements.

Especially important was also the selection of AVACF fuse. Unless the fuse was slow-acting there was increased probability of a blown fuse even after too short time in service. The fuse selection depends on the response time of the overvoltage arrester. According to authors opinion, AVACF might coordinate better with a special spark gap which presents properties such as a low response time (in the order of ns) and a low response voltage. Our experience showed that the existing overvoltage arresters were rather slow (high response time) since upon connecting AVACF with fast fuses the problem of the frequent fuse blow had arisen. However, this problem was markedly overcome by the installation of a high breaking capacity anti-surge slow-acting fuse. Nevertheless, a periodic monitoring of the fuse function and/or the AC voltage on the pipeline was deemed necessary although our experience showed that in most cases it may have been enough if it takes place every 6 months.

Concerning the field measurements, the recording of AC and DC voltage was performed using 512Kbyte data loggers on the 30V AC range (input resistance: 1μMOhmΩ) and 3V DC range (input resistance: 2MOhmΩ, attenuation at 50Hz: 60dB) respectively. These two-channel data loggers were equipped with a built-in AC-filter, which prevented the DC voltage recordings from being falsified by AC-interference. According to a recently reported work [18], in any case the falsification of the measured DC voltage even with unfiltered measuring equipment is not significant in the range of 50Hz AC voltage values. Additionally, the output DC current supplied by the T/R unit was monitored by means of a data logger connected in the terminals of the T/R unit ammeter. The sampling rate of the data logger was set at 2sec so that potential during "off" periods to be recorded.

On/off switching was achieved by a special time relay. Care was taken to connect the time relay in such a way that during "off " periods the pipe was completely isolated from any equipment of the T/R unit. Switching intervals were set at 12 or 27sec on and 3sec off.

The "on/off" potential waveform recordings were acquired by a combined instrument arrangement consisting of an active AC filter and a portable digital oscilloscope. The sampling rate was 0.2sec.

The effectiveness of the cathodic protection system was estimated by measuring the on potential, the off" potential and the AC proximity voltage at the measuring posts in two phases, i.e. before and after the installation of AVACF. In this work, potentials and voltages in the on state are presented since the off values followed similar patterns.

Line currents were measured by means of a microvoltmeter using the voltage drop method at pipe sections of 50m length.

RESULTS AND DISCUSSION

T/R unit station of the protected section was at chainage 40.1 km. It was in the area where the highest AC proximity voltages have been measured. Before AVACF connection, T/R unit typical operating parameters were 1.9V output voltage, –1.08V "on" potential, -0.90V "off" potential (vs. $Cu/CuSO_4$ reference electrode) and 25mA output current.

After AVACF installation, the system was initially operating with 1.8V output voltage, –-1.18V "on" potential (vs. portable $Cu/CuSO_4$ reference electrode) and 22mA total average current. The calculated current density was equal to i=22000μmicroamperes/107500m^2=0.204μmicroamperes/m^2, a value which was considered satisfactory given that the maximum DC density anticipated in the cathodic protection design study was 3microamperesA/m^2. Following to the installation of a time relay at switching interval 12sec on and 3sec off, potential measurements vs. portable $Cu/CuSO_4$ electrode were carried out. The typical potential values were —1.18V on"and —1.00V off"at T/R unit site.

Prior to AVACF connection, the total DC current furnished by the T/R unit was increased during the energised overvoltage arrester periods while during the inactive arrester periods it correspondingly followed the AC potential changes (see Figure 3). After the AVACF were connected at KG test posts, the average direct current supplied from T/R unit was reduced and it was considerably stabilised (Figure 4).

On the site where the highest long-term AC voltage was regularly induced on the pipeline was at one end of the pipe section near the insulating joint. There, the test post KG 47.3km"was situated and the corresponding overvoltage arrester installed. This was the only one arrester periodically energised for long time intervals.

Figure 5 demonstrates the DC and AC voltage across pipe and earth wire at that measuring post, recorded before AVACF installation at the same time interval with the current recording of Figure 3. During the periods, when the arrester was active, a considerable reduction of the DC voltage was observed suggesting that direct current was conducted by the active arrester. As a consequence, the cathodic protection effectiveness of the pipeline was adversely influenced and the measurements were disturbed leading to difficulties in the cathodic protection data acquisition and analysis. During periods of high AC voltage, especially between 20 and 25V, despite AVACF was inactive, a similar trend of DC voltage appeared but to a lesser extent (Figure 5). The mechanism of this DC potential change might be ascribed to the depolarisation effect of AC on the cathodic polarisation characteristics of steel. Laboratory investigations have shown that the DC potential is influenced by the magnitude of the AC voltage levels[2-4]. Hence, the slow deviations of the average pipe-to-soil potential, depicted in Figure 5, could be attributed to the respective AC voltage variations. These pipe-to-soil potential deviations were significant near the ends of the pipeline, a fact also predicted by the Distributed Source Transmission Line (DSTL) theory[19,20].

Before AVACF installation, the DC voltage values were around -350mV with frequent deviations towards 0mV at periods of active overvoltage arrester or in the case of high AC voltage. After the AVACF installation, the AC and DC voltage recordings were dramatically altered, as the fluctuation of the DC voltage was highly reduced, shown in Figure 6. This fact is very important because any low-frequency occasional potential deviations from the protection criteria increase the corrosion rates[21,22]. In the case of high pipe-to-soil potential fluctuations, the time-averaged value of the DC potential hardly suffices for estimation of the protection potential. The reduction of the pipe-to-soil potential fluctuations upon AVACF operation validated the authors' view that the AC-interference was the reason for any pipe-to-soil potential fluctuations and deviations recorded prior to AVACF connection. Additionally, the DC voltage across pipe grounding shifted to a level of -500mV.

During the inactive arrester periods, the pipeline AC voltage values ranged from 12 to 25V, whereas during active arrester periods they remained at values lower than 10V. From the above mentioned results it is clear that the overvoltage arrester allowed pipeline to attain high AC induced voltage (up to 25V) for long time intervals. AC-corrosion of cathodically protected pipelines has been reported even at AC voltage levels below 5V[23]. It was therefore critical to reduce the AC voltage on the pipeline. For this purpose AVACF devices were installed.

After AVACF installation, the AC potentials measured on the whole pipeline were markedly reduced, remaining at relatively low values ranging generally from 0.19V to 1.7V at grounding sites (Figure 7) i.e. they were much lower than the maximum acceptable safety level of 65V and well below the threshold activation AC potential of the overvoltage arresters (25V). As a result, AVACF operation also eliminated the DC / AC potential fluctuations of low frequency recorded near the activation voltage of the overvoltage arresters, shown in Figure 8. Since the AC voltage was considerably diminished, the AC corrosion danger was reduced[24], verifying that AVACF installation was suitable for the safety of personnel, the cathodic protection routine measurements as well as the proper cathodic protection operation. The AC reduction could be further improved either by regulating AVACF capacitance to higher value or by reducing the grounding resistance.

The DC leakage current through the active arrester acquired values in the order of few millliamperes. Since the total cathodic protection current supplied from the T/R unit for the entire pipeline was in the same order of magnitude, the DC leakage current disturbed cathodic protection operation as well as the routine maintenance measurements. Consequently, AC-mitigating devices that may be suitable for pipelines with porous coatings hardly fit for the well-insulated pipeline. Hence, the extremely high DC blocking capability of AVACF (DC leakage current in the order of a few microamperes) makes it apt for pipelines, which are cathodically protected with very low current.

A comparison between Figure 9 and 10 reveals that AVACF operation effectively mitigated as well the important disturbances in line current measurements due to the AC-interference.

Before AVACF installation and during a period of inactive arrester, the representative "on/off" potential waveform at test post "KG 47.3km is illustrated in Figure 11. The off"potential was measured at 0.4sec after switching i.e. at the time when the slope of the potential versus time curve demonstrates a sharp change (point A on Figure 11). The depolarization rate was very slow (interval A-B shown in the plot after more than 0.4sec following the switching).

The influence of AVACF installation on the on/off"potential waveforms is illustrated in Figure 12. It is obvious that the "on/off" waveform recordings were slightly altered after AVACF installation. This change could be ascribed to AVACF capacitance discharging effect. The voltage difference between the "on" potential, $Ep_{(on)}$, and the potential of the ground, E_g, charges up AVACF capacitance. On switching off the protection current, the capacity is discharged via ground/soil/pipeline, with a time constant, which is determined by the capacity C and the resistance R of the circuit. AVACF capacitance ςαςwas about 4700microfarad. The eighteen AVACF installed exhibit a capacitance 18x4700μF≅85mF since they are connected in parallel between pipe and ground. Pipeline capacitance, being in the order of only 0.5mF[25], could be ignored in the following analysis of the parameters of the circuit. The resistance of the circuit is dominated by the pipeline coating resistance. The coating resistance, R_c, may be represented by the following empirical equation[25]:

$$R_c = |E_{on} - E_{off}| / I \qquad (1),$$

where E_{on} and E_{off} denote the pipe on"and"off potentials respectively and I signifies the protection current.

Introducing 0.2V for the IR drop ("E_{on}-E_{off}"), 20mA for the protection current I, the calculated coating resistance, R_c, is found equal to 10 Ohm, a value which corresponds to a specific coating resistivity of 1Mohm x m^2, given that the approximate total surface area of the pipeline is $10^5 m^2$.

The dissipation resistance R_g of the grounding wire is given by the equation (2)[25]

$$R_g = (\rho\rho/2\pi l) \ln(l^2/td) \qquad (2),$$

where the soil resistivity is denoted by ρ, the length of the grounding wire by l, the diameter of the grounding wire by d, (d<<l) and the depth of the grounding wire below soil surface by t (t<<l).

Inserting in equation (2) the data of Table 1 for ρ and l and assuming an average depth t=2m, the resistance R_g is calculated and found ranging from 0.05 Ohm to 7.22 Ohm (Table 1). Since there is a parallel arrangement of the earthing resistances, the total resistance should be lower than the minimum resistance. Hence, the overall grounding resistance of the earth wires is negligibly low (less than 0.05 Ohm) and as it is added to the coating resistance, it can be ignored. Consequently, the time constant,τ, is approximately equal to R_cxC=10Ohmx85mF=850msec. At the end of the 3sec period, corresponding to 3.5 τ, the 97.2% of the maximum AVACF capacitance discharge current has been eliminated.

Prior to AVACF installation, the off potential"was sampled at the steep change of the curve slope, occurring at 0.4sec (point A on Figure 11), which generally did not significantly differ (50mV max.) from the value sampled at the end of each 3sec off"time period (point B on Figure 11), as the polarization decay rate was generally too slow.

After AVACF installation, in the on/off"potential waveform, the off potential should be sampled at longer time interval after the switching, when the AVACF capacitance discharge current has been decayed to a negligible value i.e. near the end of the 3sec switched off"period (point C on Figure 12), otherwise the off potential would be inaccurately sampled.

Similar IR drops appeared in both circumstances. In any case, the error was not too significant.

CONCLUSIONS

Electronic devices, named Alternating Voltage Arresters in Continuous Function (AVACF), acting with both AC-conducting and DC-blocking mechanism, were designed aiming at the minimization of possible AC-interference while safeguarding cathodic protection of a natural gas pipeline. The pipeline had already been equipped with semiconducting overvoltage arresters with purpose to reduce AC voltage on the pipeline whenever exceeding a certain safety level of the order of 25Vrms, offering also protection from surge/overvoltage. However, those arresters were inadequate to prevent possible AC-corrosion while they could interfere with the cathodic protection of the pipeline. Before AVACF installation, the pipe-to-soil potential, the DC voltage level across pipe-earthing, the protection current and the DC voltage fluctuations were affected by induced AC voltage during inactive arrester periods. During active arrester periods, DC voltage across pipe-earthing exhibited values close to zero, showing that arresters conducted DC, while the protection current and DC voltage fluctuations were increased. These results indicated that proximity with power lines as well as arrester operation adversely influenced cathodic protection system function.

On the contrary, after AVACF installation, AC voltage levels were minimized and DC voltage variations were diminished. Therefore, the AC corrosion risk was lowered and the possibility of DC potential deviations from the protection potential was decreased. The routine cathodic protection measurements were generally not falsified. The "on/off" potential values were not considerably altered by the AVACF capacitance discharging effect, whereas the total protection current was actually decreased, indicating improved cathodic protection operation.

Additionally, among the main advantages of AVACF relative to similar existing devices were the extremely high DC blockage, the minimum disturbance on the cathodic protection measurements and its easy installation and maintenance.

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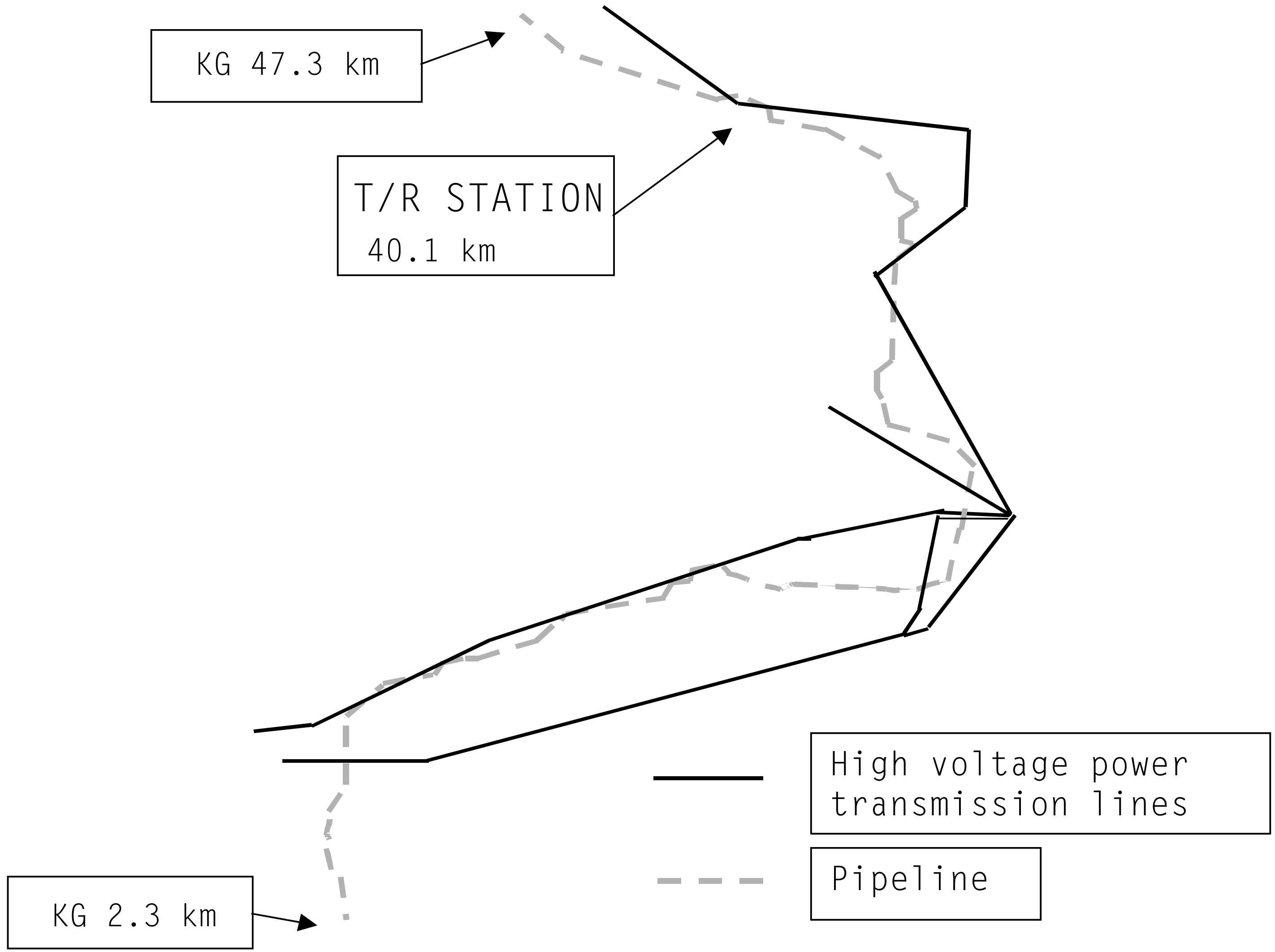

Figure 1: Map displaying the high voltage lines and the pipeline region of ac-interference by electromagnetic field

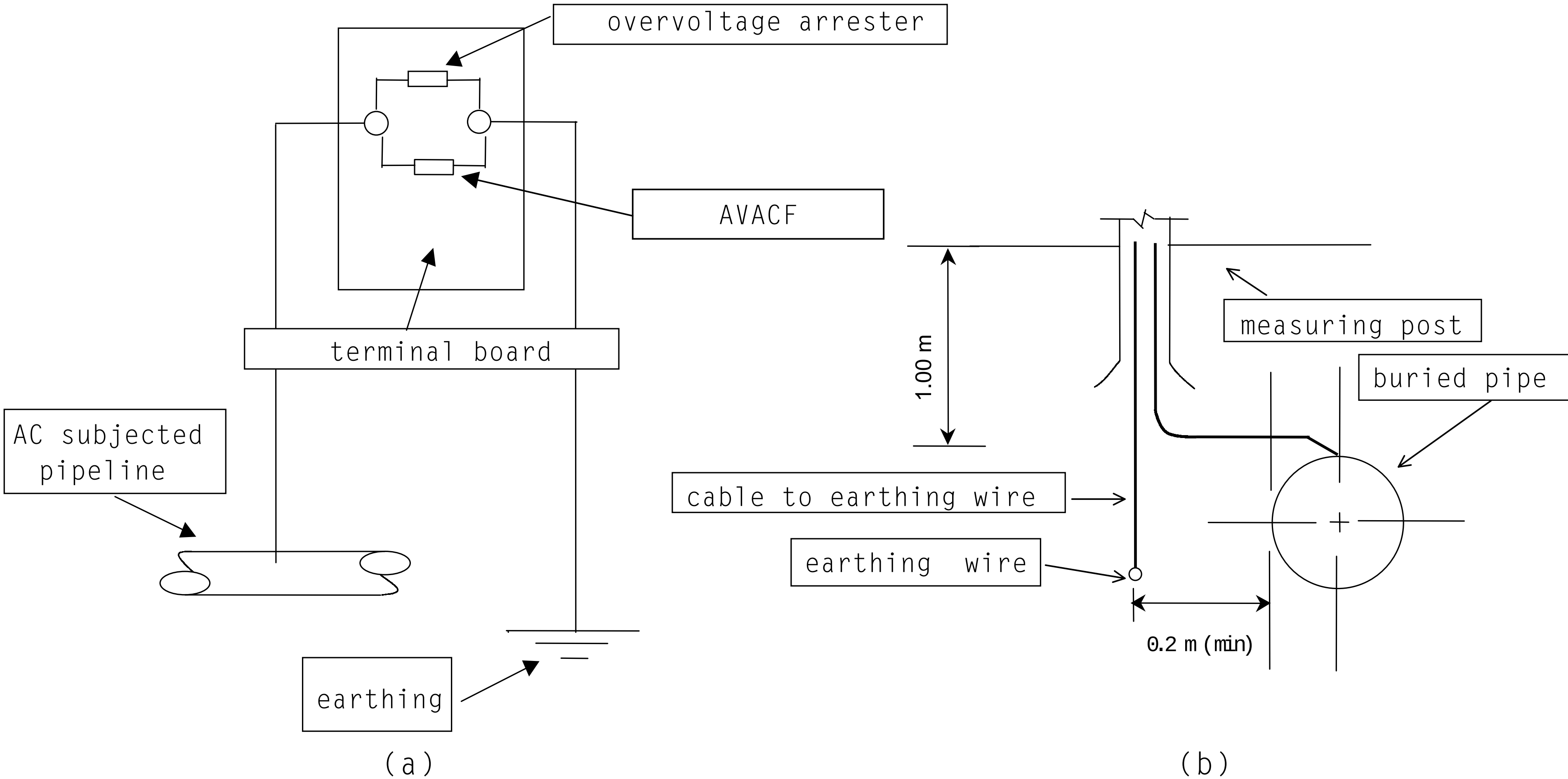

Figure 2 :(a) Diagram of overvoltage arrester and earth wire connections at the cathodic protection test post and (b) Earthing wire installation detail (cross-section)

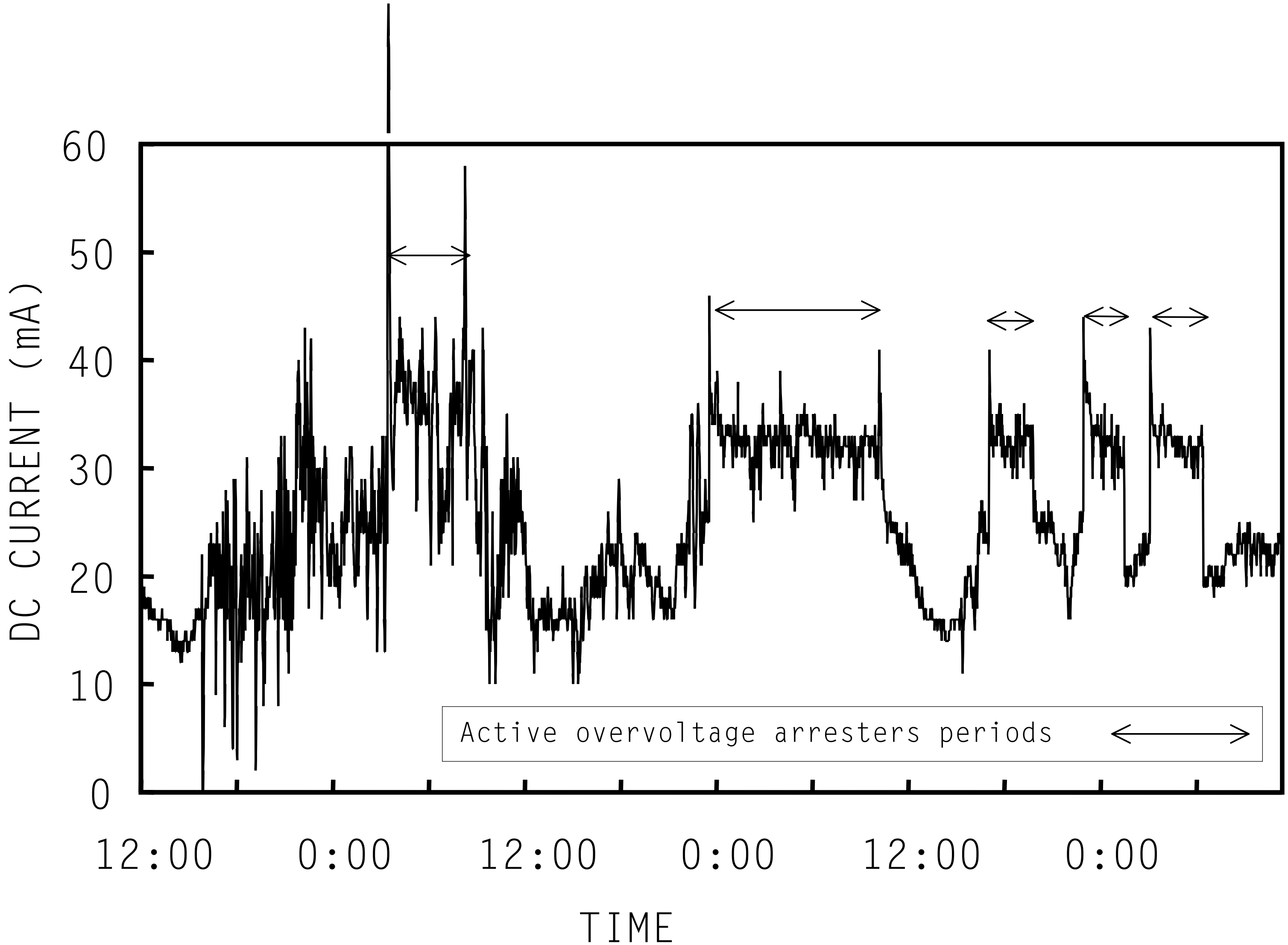

Figure 3: Time dependence of total direct current supplied from T/R unit before AVACF installation

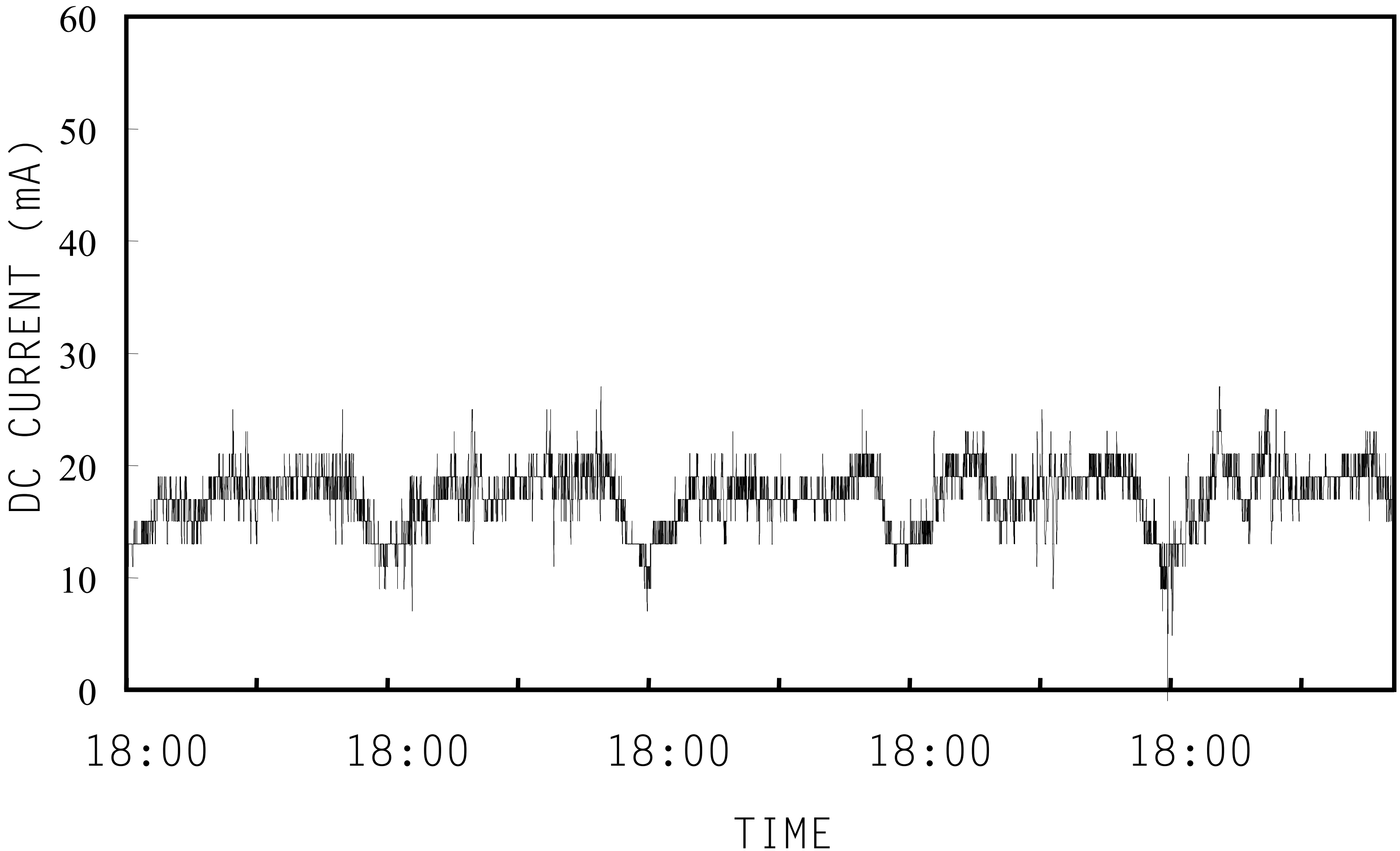

Figure 4: Time dependence of total direct current supplied from T/R unit after AVACF installation

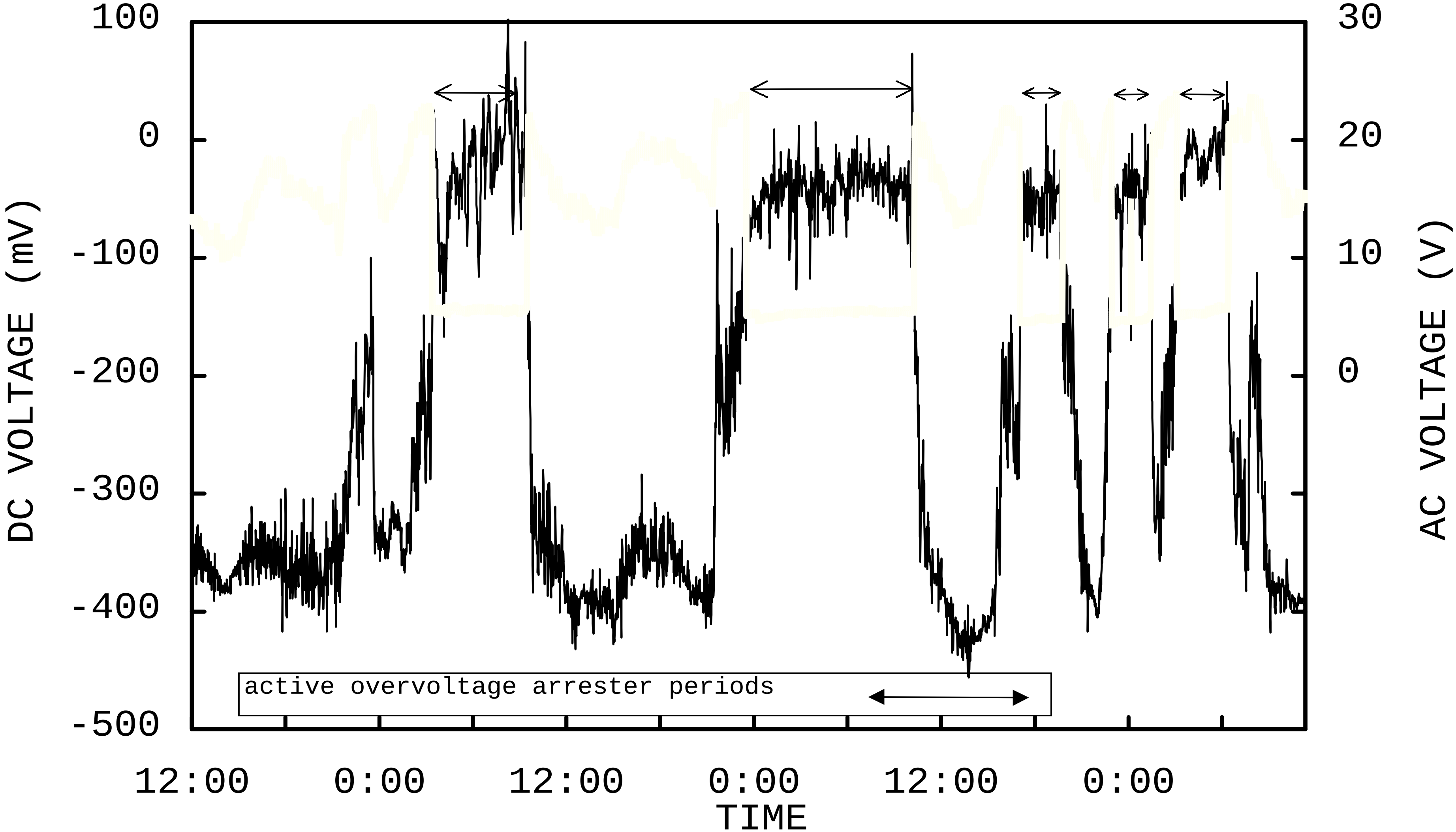

Figure 5: Time dependence of DC and AC voltage across pipe-earth wire at test post “KG 47,3 km” before AVACF installation (dc voltage ▬ , ac voltage ▬)

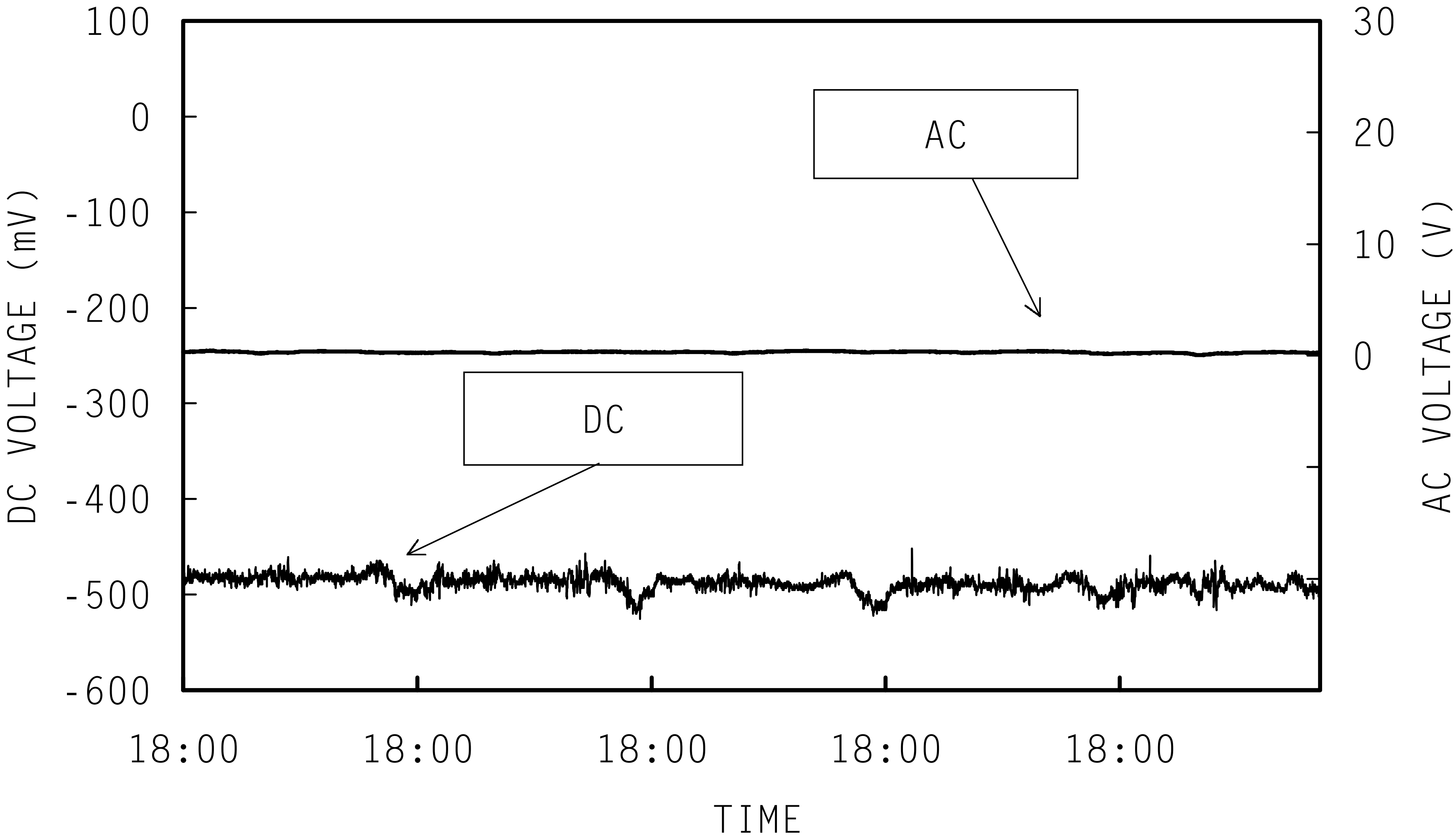

Figure 6: Time dependence of DC and AC voltage across pipe-earth wire at test post “KG 47,3 km” after AVACF installation

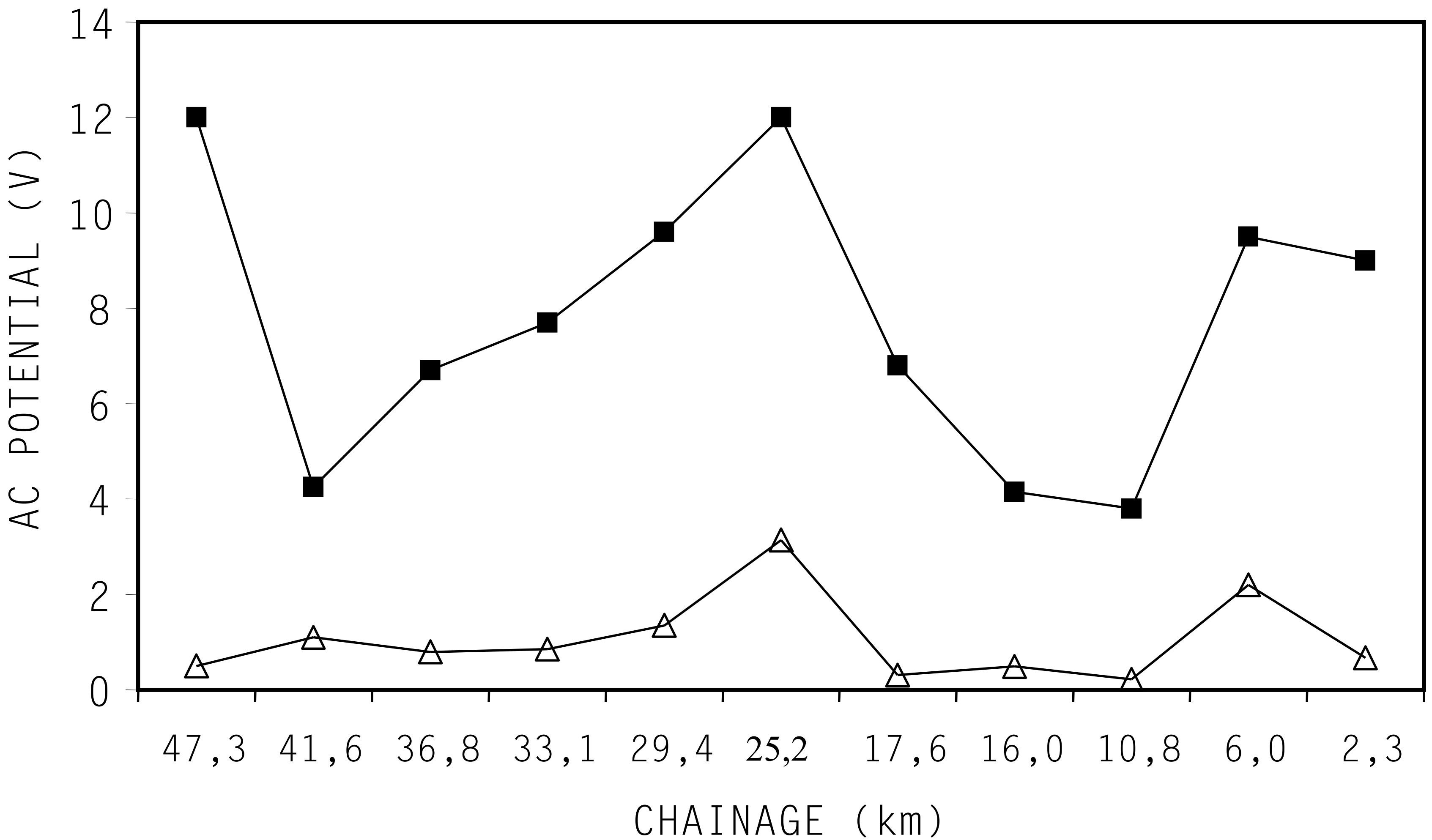

Figure 7 : AC potential versus chainage before (■) and after (△) AVACF installation

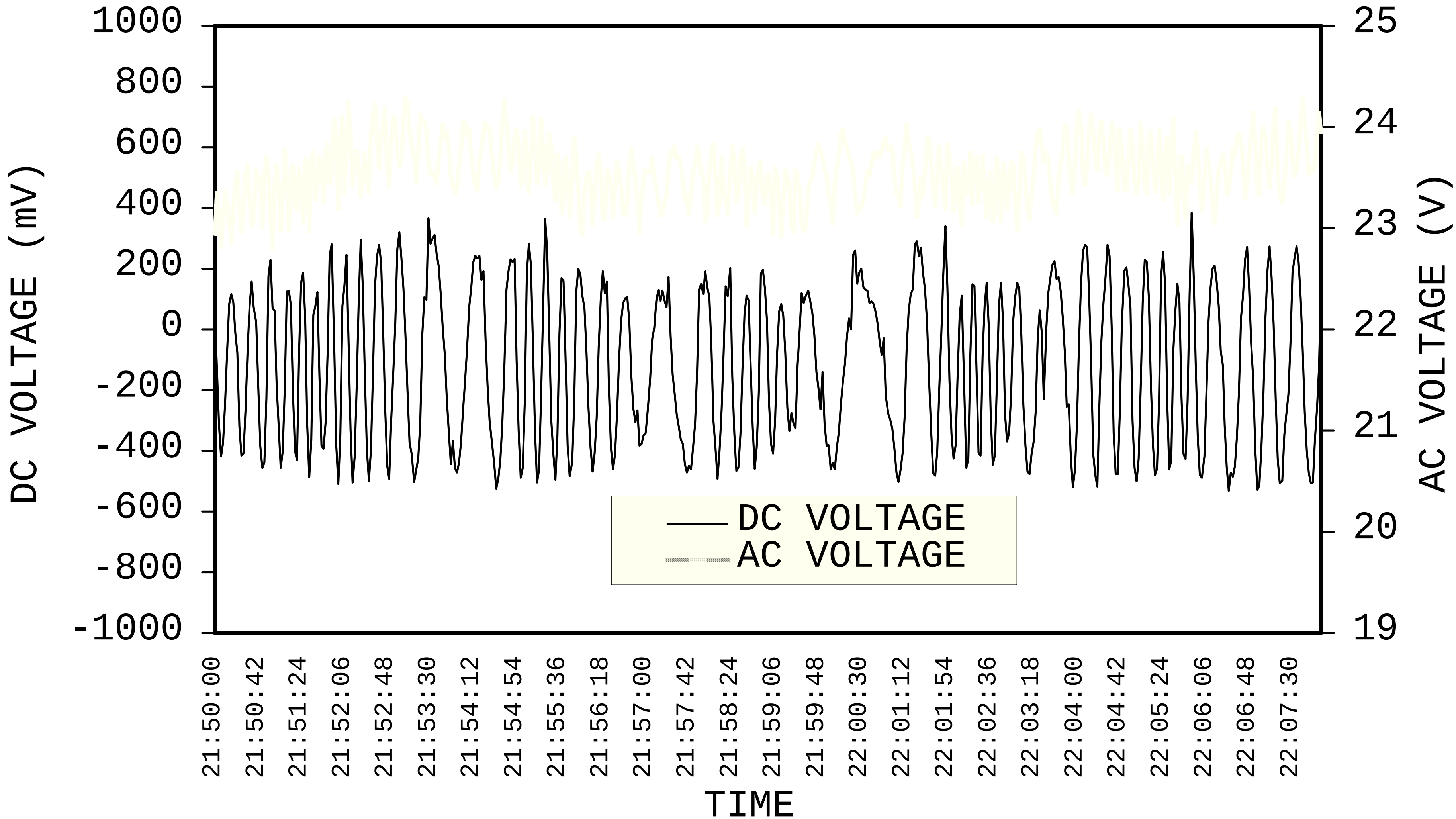

Figure 8 : Fluctuations of DC and AC voltage between pipe and earth wire at test post “KG 47.3 km”

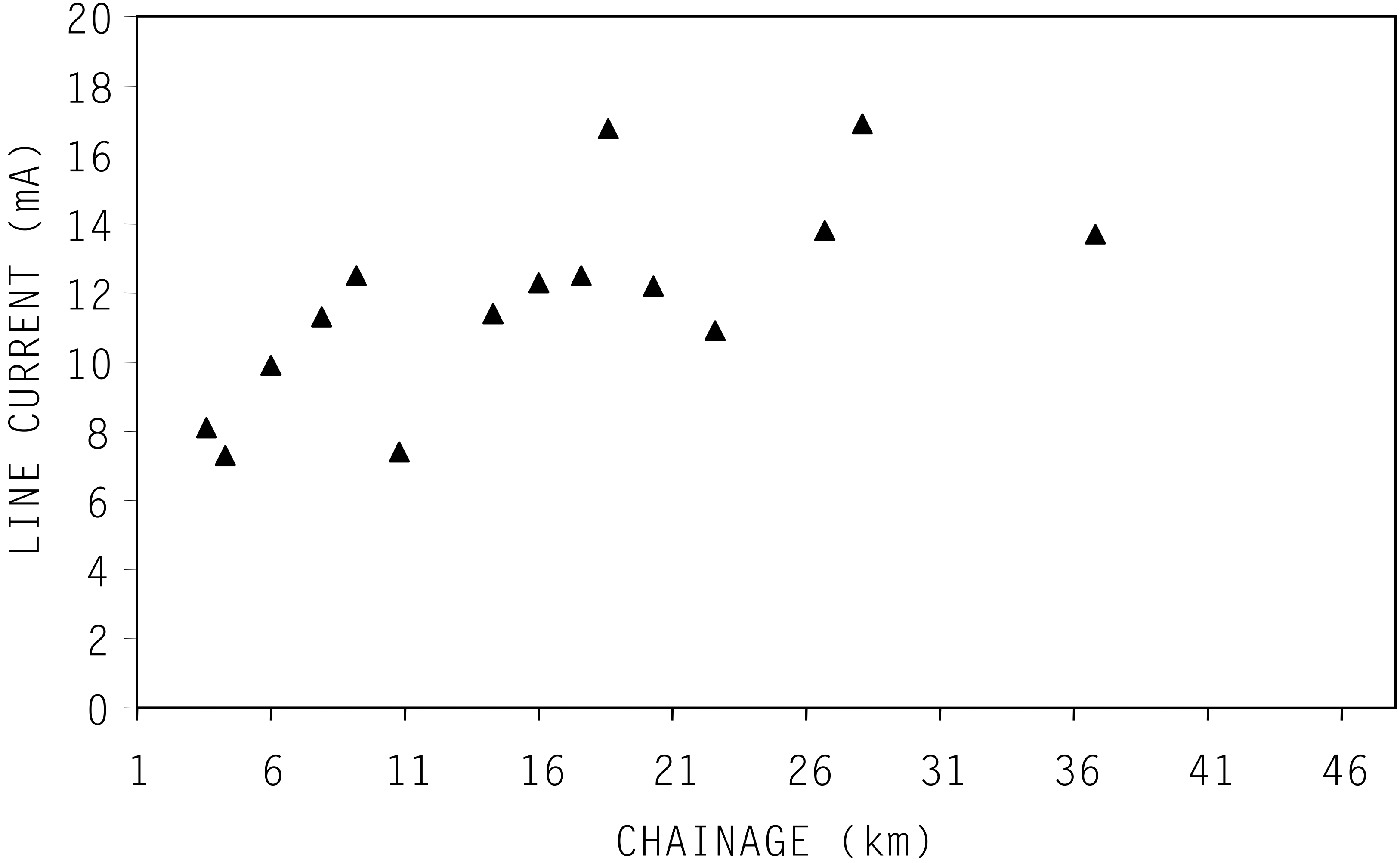

Figure 9: Line current versus chainage before AVACF installation

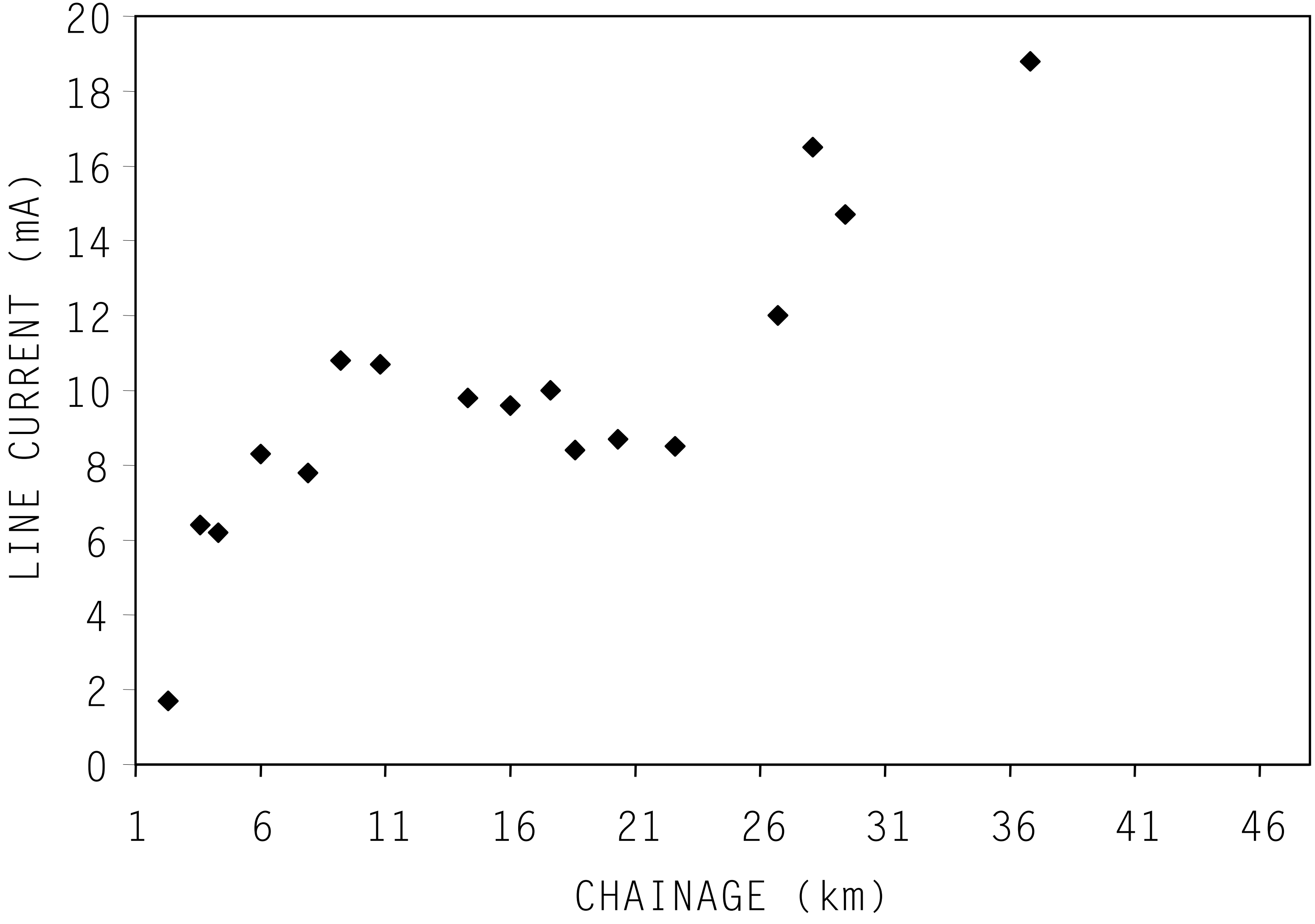

Figure 10: Line current versus chainage after AVACF installation

	CHAINAGE (km)	LENGTH OF EARTHING WIRE (m)	SOIL RESISTIVITY (Ohm-m)	CALCULATED DC RESISTANCE TO REMOTE EARTH (Ohm)	MEASURED AC RESISTANCE TO REMOTE EARTH (Ohm)
1	2.3	110	2.4	0.05	0.23
2	3.6	110	8.3	0.16	0.81
3	4.3	105	99.4	1.96	1.81
4	7.9	220	570.4	6.00	5.45
5	9.2	200	231.7	2.64	15.7
6	10.8	90	103.4	2.33	6.2
7	12.5	200	165.2	1.88	3.03
8	14.3	200	173.5	1.98	1.65
9	16.0	200	183.0	2.09	4.7
10	17.6	220	696.5	7.22	26.25
11	18.6	200	118.5	1.35	3.23
12	20.3	200	137.1	1.56	7.9
13	22.6	100	139.4	2.87	3.26
14	26.7	200	457.6	5.22	5.4
15	28.1	200	415.5	4.74	5.16
16	36.8	65	91.2	2.70	2.49
17	41.6	30	31.4	1.76	2.24
18	47.3	60	73.0	2.30	1.58

Table 1 : Pipeline grounding system data