1ST QUARTER PROGRESS REPORT OF IGNITE FUNDED PROJECT

# Prediction of Remaining Useful Life (RUL) of Aerial Bundled Cables (ABC) in Coastal Areas

**PI: Dr. Faisal Amir**

**Co-PI: Tariq Mairaj Rasool Khan**

# Table of Contents

## Table of Figures

# 1 Introduction

The Ignite funded project, **"Prediction of Remaining Useful Life (RUL) of Aerial Bundled Cables (ABC) in Coastal"** started on December 1st, 2017. This document describes the project summary, scope, literature review and activities/milestones that have been performed at the NDT Centre during the first quarter of the project.

The activities for this quarter included recruitment of team; security clearances and opening of bank accounts; development of data logger; and finalization of the data acquisition plan with K-Electric team.

A website is also set up according to the deliverables of the first quarter. The web site link is http://ndt.pnec.nust.edu.pk/RULofABC/About%20Us.html. The web site contains all detailed information of the project.

The details are discussed in the subsequent sections.

# 2 Project Summary

Aerial bundled cables (ABC) are overhead power lines using multiple insulated phase conductors bundled tightly together. The cables have recently been used in Karachi for power transmission instead of standard copper cables to avoid electricity theft. The partial replacement of existing standard copper cables with ABC cables has decreased the electricity and/or cables theft considerably in the metropolis. However, the performance and life of such cables in coastal areas is not known due to less frequent usage of the cables. Due to the above mentioned fact, KE (the premier company supplying power to the metropolis) is interested in finding the degradation rate of the cables with respect to the environmental conditions including moisture, thermal and mechanical loading conditions. Knowledge of degradation rate will enable M/s KE to predict remaining useful life (RUL) of the cable. RUL knowledge will enable M/s KE to plan repair/replacement actions well in time to ensure smooth and continuous supply of electricity. The RUL prediction requisites usage of appropriate non-destructive testing techniques (NDT) to access the state and in turn degradation rates of the ABC installed in different parts of metropolis. Suitable NDT data with respect to time instants from in-service ABC cables will not only offer diagnostic information of the cable. The NDT measurement data will also assist in setting the acceptance Criteria for assessing longevity of in-service Low-Tension (LT) and High Tension (HT) ABC. M/s KE team will extend their assistance in the NDT data acquisition. A user friendly GUI will also be developed for M/s KE managers to avail the post project benefits. The GUI will offer diagnostic as well as prognostic results of ABCs upon feeding of the historical NDT data.

# 3 Project Scope

The scope of the project is to predict the remaining useful life of ABC cable installed in

Karachi in recent past. Such prediction will facilitate M/s KE to plan repair/replacement action well in time to avoid sudden failures. The scope includes following:

- Collection of NDT data from the ABCs installed in different regions of Karachi at the intervals of two months for one year duration.
- The data collection is followed by the processing of NDT data to diagnose the existing state of the cable.
- Prediction algorithms using the historical database so generated and underlying fatigue models for cables and connectors will be developed to predict the remaining useful life of cables in different regions of Karachi.
- Based on the findings, the mitigation methods will also be recommended for installation of cables in different regions of Metropolis

# 4 Literature Review

Aerial bundled cables (ABC) are overhead power lines. The cable is constituted of insulated phase conductors bundled tightly together with a bare neutral conductor. The cable is a very innovative concept for overhead power distribution as compared to the conventional bare conductor overhead distribution system. The explicit contrast between the conventional cables and ABC cables distribution system is shown in figure 1. Above all the ABC are very less prone to electricity pilferage and theft. Moreover, the cables offer safety and reliability, lower power losses and ultimate system economy through cost reduction in the installation and operations.

**Figure 1. Traditional System**

Figure 2. After Installation of ABC

## 4.1 NDT (Non Destructive Testing) of Aerial Bundled Cables (ABC)

Nondestructive testing (NDT) is the process of inspecting materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system [1]. There are various NDT techniques practiced based on the test specimen material and defect shape, size and location. The electrical supply cables are subjected to different thermal, moisture and the mechanical loading (both static and dynamic) conditions during service. The conditions modify the chemical, electrical and mechanical properties of the cables. The NDT methods for testing ABC cables and connectors include Ultrasonic testing (UT), Eddy-current testing (ET) and, most importantly, Thermography/ Thermal Imaging.

## 4.2 Development of Prognostic Algorithms

### 4.2.1 Prognostics

Diagnostics involves identifying and quantifying the damage that has occurred, while prognostics concerns with predicting the damage that is yet to occur. Prognostics algorithms are designed for the prediction of future health states and failure modes based on current health assessment, historical trends and projected usage loads on the equipment. This leads to predictive diagnostics, which includes determining the Remaining Useful Life (RUL) or time span of proper operation of a component, and consequently a system.

Engineering prognostics is used by industry to manage business risks that result from equipment failing unexpectedly. In the previous days, the deterioration in the Electric cables were analyzed manually by the humans and based on their analysis; they would predict the remaining useful life of these cables. However, human decision making is not always sufficiently reliable or accurate. Therefore, over recent years a significant amount of research has been undertaken to develop prognostic models that can be used to predict the remaining useful life of engineering assets.

### 4.2.2 Remaining Useful life Prediction

Remaining Useful Life (RUL) of a component identifies lead time to failure. It is also known as Estimated Time to Failure (ETTF). It is formally defined as the time span from the occurrence of a failure event to functional failure, for a given failure mode. In context of our project, it is the desired output, which will represent the useful life left on an asset at a particular time of operation. Thus, RUL estimation shall play an important role in scheduling maintenance and replacement of degraded component before functional failure. The RUL of an asset is clearly a random variable and it depends on the current age of the component, the operating environment, and the observed condition monitoring (CM) or health measurements.

#### *4.2.2.1 Estimating RUL from Degradation History*

Data analysis of the material undergoing degradation is of primary importance. It plays a vital role in various RUL prediction techniques and methodologies. Conclusively, deep and thorough understanding of degradation is essential for any material being tested for RUL prediction. An understanding of the degradation of the material under study can lead us to successful prognostics. According to literature [2], the degradation types which affect the system are:

1) Corrosion
2) Deformation
3) Fracture
4) Wear

#### *4.2.2.2 RUL Prediction Models*

There are many types of prediction models used in the literature:

1. Knowledge Based Models: Require extensive thumb rules from domain experts. Relies exclusively on rules defined by domain experts.
2. Life Expectancy Models: Require historical data with expected risk of deterioration under known operating conditions.
3. Artificial Neural Networks: Require mathematical representation of system derived from observation data only. Generally, more complex than knowledge based and life expectancy models.
4. Physical Models: Require mathematical representation of system derived directly from deep understanding of physical processes. They are highly complex, application specific and failure-mode specific.

Out of these models, the models which are suited in our case are *Life Expectancy Models*. Life Expectancy Models are further divided into two categories:

1. Stochastic models
2. Statistical models

Within stochastic models, we selected the *Bayesian techniques* with *particle filters*.

### 4.2.3 Bayesian Techniques

Classical Bayes theorem enables a recursive algorithm to be implemented in computer efficient manner to determine *posterior probability*, given a *prior probability* and an *update* or *likelihood function*. Posterior probability is the conditional probability of a state given previous measurements. Prior probability is determined by the *state-transition equation*, and expresses the uncertainty of a state before any new measurements. This is a function of uncertainty of previous states. The update or likelihood function is determined by the *measurement equation*, which gives the current measurement given previous states. A typical flow of Bayesian model is shown in figure (2) as:

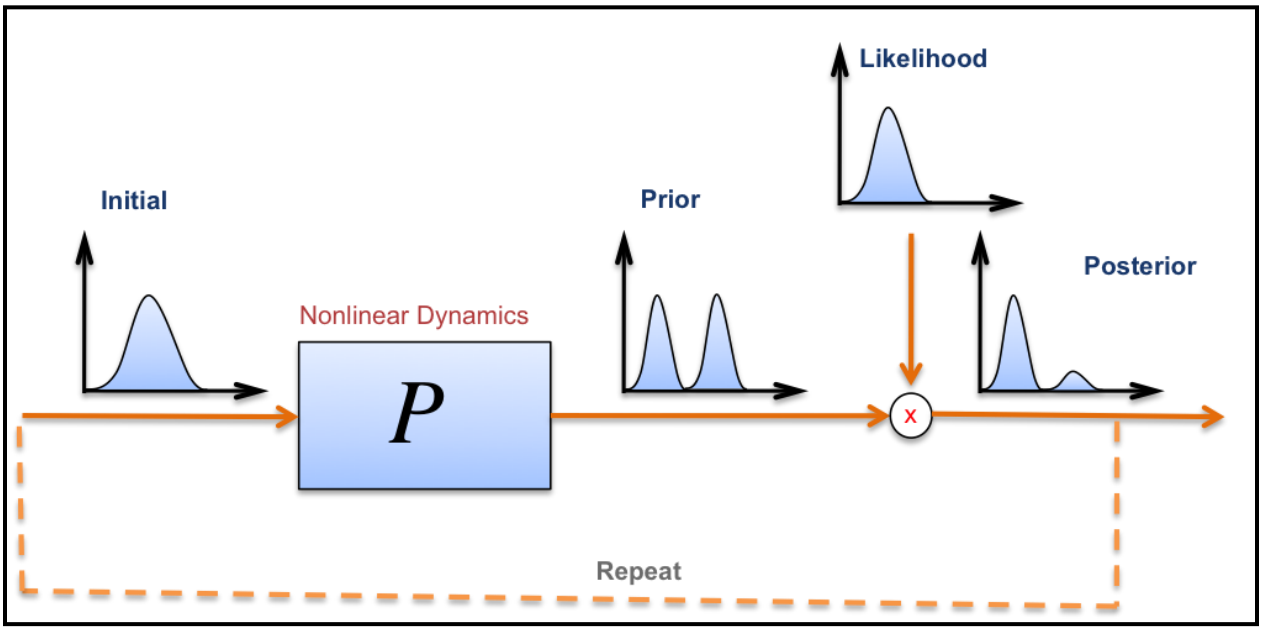


Figure 3. Bayesian Technique

### 4.2.4 Particle Filters

Particle filters use real-time on-line Monte Carlo simulations to model the decrease of uncertainty due to sensor measurements and the increase of uncertainty as time evolves in the physical system of interest. This is a very direct approach to modeling uncertainty, facilitated by the availability of fast, low-cost modern computers with large memories.

Particle filters are a generalization of Kalman filters. Kalman filters are applied for linear state transition and measurement functions, and assume all related noises to be Gaussian. Extended Kalman filters can handle non-linear functions but are unable to handle non-Gaussian noise. In practice, however, functions tend to be non-linear and noises tend to be non-Gaussian or multi-modal. For such scenarios, particle filters can be used to model multivariate, dynamic processes with multi-modal noise / non-Gaussian noise profiles.

Particle filters use Sequential Importance Sampling (SIS) to simulate the entire next state in every iteration of the filter. They do this by drawing a set of random samples, termed particles, from a

theoretical density function and then adjusting the associated set of particle weights on each iteration. Adjusting the weights with the actual data values is known as the update process. The update and propagate steps are shown in figure (3) as:

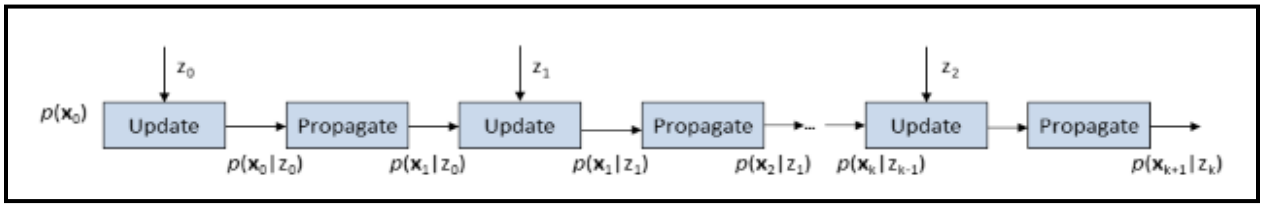


Figure 4. Particle Filter Flow Diagram

# 5 Principal project progress/Milestones

Following were the milestones achieved in the first quarter as per the approved proposal:

1. Receipt of Mobilization Advance
2. Recruitment of team
3. Security clearances and opening of bank accounts
4. Equipment purchase
5. Design and testing of first data logger
6. Development of mechanical casing for the instrumentation to protect from atmospheric conditions
7. Finalization of data acquisition plan with K-Electric team and test visit(s) to upgrade the NDT procedures
8. Website

## 5.1 Receipt of Mobilization Advance

Mobilization advance for the project amounting to Rs. 1,753,000 (Rupees One Million Seven Hundred and Fifty Three Thousand only) was received on 22nd November 2017. Reference letter is appended in Annex A.

## 5.2 Recruitment of Team

Job Ads as per the project contract were posted on Rozee.pk, Facebook and university webpage for recruitment of relevant HR. Copies of same are appended in Annex B. After receiving applications on the project email hiring.abcproject@gmail.com, shortlisting was done based on the primary criteria of having the right experience followed by interviews conducted at NUST – PNEC NDT Centre. Total of 8 team members have been recruited as per the approved proposal and their details are appended below.

### 5.2.1 Team Lead & Research Assistant

Recruitment for the positions of Team Lead & Research Assistant were carried out as approved in the budget.

Shortlisting and selection was based on experience, education, motivation and interest areas. Following candidates have been successfully hired. Their resumes are appended in Annex C.

1. **Team Lead:** Sumayya Asad – Electrical Engineering graduate with MBA with 2 years' experience
2. **Research Assistant:** Muhammad Fuzail Hashmi – Electrical Engineering graduate from NUST – PNEC

Both team members work full time on the project.

### 5.2.2 PG & UG Researchers

After conducting interviews of interested individuals, a mix of 02 postgraduate and 04 undergraduate NUST – PNEC students have been selected to work on this project. Following are their details.

Post Graduate

In order to fulfill this requirement, recruitment activity was conducted for postgraduate students. In this regard, prospects of research in Non-destructive testing were highlighted to the postgraduate students by the PI and Co-PI of the project. An advertisement was also posted at the campus notice board so as to circulate the information about the research position to all the MS/PhD students. A total of 10 students showed interest for working in this domain. Of these students, four were short listed. On the basis of research interest and involvement towards Non-destructive evaluation, the following students were selected to work as research fellows

1. Cdre. Dr. Imran
2. Waleed bin Yosuf

Undergraduate

For attracting undergraduate researchers, advertisement was posted on the university website and notice boards. Interested candidates with the right mix of qualification and experience were interviewed for confirmation on the project.

1. Muhammad Atayyab Shahid (Mechanical)
2. S/Lt. Usman Mehmood (Mechanical)
3. Murad Abdullah (Electrical)
4. Muhammad Noman Khalid (Electrical)

These candidates have been hired to work part-time.

Project activities are easily divided between the electrical and mechanical teams depending upon their core competencies and area of interest.

### 5.2.3 Accounts Staff/Coordination

Apart from the development activities, the project involves different management activities. For the proper management of project labs, equipment, documentation and finances, certain support staff was required. For this purpose, 01 accounts staff has been hired by NUST – PNEC NDT Research Centre to work full time. His name and resume are provided.

1. Mr. Muhammad Sabir

### 5.2.4 K-Electric POCs

Following 02 personnel from K-Electric have been authorized to work on this project. They will support the team in installation of the data loggers at the approved sites and NDT data acquisition. In future, they will be given hands on experience on the software developed by NUST – PNEC NDT Research Centre.

1. Mr. Ali Imran Chaudry
2. Mr. Muhammad Nouman Rao

## 5.3 Security Clearances & Opening of Bank Accounts

Security clearance of all recruited candidates as per the college requirement of NUST – PNEC has been completed. Their personal cards have also been made for easy entry/exit in the university premises.

Furthermore, their bank accounts have also been processed in the Bank Al-Habib PNS Karsaz Branch (same as the project account bank) for easy transfer of salaries during the course of the project.

## 5.4 Equipment Purchase

Following equipment will be used on the project as per the details mentioned.

| *S. No.* | Equipment | Purpose | Purchased (Yes/No) |
|---|---|---|---|
| *1* | Ultrasonic Testing Probe | Testing the insulation of the ABC conductors | Yes |
| *2* | Thermal Imaging Camera | Getting thermal profile of the conductors in graphical form | No |
| *3* | Laptop | Software development | Yes |

For equipment purchases, invitation tenders were launched on PPRA. After getting quotations from three different vendors, the most economical one was picked for procurement. Details of equipment are mentioned below.

### 5.4.1 Ultrasonic Testing Probe

Invitation Tender for requirement of Ultrasonic Probe was launched on PPRA website (Ref. Tender No. TS337147E - http://www.ppra.org.pk/). After successful bidding, UE Systems UE 9000 has been procured from Prestige Trading Group (PTG) Ltd. Actual equipment snapshot is appended below.


Figure 5. Ultrasonic Testing Probe (UE 9000)

The ultrasonic testing probe UE 9000 will be used for testing of insulation between the ABC conductors. Due to its high penetration capability, thickness; arcing and corona effects occuring in the conductors will easily be measured.

### 5.4.2 Thermal Imaging Camera

Invitation Tender for Thermal Imaging Camera has been advertised and bidding is awaited. The same will be procured in the upcoming 2nd quarter.

## 5.5 Design & Development of Data Logger

The fundamental instrumentation section of the project i.e. the Temperature & Humidity Data Logger has been designed and successfully developed at NDT lab.

### 5.5.1 Methodology

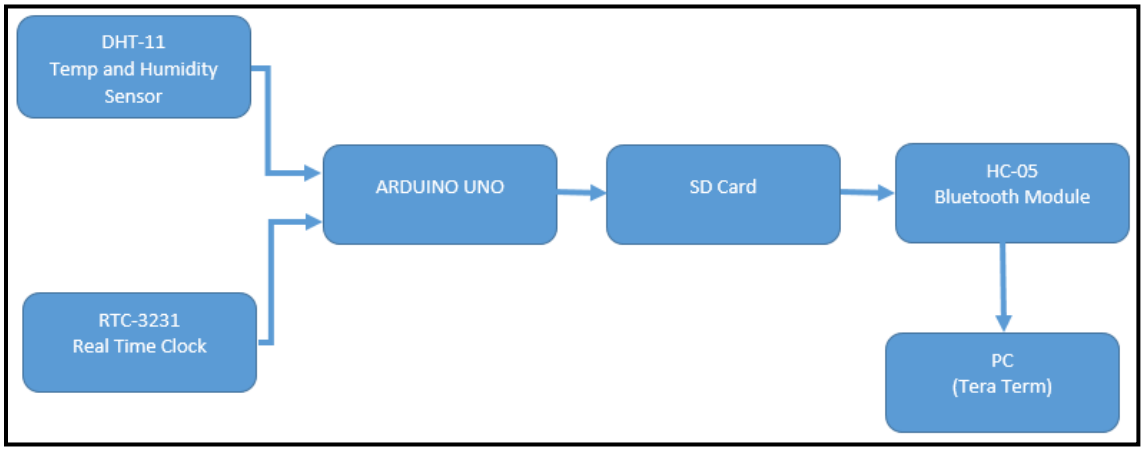


Figure 6. Methodology for Temperature & Humidity Data Logger

It consists of the following components:

- DHT-11 – Temperature & Humidity Sensor
- Arduino Uno
- SD Card shield
- HC-05 Bluetooth Module
- RTC-3231 Real-time Clock

DHT-11 senses the temperature and humidity of the surrounding. This data is sent to the microcontroller for further processing. As the logger needs to store the data at each moment so SD card is used for this purpose. All the data coming from sensor is stored into SD card as text file. RTC-3231 is also connected to maintain seconds, minutes, hours, day, date, month, and year information at which data is logged. The data is sent from SD card to PC using Bluetooth module HC-05.The data is received on PC/mobile using an application known as Tera Term. The log option in Tera Term creates a file of all the data sent from SD card to PC. Now this is the file which contains the historical data of temperature and humidity of the surrounding. And will be used for further diagnostic and prognostic algorithm development.

### 5.5.2 Features

Following are the features of the designed instrumentation:

- Detection of temperature & humidity of the surroundings
- Real-time data saving on SD card and also sent to PC/mobile via the Bluetooth module
- Password protection
- Starts sending data when an action key is pressed after logging in
- Data is deleted from SD card after being retrieved on PC on auto

### 5.5.3 Hardware Design & Output

The instrumentation has been designed and developed indigenously by the PNEC NDT team. The hardware is shown below.

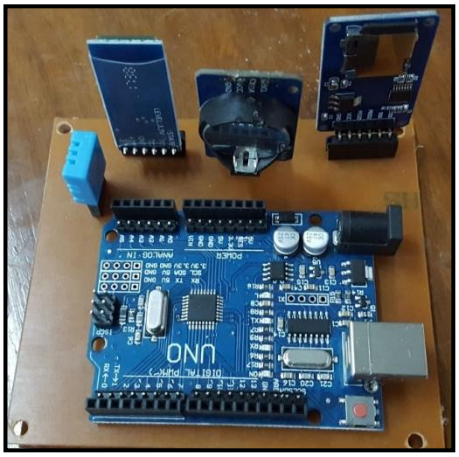

Figure 7. Data Logger Hardware (a)

Figure 8. Data Logger Hardware (b) with Solar Panel

The output of the Data Logger on mobile app is appended below.

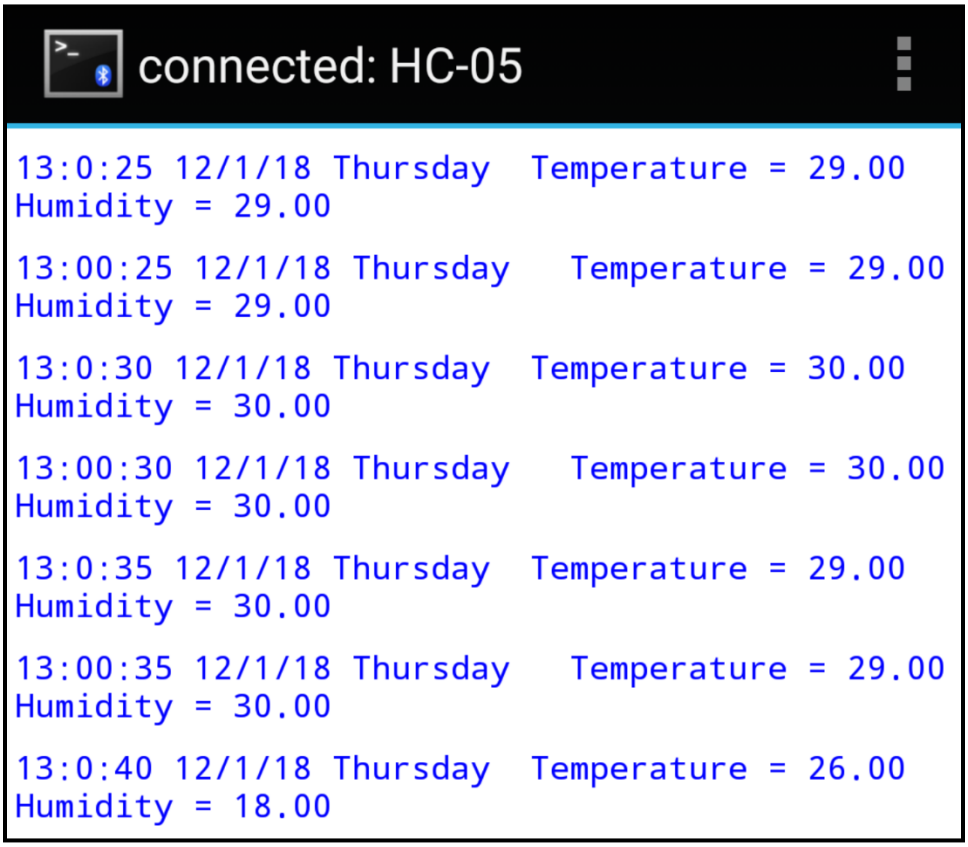


Figure 9. Output of Data Logger

## 5.6 Mechanical Casing

To ensure correct and reliable performance of the instrumentation, mechanical casing has been designed to protect it from atmospheric conditions. The solar panel, instrumentation data logger and battery; all will be enclosed in the metal box and the same will be installed at the electric poles where ABC is present.

Design specifications have been finalized after discussing the requirement and parameter restrictions from KE end. Box design is carried out on SolidWorks software. Snapshots of the software prototype, taken from different angles, are appended below.

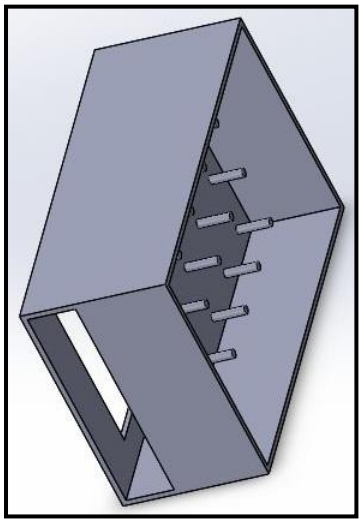

Figure 10. Mechanical design (Base Front View)

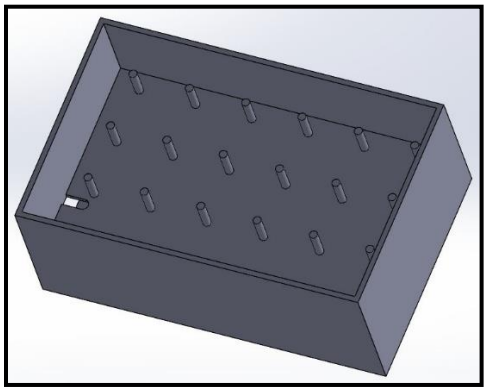

Figure 11. Mechanical Design (Base Side View)

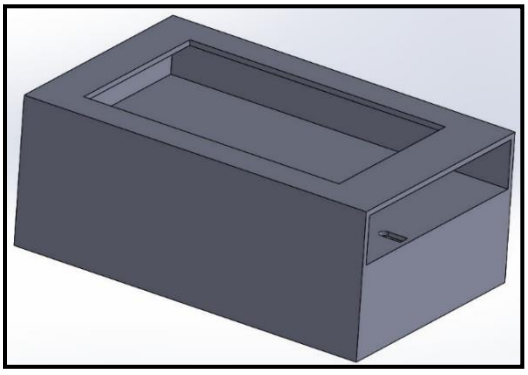

Figure 12. Mechanical design (Top View)

The hardware design as per the specifications finalized looks like this.

Figure 13. Mechanical Casing Hardware (a)


Figure 14. Mechanical Casing Hardware (b)

## 5.7 ABC Samples and Data Acquisition Plan

Samples of Aerial Bundled Cables (ABCs) as per approved plan have been acquired at the PNEC NDT Lab for lab testing. Cross-sectional view of the same is shown below.

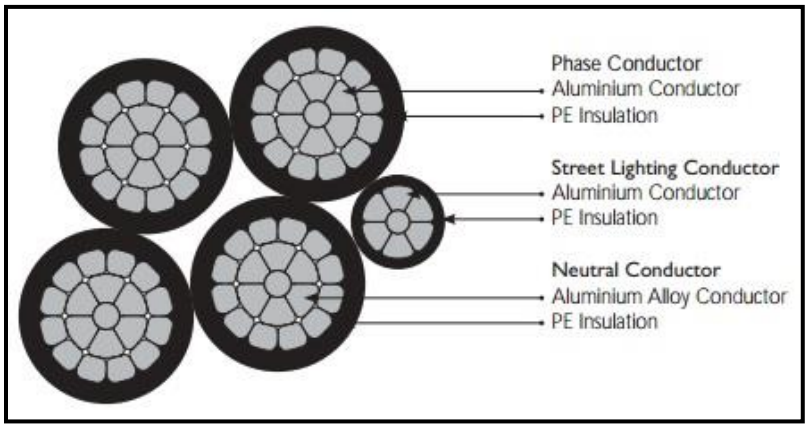


Figure 15. Cross-section view of ABC (a)

Figure 16. Cross-section view of ABC (b)

Furthermore, data acquisition plan has been finalized with K-Electric team. They have confirmed following three different locations for initial installation of the data loggers and acquisition of NDT historical data.

- Clifton
- Defence
- Saddar

Now that data logger and mechanical hardware have been finalized after the lab testing, first installation is planned for 15th March at IBC Clifton. In this K-Electric team will provide full support for accessing their pole connected with the ABCs.

After receiving the real-time data, changes and upgradations will be made, if required, before proceeding for further installation to remaining 02 sites.

## 5.8 Project Website

A project web page has also been set up on the main NUST – PNEC NDT website. All details/progress is updated on it timely. Reference link is http://ndt.pnec.nust.edu.pk/RULofABC/About%20US.html

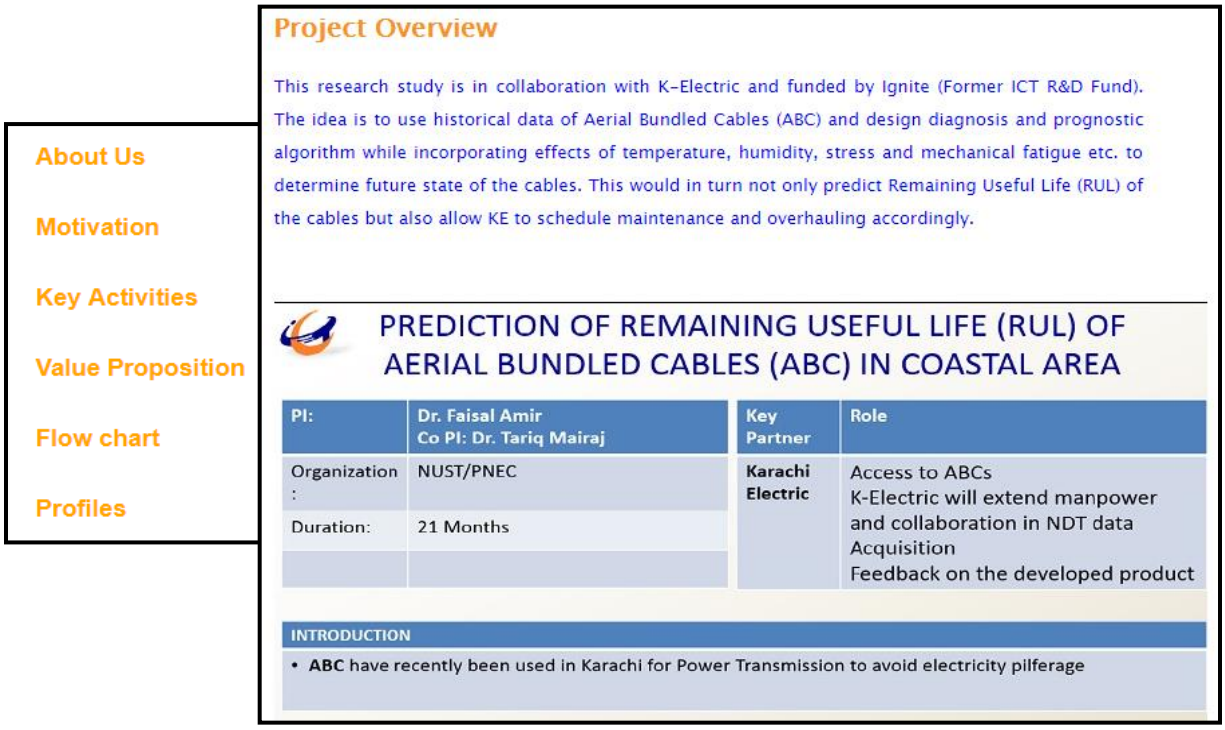


Figure 17. Project Webpage

After finalizing the fundamentals of the 1st quarter, we are all set to kick off first installation and start working on deliverables of the 2nd quarter.