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Web Application for Monitoring Health Index of Electrical Power Transmission Lines and Cables

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Abstract

Infrastructure asset management is one of the major concerns in Tenaga Nasional Berhad (TNB). Failure of any transmission tower would cause disruption in power supply affecting a huge area, huge economic losses to TNB, and danger to maintenance workers and the public. Thus, efficient maintenance and management system for transmission towers is crucial. To monitor the transmission towers and lines condition, a group of researchers and engineers in TNB have embarked on a research to formulate a systematic framework to determine indicator statuses of power transmission lines and a web-based system to monitor the transmission lines and cables conditions based on the statuses. The system is known as TNB Transmission Line and Cables Health Index (LCHI). In LCHI, the elements to determine condition of transmission lines and cables are insulator, conductor, spacer/damper, mid-span joint, tower footing resistance, right of way, ground clearance, slope condition, bracing and crossarm, cross-linked polyethylene cable and oil-filled cable. These elements can be classified into three components: electrical/mechanical, surrounding environment and structural. This paper

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explains the health index determination framework and the evolutionary prototyping approach adopted to develop the system. Also, it explains the process flow, components and elements used to determine health index of the transmission lines and cables. This is followed by explanation on the context and main features of LCHI system. In the energy sector generally, the system plays an important role in prioritizing maintenance, refurbishing or replacing transmission towers to avoid power supply disruption.

Keywords: Transmission lines, transmission towers, transmission cables, health index, condition rating.

1 Introduction

Tenaga Nasional Berhad (TNB) is Malaysia's leading power utility company. TNB owns a monopoly over transmission and distribution in the Peninsular Malaysia and holds about fifty percent of the generation capacity in the country through its generation subsidiaries in Peninsular Malaysia [1]. “Transmission” means the high voltage part of transmission and distribution system connecting power plant to near-required substations. “Distribution” literally refers to the low voltage part of transmissions and distribution system connecting substations and switchgear boxes for customers. The transmission and distribution system consists of “transmission towers (e.g. suspension or crossing), power lines (overhead or underground), insulators, vibration dampers (e.g. Stockbridge type), switchgears and transformers” [2]. According to Bayliss in his book in [3] and Thongchai in [4], there are four basic components that form a transmission line: 1) foundation - concrete pole foundation providing ground anchorage, 2) structure – the entire transmission pole including the legs of the tower, the body of the tower and the cross arms, 3) insulator – used to connect the conductors to the cross-arm transmission tower consisting of a mixture of dielectric and mechanical resistance materials, and 4) conductor/earth wire – bare or insulated conductors transmit rated electricity from one tower to another. The functions of the components and failures correspond to them explained in [4] include unstable pole due to rusty and brittle pole, shifted tower foundation, structural deformations and failure due to corrosion, damage to glass, porcelain, and polymers materials used in insulators, and deteriorating joints caused by conductor corrosion in heavily industrialized areas among others.

In East Malaysia, electricity is provided by two smaller companies, Sabah Electricity Sdn. Bhd. (SESB) for the State of Sabah and Sarawak Electricity Supply Corp. (SESCo)) for the State of Sarawak [1]. Approximately forty percent of the country’s generation capacity are contributed by independent power producers such as YTL Power Generation, Ranhill, Pengerang Power, TNB Janamanjung, Jimah Energy Venture and few more others as listed in [5]. The TNB Grid Division connects the energy generated by TNB and IPPs (Independent Power Producer) to the network of the Distribution Division throughout Peninsular Malaysia. Electricity is also transferred directly via the National Grid to big industrial clients.

Infrastructure asset management is one of the major concerns in TNB as maintaining its assets to continuously provide power can be a major influence factor to the country's economy and social well-being. The country's National Grid system transmits hydro-electric and thermal power along thousands of transmission towers connected via 443 nationwide transmission substations by 23,082 kilo meters length of national transmission network [6, 7]. According to the statistical report produced by the Energy Commission of Malaysia in 2016, in the last 5 years, TNB Grid (formerly known as Transmission Division) "recorded a declining performance based on the Delivery Point Unreliability Index (DePUI) data" [8][13-19][21-24]. The same report stated that "in 2016, there were three trippings with load losses of 83 MW, 288 MW and 104 MW including a load shedding which involved several areas in the state of Perak".

Failure of any transmission tower would cause disruption in power supply affecting a huge area, danger to maintenance workers as well as the public and huge economic losses to TNB. Thus, efficient maintenance and management system for transmission towers is crucial. Transmission tower failures are often caused by broken pin, cross arms and slope. Currently its in-house asset maintenance focuses more on maintaining electrical components rather than structural assessment of transmission towers via a web-based system known as Transmission Operation Monitoring & Analyzing System. Among the features of the in-house system is known as Equipment Health Index, which provides rating to transformers, reactors, air-insulated switchgear (AIS) and gas-insulated switchgear (GIS) circuit breakers. Existing practices and data types of Grid Maintenance include:

- Rentice clearing and maintenance – hardcopy reports three times per year
- TowerTop Inspection – UAV videos taken every 4 years
- Drone – videos taken every 3 months
- Thermoscanning – hotspot thermal images every 4 years

The standard practice in TNB requires the patrolmen to monitor the condition of power transmission lines and towers by using a document designed as a check list and then to calculate the score for a period of time to ascertain the risks periodically without any integrated system. In order to monitor the transmission lines and transmission towers condition, a group researchers and engineers in TNB has embarked on a research to produce a more systematic online system to assess the physical condition of the transmission towers based on the indicator statuses. The physical condition including structural and non-structural of the transmission lines and towers are measured systematically and documented according to national and international risk management procedures and guidelines. The structural condition includes insulators, conductors, spacers/dampers, mid-span joints, bracings, and crossarms. The non-structural conditions includes tower footings resistances, right of ways, ground clearance and slope conditions. The overall condition of transmission lines, transmission towers and cables will be impacted by the condition of each item, and therefore the conditions of all these critical items shall be monitored using a web-based system named as TNB Transmission Line and Cables Health Index or LCHI in short.

In the remainder of this paper, Section 2 presents the related work of transmission lines health index monitoring studies conducted by other researchers. This is followed by Section 3 that presents the evolutionary prototyping methodology adopted to develop LCHI, which is centred around the health index determination framework used to determine conditions of the transmission lines and cables. Section 4 explained the context and features of the web application to monitor the health index of those conditions. Several screenshot of the interface of the web application is also provided in this section. The paper ends with the last section, Section 5 which concludes this paper and provides some recommendation for future improvement.

2 Materials and Methods

This section begins with review of three similar or related work found in the literature conducted by other researchers related to overhead power transmission lines health index. This is followed by description of the evolutionary prototyping approach adopted in developing LCHI system.

2.1 Structural Health Monitoring

Skarbek, Zak and Ambroziak in [2] presented several strategies for detecting damage in the Structural Health Monitoring (SHM) of overhead power transmission system. The authors also report possible economic effects of the SHM of transmission and distribution system for electrical energy company. However, their research focuses only at damage detection of steel latticed towers and span, which should be divided into 2 categories: damage of a tower and damage of a line. They further explain typical tower damage can be categorised as “fatigue cracking, crossarm cutting, foundation cracking, rotation of a tower (due to miry terrain), rivets loosening, etc”. On the other hand, damage of a transmission line may be contributed by breaking, shirt-cutting, insulator cracking, rust occurrence, fatigue, and cracking commonly caused by ageing, vibrations (conductors galloping, aeolian vibrations) and human factors [2]. In their study, transmission tower damage indexes are calculated based on Finite Element Method (FSM) for a damage assessment based on natural frequencies calculations and using artificial neural networks. Although further study is needed, the researchers discovered “simple processing of the frequency shift may give better results than the application of the artificial neural network”.

2.2 Condition-Based Health Index

The work presented in [4] demonstrates “idea of inspection for maintenance of overhead power transmission lines based on the checking list used by patrolmen or line inspectors”. Patrolmen or line inspectors fills up checking sheet with physical conditions (good, normal, poor), aging or depreciation data for overhead transmission lines. The scores obtained from the checking document is then calculated to generate health index. The health index can be used as an indicator for determining or for providing planning of maintenance for electrical power transmission line system as suggested in Table 1. The four categories of criterion design for overhead power transmission line system presented by the researchers in [4] include: i) concrete pole, ii) insulator, iii) conductor, and iv) grounding/lightning system. Each component is given mode score and consists of several items (each is given item score) as follows:

- Concrete pole (50%) – leaning pole [20], cracked pole [20], weed coverage [10], treeing [10], sanek guard [20], building nearby [10], car crash prevention [10].
- Insulators (25%) – cracked insulator , dirt [20], corrosion.
- Conductor (15%) – cracked wire , unusual thing (kite, etc) [10], loosen connector.
- Grounding/lightning (10%) – broken ground lead wire, ground resistence, no overhead ground wire, broken overhead ground wire.

Table 1 Categories Of Health Index Conditions [4]

% HI & THI	Condition	Requirement
86-100	Very good	Normal maintenance
71-85	Good	Normal maintenance
51-70	Fair	Increase diagnostic test
31-50	Poor	Start Planning Process to Replace/Rebuild
0-30	Very poor	Immediately Asses Risk; Replace or Rebuild

2.3 Reliability-Centered Maintenance For Overhead Transmission Lines

Zhang and Lin in [9] present a model for estimating the overhead power transmission lines failure rate by use of monitoring data and the non-supplied energy index (EENS) evaluation method to establish the overhead transmission lines' trustworthiness. The model quantitatively analyze the reliability of the overhead transmission lines by assigning a weighting factor between 10 and 1 to the so-called main monitoring items where weight 10 is the most significant and weight 1 is the least significant. Each monitoring item has several sub-items as listed in Table 2. Each item or sub-item requires a particular strategy or technology for surveillance or inspection. To connect monitoring items to the overhead transmission lines failure rates, monitoring measurements must be combined for all critical monitoring items into the so-called "an overall condition index for whole overhead line" [9].

Table 2 Monitoring Items For Overhead Transmission Lines Suggested in [9]

	Monitoring Items	Weights
Foundation	Foundation displacement, settlement, Damage of slope protection and flood control facilities	8
Tower	Tower tilt, deformation, missing components, loosing screws and corrosion	10
Conductor	Corrosion, broken strand, injury, burn by flashover, condition of sag and jumpers	10
Insulator	Contamination and seal degree of insulators	10
Fittings	Displacement, corrosion, wear deformation and damage	8
Grounding device	Condition of grounding devices, grounding resistance	6
Auxiliary facilities	Damage of lightning protection facilities and bird prevention facilities	4
Surroundings	Safety distance clearance, distance departing from trees and buildings	4

2.4 Evolutionary Prototyping Approach

Just like in most other projects, we acknowledge that communication between designers and end consumers is important. Hence, in developing the system, we adopted evolutionary prototyping approach because Prototypes have demonstrated adequate assistance for such communication [10]. Also, Prototypes are a good source of creative thoughts and ideas, whether in an academic environment and even in industry as mentioned in [11]. The types of prototypes constructed in this project can be categorized as user interface prototypes and functional prototypes that execute strategically significant components of both the user interface and the scheduled application functionality as defined in [10].

A total of six user interface prototypes and two functional prototypes were produced in this research before both researchers and engineers agreed on the functionalities, and final look and feel of the system. The evolutionary prototyping approach adopted in developing LCHI system is as illustrated in Fig. 1, which can be summarized as follows:

- Health Index Determination – This step determines the elements (i.e. parameters of transmission lines) and algorithms to determine health index of transmission lines and cables via series of meetings and discussions between the technical team members and the engineers. Some of the elements were suggested the engineers based on many years of experience dealing with the elements of the transamission lines.
- Requirements Gathering – This step clarifies requirements and design elements of the prototypes and the final look and feel as well as functionalities of the system.
- Prototype – In this step, we produced several low- and high-fidelity user interface prototypes using sketches and Microsoft Power point. These were followed by functional prototypes developed using .net framework and Microsoft SQL Server database management system. During this stage, the prototypes were gradually improved until the final system is delivered.
- Test – Both researchers and engineers test the prototypes to look for more improvement opportunities. At this stage, mock data were used to test the correctness of the programming algorithms developed by the programmer based on the health index determination framework.
- Production – Once the stakeholders are satisfied with the prototypes, then only the final system is placed in the production server to be accessed by the end users.

3 Results and Discussion

This section described the health index determination framework, the power transmission lines and cables elements, and the TNB Transmission Lines and Cables Health Index web application.

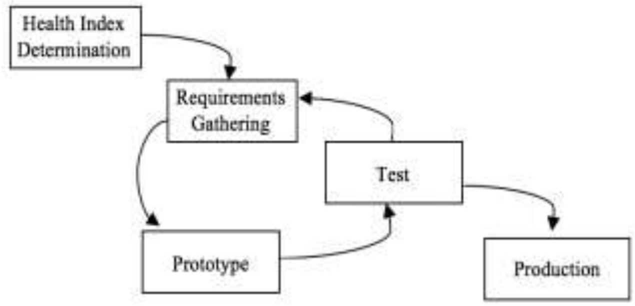

Figure 1 Evolutionary Prototyping Approach Adopted In The Research

3.1 Health Index Determination

Hazard or defects or problems of transmission lines and cables are currently detected using human visual observations to produce assessment report, UAV (Unmanned Aerial Vehicle) and drone videos, and thermoscan hotspots. Among the objects identified for transmission tower assessment and management using visual inspection are tower exposure and specification, tower foundation, tower structure, tower classification, tower status, and geographical data of the tower as shown in Fig. 2.

Figure 2 Objects For Transmission Tower Assessment And Management Using Virtual Inspection

In 2016, it was reported in [8], the unscheduled supply percentage for low and medium categories of voltage interruptions in the country was 12.94% caused by environment factor [8]. Based on the compilation seventeen years of reports of electrical interruptions in Peninsular Malaysia from 2000 to 2016 described in [12], it can be concluded that the electrical interruptions were contributed by the surroundings (31%), structural failures (17%), conductor issues (40%) and third party disruptions (12%).

In this research, the proposed parameters of transmission towers' elements and the framework to determine health index of transmission lines and cable elaborated in detail in [12] were adopted from several other research reported in [4, 10-21]. Fig. 3 depicts the simplified process for determining health index of transmission lines and cables. To determine the transmission line health index, the condition ranking of three components have been taken into account: electrical/mechanical, surrounding environment and structural. These three components contain nearly all aspects related to a electrical power transmission line. The foundation basic component that form an overhead power transmission line as mentioned by Bayliss [3] and Thongbai [4] have to be excluded in this framework due to insufficient data. The elements of electrical/mechanical component include insulator, conductor, spacer/damper, and mid-span joint. The other elements are tower footing resistance (TFR), right of way (ROW), ground clearance, and slope condition are considered in determining the surrounding environment component and bracing and crossarm elements for the determining the structural component. Similar to the concept of monitoring items used in [9], Fig. 3. indicates condition reading of sub-elements of the main elements or parameters must first be determined in order to calculate the condition score of the elementsparameters.

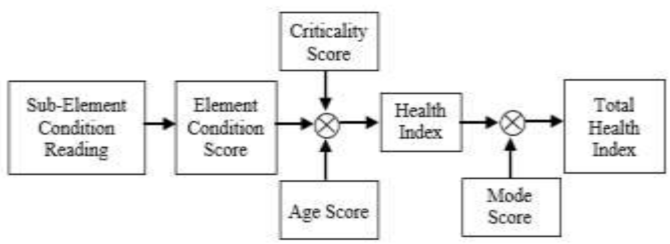

Figure 3 Process Flow For Determining Health Index Of Power Transmission Lines And Cables. Adapted From [12]

The system determines age score based on the service life data inferred from historical data gathered by the electricity utility company from the annual reports and service evaluation reports produced the energy commission in the country. The system then defines the criticality score of the line that the electricity utility company sets in relation to the frequency of service disturbance that occurs over a particular period. The health index (HI) of an each element is then calculated based on the formula in Equation (1). Then it proceeds to calculate the Total Health Index (THI) representing the proportion of total overhead transmission lines using formula in Equation (2) as explained in [12].

$$HI = \sum_{i-1}^{m} C_i \times I_i \times CF_i \, xAF_i \qquad (1)$$

Where:
I – item or element score (up to 100%)
C - condition score
CF - criticality score
AF - age score
m - total number of elements

$$THI = \frac{\sum_{i=1}^{n} HI_i \times M_i}{100} \quad (2)$$

Where:
HI – health index of each item/element
M - mode score (up to 100%)
n - total number of components

The descriptions of the elements of power transmission line for determining health index of power transmission lines and cables are provided in Table 3. Using same process flows, the health index of transmission cables are determined by tests performed to cross-linked polyethylene (XLPE) and oil-filled cables, which are described in Table 3 as well.

It is anticipated that the overall health index findings will be able to clarify what components, environmental exposure, and geographic situation affect the transmission lines and cables ' health. Several scenarios of the proposed framework for determining health index of transmission towers and cables have been tested and demonstrated in [12].

3.2 Transmission Lines and Cables Health Index Web

Generally, LCHI system needs to interact with several other systems being used in TNB in order to get basic ratings of elements.The LCHI system gets slope condition rating of transmission towers from another system known as Innovative Monitoring Rating System (IMRS) and condition ratings of other elements to determine health index from the Systems Applications and Products (SAP) Enterprise Resource Planning (ERP) system. The ratings then shall be converted into equivalent percentage score values before both HI and THI can be calculated for the elements and transmission lines and cables. The administrator of LCHI amongst the selected engineers in TNB is given additional feature to change the mode scores to be used in determining the HI and THI. Fig. 4 shows the context of web-based LCHI system as described earlier. The LCHI system allows engineers, and administrators of the system to view the HI and THI of transmission lines and cables, which are assigned with four-colour codes to represent different ratings, similarly as used in [4], given to HI and THI as listed in Table 4.

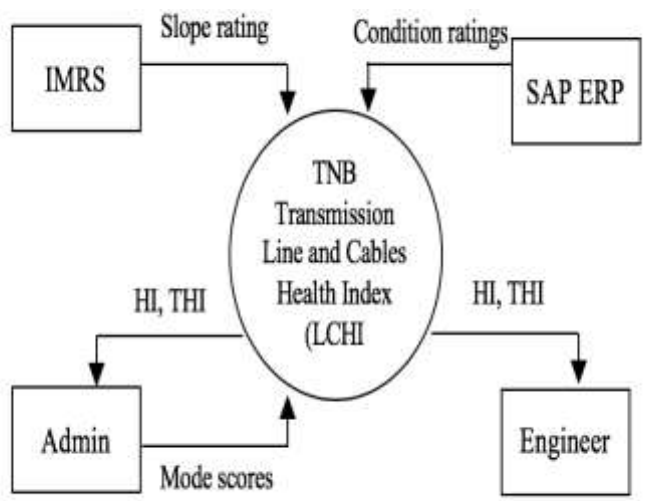

Figure 4 Context of LCHI

The main features of the web-based LCHI system for the use of both engineers and administrator are as follows:

- Health Index of Zone: This feature aims to provide an overview of the overall health index of transmission lines in the country. It provides a list of total number of towers for each health index rating, which is grouped into five zones of transmission lines in Peninsular Malaysia – North, East, Selangor, Kuala Lumpur and South. Unlike the Selangor and Kuala Lumpur zones, the north zone include transmission towers located in Kedah, Penang, and Perak states, the east zone include transmission towers located Kelantan, Terengganu and Pahang states, and the south zone include towers in Johor, Melaka and Negeri Sembilan. Users may access this feature from the main page of LCHI as shown in Fig. 5.
- Health Index of Transmission Lines: This feature enables users to observe the THI ratings given to all transmission towers of transmission lines within the five zones and sub-zones (or states). The system enable users to manipulate the information provided in the page including to perform sorting of zones, sub-zone, lines and kV. Also, the system allows users to search and to view THI ratings of a specific transmission line.

Table 3 Power Transmission Lines and Cable Elements

Component	Element / Parameter	Description
Electrical/ Mechanical	Insulator	Insulating supports used to attach power transmission lines to transmission towers.
	Conductor	A medium to transport electricity from one place to another
	Spacer Damper	Used to create a distance between the conductors to avoid the conductors from knocking together and hence, avoid damage done to conductors.
	Mid-span Joint	Used to connect two lengths of overhead line conductors together between the transmission towers.
Surrounding Environment	Tower Footing Resistance	Resistance offered by the metal parts of the tower.
	Right of Way (ROW)	A strip of land for operating, and maintaining transmission line.
	Ground Clearance	Clearance distance from a power line.
	Slope Condition	Rating of condition given to slope of tower.
Structural	Bracing	Used to interconnect the legs of transmission lines.
	CrossArm	Holds the cable and the insulator to the transmission tower.
Cable	XLPE Cable	Low voltage (600/1000 V) to 132 kV cross-linked polyethylene cable.
	Oil-filled Cable	In the cable sheath itself or a containing tube, low viscosity oil is held under pressure.

Table 4 Classification of Physical Health Condition

% HI & THI	Rating	Color Code
75-100	Good	Green
50-75	Moderate	Yellow
25-50	Low	Amber
0-25	Critical	Red

- Health Index of Elements: This feature summarizes the health index ratings of the ten elements of transmission lines and two elements of transmission cables. The summary of each parameter is represented by horizontal rectangular bars with lengths proportional to the values that represent THIs of different ratings. A sample page of the summary page is as shown in Fig. 6.
- Health Index of Transmission Towers: This feature provides list of detailed health index ratings of transmission towers, categorized into condition ratings of tower elements of transmission lines including insulator, bracing, crossarm, TFR, and slope ratings. This feature also enable users to sort zones, sub-zones, lines, and kV.
- Health Index of Span: This feature allows users to view condition ratings of conductor, spacer/damper, mid-span joint, right of way and ground clearance. Similarly to other earlier features, users may search for specific transmission line to view ratings of span elements.
- Health Index of Cables: This feature provides list of detailed health index ratings of transmission towers, categorized into condition ratings of two elements of transmission cables: XLPE cable and oil-filled cable.

Figure 5 Main Page of LCHI

Figure 6 Summary Of Health Index Of Transmission Lines Elements

4 Conclusion

Efficient maintenance and management system for its transmission towers is essential to TNB, Malaysia's biggest power utility corporation. In order to monitor the transmission towers condition, a group researchers and engineers in TNB have embarked on a research to produce TNB Transmission Line and Cables Health Index web-based system. The system aims to assess the physical condition of three components of transmission lines and towers, which are: electrical/mechanical, surrounding environment and structural. The elements to determine condition of transmission lines and towers are insulator, conductor, spacer/damper, mid-span joint, tower footing resistance, right of way, ground clearance, slope condition, bracing and crossarm. In addition, two elements are used to determine the condition of cables: cross-linked polyethylene cable and oil-filled cable.

The web-based system was developed using the evolutionary prototyping methodology as explained in Section 2 of this paper. Brief explanation of the framework to determine health index of transmission towers and cables is also provided in the same section. As explained in this paper, among the main features of the system are HI of zones of transmission lines, HI of transmission lines, HI of individual parameters, HI of transmission towers, HI of span, HI of cables and setting for the Administrator role. In the energy industry, the web-based system plays an significant role in prioritizing the maintenance, renovation or substitution of transmission towers, especially in the nation, to prevent power supply disturbance.

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