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NB-IoT based Status Measurement System for 33kV Power Distribution Networks in Smart Grids

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Abstract: In the recent decade, there has been a lot of focus on developing intelligent systems and appliances to suit the century's needs and make life easier. During the same period, the electric power industry introduced Smart-Grid, a crucial innovation to meet today's electric supply-demand and effectively use electric resources. The smart grid is an aspect of the electricity industry's evolution and reformation. An electrical power grid is a complex system consisting of generation, transmission, distribution, storage, and utilization. Coordinating these systems further increases the complexity of this interconnection of systems. The existing power distribution system available in the industry consists of monitoring equipment such as Supervisory Control and Data Acquisition(SCADA) to monitor some network parts. However, there's no automated way of monitoring power outages or load current flow in some sub-sections of the distribution line. Physical inspection is not convenient as it's more time-consuming.Moreover, these sub-sections may have up to ten distribution transformers or even could be more. In this work, A novel IoT-based power line monitoring system has been introduced to overcome those issues. Narrow Band Internet of Things(NB-IoT) is used in this system as the primary wireless technology. A current sensor measures electrical line currents, and sensor values are pushed to a remote IoT cloud. Implemented system tested in several 33kV power lines and result and performances of the system is presented.

Index Terms: IoT for Smart Grids, SCADA, NB-IoT.

1. Introduction

Future Smart Grid applications will require acquiring data from the electrical system, and IoT device implementation is a must. Wireless sensor networks offer access over remote areas with centralized monitoring .these data can be utilized for enhanced outage management of distribution systems in a real-time manner. In many countries, including Sri Lanka, power distribution lines are made from 11kV to 33kV. It is an essential requirement to have consistent monitoring of the status of the distribution line in critical areas. Generally, these lines are monitored by humans using the traditional meter. There are many drawbacks when measuring the voltage status manually. It requires human resources and can be of low accuracy. There is no mechanism to identify if there is any fault immediately. These issues could be overcome by designing an automated power line status monitoring system. This task is efficiently achieved using self-powered IoT electronic devices deployed in the Medium Voltage (MV) distribution network. The project's novelty is implemented NB-IoT to this power line monitoring battery-operated device. This device can measure the electric field availability & measure the line current in real-time.

Existing work on designing IoT systems for power line monitoring contributes significantly. Several systems have been implemented to measure the voltages and temperature of the power lines [1-6]. Most of the designs have used LoRA, Zigbee, GSM, and a few designs on NB-IoT. ZigBee's good self-organizing network function, LoRa multi-hop transmission, and NB-IoT data upload are stable in communication. The packet loss rate during the test is 48/1440, which is about 3.3% [2]. The work [7] proposes an IoT-based sag monitoring system. The sag value of a transmission line is calculated using two approaches in this study. The sag value might be either a theoretical value determined from the theoretical line or a practical value calculated from the practical line. The temperature following IEEE Std. 738-2012 or A sag sensor is used to determine the value. Aside from the obvious, The line was measured using the proposed sag sensor. The temperature was estimated using IEEE Std. 738-2012. It's also possible to utilize it to provide theoretical sag. Wind speed, ambient temperature, and other data line current data and sunlight data at a glance. The temperature of the line and the sag value could be calculated. It may, however, be challenging to obtain these. real-time parameters with excellent precision.

The main objective of this work is to design Narrow Band IoT-based status monitoring of 33kV power distribution lines. During the design, a sensor and an energy harvesting circuit is used to detect the current of the power line. The sensor is connected to a microcontroller-based circuit to process the data. The sense data were transmitted to a remote IoT cloud. Furthered, Python 3 was used architect the system, and all the electronics circuits were designed using CAD tools and manufactured as PCBs.

The proposed system can also measure voltage dips, transients, flickering, and feeder temperature. This design features narrow band IoT to establish communication with the server end and publish measured data through MQTT lightweight protocol [8]. The measurement values obtained from the sensors will be a push to a remote IoT cloud. And the administrator can remotely monitor the status of the power line using a mobile device or a PC. Further, this system provides the exciting visualization of data on a dashboard. Thus the user can understand the behavior of the voltage status of the power line at a glance.

2. Background

2.1 Electric field sensing(33kV)

The electric field is created by an electric charge's presence and describes the magnitude and direction of the force it exerts on a positive electric charge. The magnitude of the electric field depends on the different potentials between charge-carrying bodies(conductors) regardless of the amount of current flowing through the conductor.

The electro smog meter has to measure the electric and magnetic field, equipped with three axes sensors and measured simultaneously. The measuring range is normally 20mV/m to 108V/m for an electric field. We could find some measured research data on the electric field, and our sensor electronics were designed based on those values [9-10].

2.2 Narrow Band-IoT Technology

Narrowband IoT (NB-IoT) is a cellular base wireless communication standard for the Internet of Things. NB-IoT belongs to low-power wide-area networks (LPWAN), enabling connected devices to need small amounts of data, low bandwidth, and long battery life. This makes it suitable for various applications and uses cases for IoT. Those modules consist of energy-saving options (eDRX and PSM or Power Saving Mode),

NB-IoT has deep penetration capability through buildings and reaches far away. The bandwidth of NB-IoT is 200KHz or 180KHz. NB-IoT can perfectly connect a massive number of devices - up to 50,000 per network cell. Narrowband technology uses only a portion (guard band) of the available spectrum, so network efficacy may not reduce. This low bandwidth minimizes power consumption & enabling battery life of more than ten years. Most service providers deploy this NB-IoT feature [10-12].

We used the MQTT protocol to communicate in-between the device and server. Considering data security, it won't access unauthorized persons. Passwords, encryption, authorization & authentication are the techniques to ensure MQTT confidentiality. In this application server issue, access tokens to enhance client-server protection provide additional protection to the access security mechanism. The client always required that token while accessing the IoT Server[13-14].

Further, MQTT is a lightweight TCP/IP layer protocol. Headers of the MQTT are not heavy there, for it needs a short period to transmit data. Fewer bytes of data amount to transmit, and energy-saving applications mostly use MQTT.

2.3 Battery Selection(LiFePo4)

Lithium-ion batteries can overheat and catch fire, but LiFePo4 is fired safely. Battery selection has to consider technological and environmental facts. We compared some facts, output voltage, maximum working temperature, deliverable current, discharge and charging time, charging cycles (lifetime longer than x5), and pack size. The battery's nominal voltage is 3.2V, and the maximum is 3.65V. The working temperature of the battery is higher, so it can use an outdoor rush environment[15].

2.4 Current Measuring of Distribution Lines

In typical distribution and transmission networks, the current measurements of the power lines are measured using current transformers. Practically current transformers are mounted in well-insulated tall structures, and often they are installed only in power stations, grid substations, or in particular nodes in the network. Also, with the ratings of the CTs, they are not supposed to measure an extensive range of current with reasonable accuracy because those are saturating with high current.

Contrastingly, it is not feasible to use CTs to measure the current feeders in sub-sections that don't belong to the core network. Rogowski coils are used for the current measurements in large ranges where the conductors are in the accessible height from the ground. Therefore, our application should look into the ability to use Rogowski coils in the poles of distribution lines.

Magnetic-field-based energy harvesting techniques are preferred compared to other methods because of the capability of harvesting energy throughout a more significant time on a reliable network and harvest more energy than the other methods.[16-18]

A. Core Shape

Toroidal-shaped cores have numerous advantages over shell-type and core-type constructions, such as an almost ideal magnetic circuit due to the proper grain alignment with the flux path.

B. Linear Region Operation

The operational limits of the harvester have been experimentally determined to limit the operation of the harvester within the linear region of the B-H curve.

2.5 Testing with MV power line

We have to deal with the MV power distribution line during this project. The device needs to be connected with the MV power line, and it needs to be done safely. Insulating sticks are suitable for use on systems with operating voltages above 1kV. Insulating sticks are specified for use within medium/high voltage substations and for working on live overhead distribution lines. Insulating sticks are constructed from glass fiber-resin polyester and resin epoxy foam and have lockable buttons to secure the extendable telescopic sticks[19].

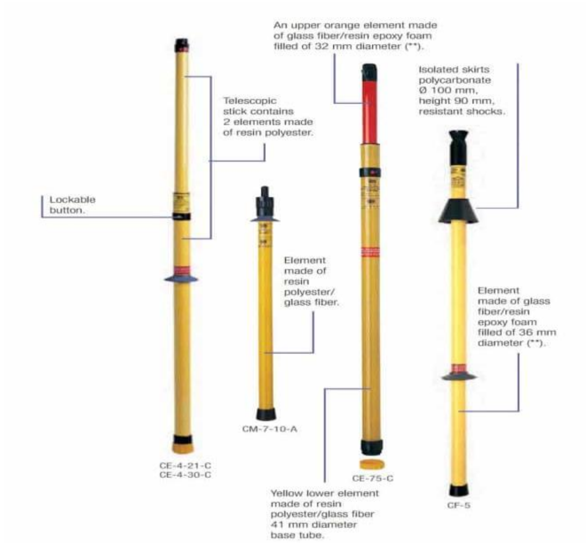

Fig.1. High voltage operation rod[19]

3. Experimental Setup

The simplified block diagram shows in Fig.2 how the design energy harvesting and the measurements are being done. Since the Rogowski coil's induced voltage is AC, it is first passed through an integrator circuit. The sigma-delta analog to digital converter built-in MCU converts the analog values to digital values. So, the main conductor current can be calculated accordingly.

Electric field sensing two types of circuits are being used to increase the operation's reliability. One of them senses the field and provides the digital output according to the availability of the 33kV of the feeder. The second circuit consists of the potential dividing technique, and it gives analog output proportional to the feeder electric field.

On the other hand, harvested energy is conditioned to supply steady 5V. A TRIAC, a metal oxide varistor and a transient voltage suppressor, and a Zener diode were added near the current transformer to protect the circuit (avoid overvoltage). Since the varistor's electrical resistance varies with the applied voltage, it can reduce the effect of high voltage surges on the circuit. The transient-voltage-suppression (TVS) diode operates and drives TRIAC by the shunting excess current when the induced voltage exceeds the avalanche breakdown potential. It is a clamping device, suppressing all overvoltage above its breakdown voltage. So, these devices collectively help protect the current transformer from the transients and overvoltage.

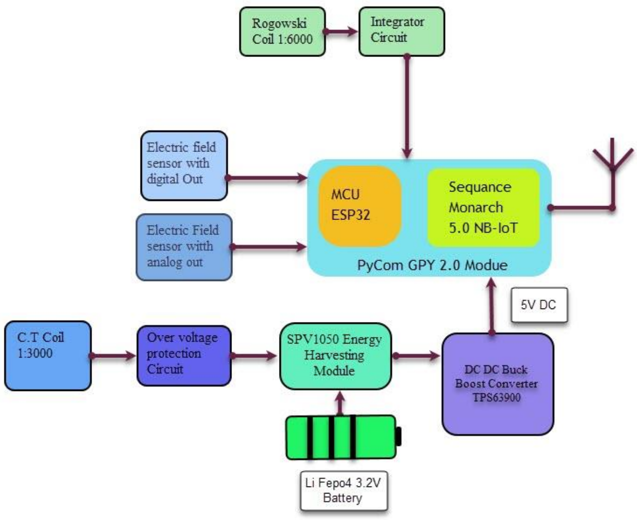

Fig.2. System Overview

However, one of the application requirements is to indicate lineouts. The current transformer can only harvest power from the conductor while the line is energized. Therefore, there must be a method to store energy while the line is energized and release energy once the line is out of power.

A LiFePO4 Rechargeable battery was selected for the alternative power source. Compared to other types of batteries, Lifepo4 has steady output for long life. It has a nominal capacity of 3200mAh with a nominal voltage of 3.2V.

3.1 Power budget calculation

$Minimum\ operating\ voltage\ level\ of\ rechargeable\ battery\ -\ Vmin$
$Maximum\ operating\ Voltage\ level\ of\ rechargeable\ battery\ -\ Vmix$
$Average\ Power\ consumption\ Pycom\ GPY2.0\ module\ -\ W1$
$Power\ consumption\ of\ E\ field\ sensor\ -W2$
$Power\ Consumption\ of\ DC-DC\ Module\ -\ W3$
$Power\ consumption\ of\ an\ OAPMP-\ W4$
$Power\ consumption\ of\ TPS63900\ -\ W5$
$Power\ consumption\ of\ SPV1050\ -W6$
$Other\ Power\ Losses-\ W7$

Typical Power Consumption values of Components,

$$W1 = 1.50W, w2 = 10mW\ \ W3 = 80mW, W4 = 90mW, W5 = 20mW, W6 = 250mW$$
$$W7 = 40\ mW, Vmax = 3.6V, Vmin = 1.8V$$
$$Average\ Power\ Consumption = (W1 + W2 + W3 + 2W4 + W5 + W6 + W7) = 2.0W$$

Battery Power Calculation
During transmission, power consumption adds up to W= 2.0 W
Assume the time. T is the time when the energy supplied from the rechargeable battery

$$C(Vmax - Vmin) = W * T$$
$$3.2(3.6 - 1.8) = 2.0 * T$$
$$T = 5.76/2$$
$$T = 2.88\ hours$$

Here, the most critical time is obtained by applying the most significant theoretical power consumption. This time should have a more significant value. But as the transit time doesn't last more than a few seconds per a period of transmission.

3.2 Energy Harvesting

The SPV1050 shown in Fig.3 has an ultralow-power and high-efficiency energy harvester and battery charger & integrates the switching elements of a buck-boost converter. Its input voltage range from 75 mV to 18 V and also has a built-in battery charging function, supporting PV cells.

Fig.3. Energy harvesting module (SPV1050)

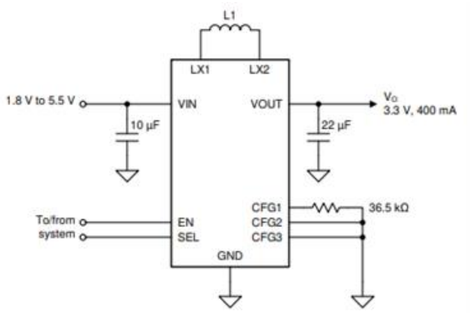

Fig.4 TPS63900 Application Circuit [15]

TPS63900 device shown in Fig.4 has a high-efficiency synchronous buck-boost converter with a shallow quiescent current (75 nA typical). The device has 32 user-programmable output voltage settings from 1.8 V to 5 V. With its wide supply voltage range and programmable input current limit (1 mA to 100 mA and unlimited), the device is ideal for use with a wide range of primary like 3S Alkaline, 1S Li-MnO 2 or 1S Li-SOCl 2, and LiFepo4 battery types. The converter can be disabled to minimize battery drain. The load is completely disconnected from the battery [20].

3.3 Main controller & software

The GPy is a Micro python-programmable triple bearer, and the GPy offers WiFI, BLE, and cellular CAT-M1/NB1.this is one device that includes ESP32 microcontroller and NB-IoT Modem. The main controller is ESP32 and initially tested the communication with the simcom SIM7020E module. Seventeen bands supported from 699Mhz to 2170Mhz. We have to insert an NB network-activated sim card (Sri Lanka Mobitel's service provider). This NB feature had to enable on the cellular tower and do some hardware modification. This device is compatible programming with Atom compiler with python programming or VS code complier with C++ [21-22].

3.4 IoT Cloud

There are many Open source IoT platforms. Things board is the most popular open-source platform in its class. Things Board's freeware and licensed software is widely used by both IoT enthusiasts who design and prototype their smart solutions in their garages and industrial customers with a wide range of requirements for device management, data processing, security, privacy, analysis, etc. Initially, we tested with node-red, and it was succussed but the front end was not well organized there, so we decided to look different solution.

The Opensource package needs to be installed on a PC or server, but it takes much time to understand the process initially, which can be done on Linux or windows. Finally, it enables server-side infrastructure for our IoT applications. These platforms enable, Collect and visualize data from devices and assets., Collect and visualize data from devices and assets. Analyze incoming telemetry and trigger alarms with complex event processing, control the devices using remote procedure calls (RPC), and design dynamic and responsive dashboards [23-25].

4. Design

PCB has been fabricated in-house. The main controller is the ESP32 microcontroller which has built-in WIFI. Other components have been used to detect the electric field of the distribution feeder. This gets the line status as a digital signal. It connected to the IoT server over a WI-FI signal for the first stage, and NB-IoT had not been implemented at this level. Basic schematic diagrams are shown in Fig.5-7

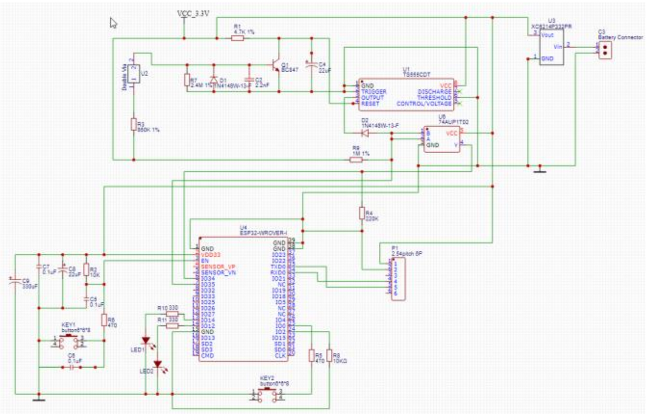

Fig.5. HT voltage detection with main controller

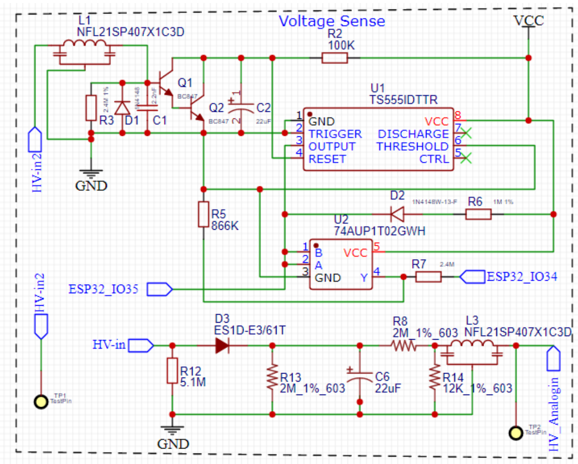

Fig.6. HT voltage analog sensing circuit

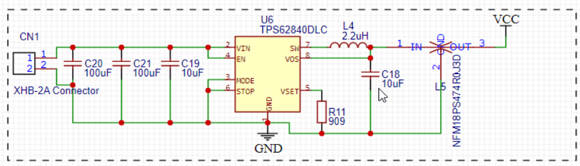

Fig.7 Schematic of the DC-DC converter

Moreover, the design has been modified due to the high power consumption of makes by the WI-FI radio module, and it requires closer internet connectivity. Those things are not suitable in a practical scenario.

In Stage Two, we have upgraded the communication module to NB-IoT. And used the dc-dc converter to operate the device with a battery. Simcom sim 7020e is the communication module connected to the mainboard via the UART interface. The modem has been configured with AT commands and the main program running on the esp32 controller senses the electric field and updates the status to the IoT server.

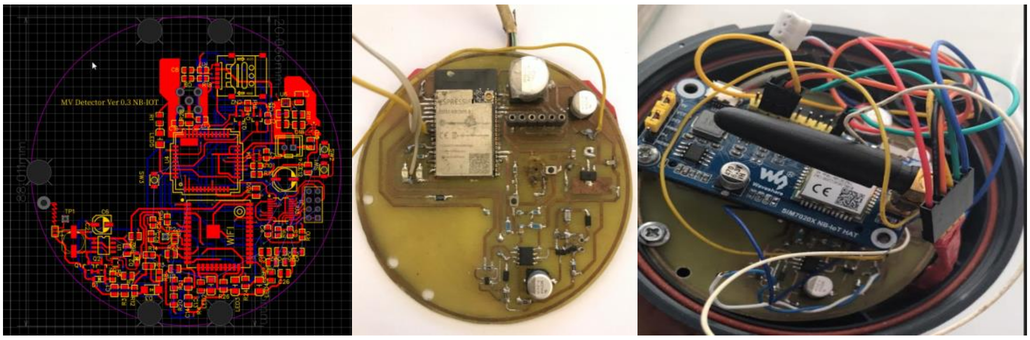

Fig.8. PCB layout & constructed modules of the prototype

In stage three, we used pycom Gpy 2.0, which consists of both Nb-IoT modem, and a total power CPU esp32.this is being programmed with python and Atom compiler. This was a big challenge to configure this module with python. Before use, many steps have to be followed for the device's firmware upgrade. I could connect this new module to send data to the IoT server successes fully

Fig.9. GPy LTE CAT-M1/NB1 module[9]

5. Testing & Evaluation

We have tested the prototype in the field with a 33kV power line, as shown in Fig.10. The device could properly detect the powerline electrified. Above mentioned insulation rod has been used to connect the device with the power line. I had some issues with this simcom NB-IoT module when connected to the MV power line. Its controller was stuck due to high EMI interference, but the main controller did not have any issue with the function.

Fig.10. Device testing with 33kV

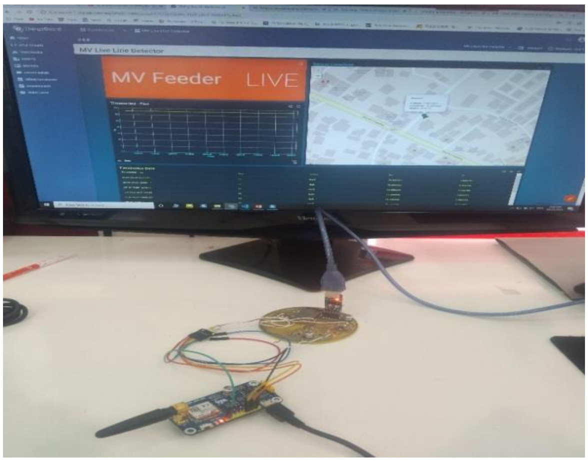

Fig.11. IoT server front end indicates sensor data

6. Conclusions

This paper presented a real-time monitoring power distribution feeders' status. In Sri Lanka, power distribution lines are 33kV, and it is an essential requirement to have consistent monitoring of the critical areas. This task is efficiently achieved using self-powered IoT electronic devices deployed in the MV distribution network. The project's novelty is implementing the Nb-IoT concept in this power line monitoring battery-operated device. These new devise capabilities are electric field sensing, current measuring, and power harvesting from the MV network. Considering the performances gained during both simulation and hardware implementations, it could complete up to a satisfactory level after three numbers of prototypes. For the selected range of main conductor current, precise current measurements can be obtained with Rogowski coil. Nb-IoT is Low-cost reliable transmission when in low cellular coverage present. Received data are critical to visualize feeder energized location and load balancing.

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