

Inductive Harvester and Data Transmission on Medium-Voltage High Power Cable Shields for Autonomous Sensor Nodes

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Abstract

Medium-voltage (MV) cable systems represent a critical component of modern electrical infrastructure, where failures often occur at cable joints due to environmental stress and aging. Continuous monitoring of such joints is therefore highly desirable; however, their underground installation makes conventional communication approaches impractical. This paper presents an inductively coupled communication system that utilizes the existing cable infrastructure as a transmission medium. A low-power embedded system is developed, combining resonant inductive coupling with software-based signal detection using the Goertzel algorithm. Experimental results demonstrate reliable data transmission over several hundred meters under realistic load conditions. The influence of cable configuration, load current, and interference sources is analyzed, and design limitations are discussed. The results confirm the feasibility of the approach and provide guidelines for future system optimization.

Keywords: inductively coupled communication, power line communication, condition monitoring, medium-voltage cable, data transmission

Introduction

Medium-voltage (MV) distribution grids operating at approximately 20 kV are essential for reliable electrical energy delivery [1]. Due to their underground installation and long service life, these systems are exposed to environmental stress factors such as temperature variations, moisture, and corrosion, which can lead to degradation and eventual failure [1]. Cable joints, used to repair or extend cables, represent critical parts due to their structural and material discontinuities. Despite their importance, the condition of cable joints is typically unknown after installation. Embedded sensing systems offer a promising solution for monitoring parameters such as temperature, humidity, and corrosion state. However, their underground placement introduces significant challenges, particularly in terms of energy supply and data communication.

This work addresses the communication problem by utilizing the cable itself as a transmission medium. With the given coaxial structure of MV cables, the presence of grounded shields and the parallel laid ground conductor, a closed conductive loop is formed, refer to Figure 1. This topology enables inductive signal injection, making inductive coupling a suitable method for data

transmission.

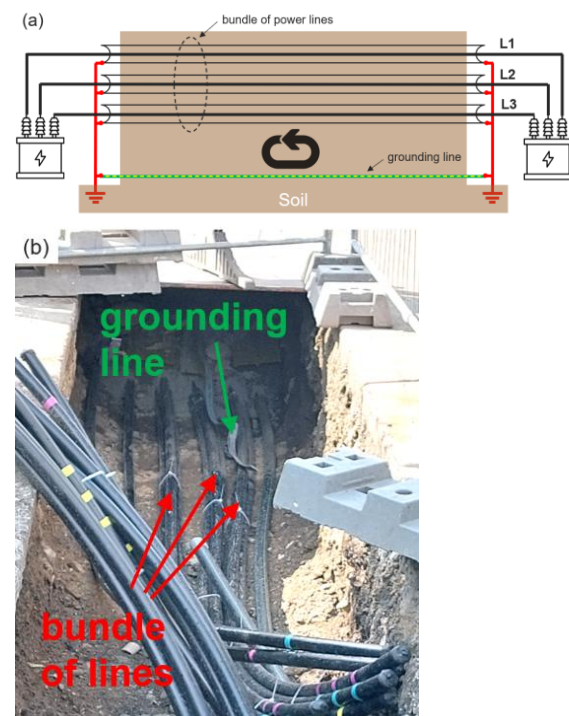


Fig. 1: (a) Schematic representation of a medium-voltage (MV) cable system, showing three-phase conductors with grounded shields and an additional ground conductor forming a closed loop. (b) Photograph of the cable installation in a real deployment environment.

Principle of Inductive Coupling

Inductive coupling relies on the generation of a time-varying magnetic field, which induces a voltage in a nearby conductor [2]. The induced voltage is governed by Faraday's law, Eq. (1):

$$u = -M \frac{di}{dt} \quad (1)$$

where M denotes the mutual inductance between the transmitting and receiving elements.

In contrast to conventional transformers, the presented system operates without a magnetic core between transmitter and receiver, resulting in reduced coupling efficiency [3]. The proposed approach extends this concept by using the cable shield and ground conductor as an intermediate coupling loop. The system can thus be interpreted as two cascaded inductive coupling stages: from transmitter coil to cable loop, and from cable loop to receiver coil, refer to Figure 2.

Although this double coupling reduces efficiency, it enables communication over significantly larger distances than in classical near-field systems such as RFID [3], based on inductively coupling mechanism through air.

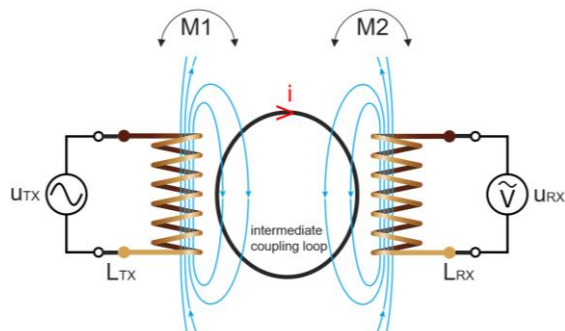


Fig. 2: Conceptual illustration of the two-stage inductive coupling mechanism utilizing an intermediate coupling loop formed by the cable shield and ground conductor.

System Design and Hardware Implementation

A. Electrical Characteristics and Frequency Selection

The cable shield and ground conductor form a low-resistance loop, which is essential for efficient coupling. However, discontinuities such as cable joints increase the loop resistance and reduce signal strength.

The operating frequency must balance data rate and transmission distance. Considering attenuation effects such as skin effect, a frequency range between 30 kHz and 60 kHz was selected. This ensures sufficient bandwidth

while maintaining acceptable propagation characteristics.

B. Transmitter and Receiver Design

The transmitter is based on the evaluation board NUCLEO-L412KB and uses an H-bridge driver (DRV8838) to excite a series resonant circuit at 30 kHz [4]. Data is modulated using On-Off Keying (OOK), where the carrier is switched according to the bit stream [5]. Figure 3 (a) shows the block diagram of the transmitter circuit.

The receiver employs a parallel resonant circuit tuned to the same frequency, followed by a notch filter at 50 Hz to suppress grid interference. Signal amplification is realized using the OPA2328DGKR [6], following standard low-noise analog front-end design principles [7, 8] and finally the signal is digitized via the microcontroller's ADC. Figure 3 (b) shows the block diagram of the receiver circuit.

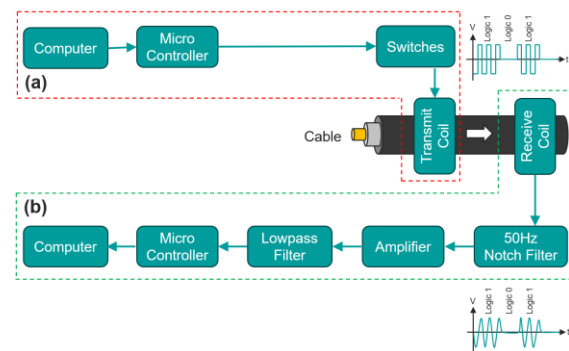


Fig. 3: Block diagrams of the system architecture: (a) transmitter unit and (b) receiver unit.

Figure 4 depicts the developed electronics for the transmitter and receiver unit with the inductive split core couplers.

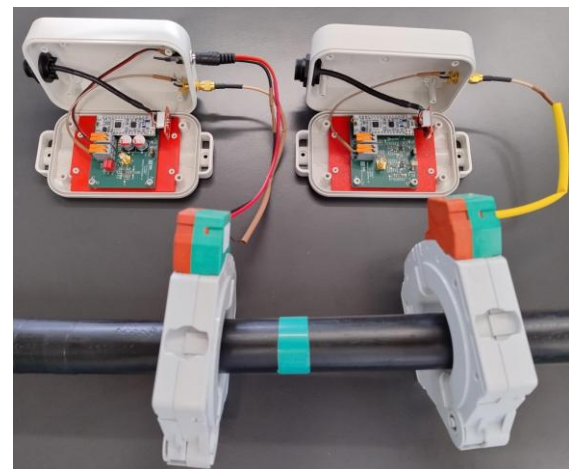


Fig. 4: Photograph of the developed transmitter and receiver prototypes, including inductive coupling elements mounted on a shielded MV cable.

Software Implementation

To minimize hardware complexity, signal detection is implemented entirely in software. The receiver continuously samples the input signal and evaluates the presence of the carrier frequency using the Goertzel algorithm [5]. The algorithm efficiently computes the spectral component at a predefined frequency of 30 kHz, making it well suited for low-power embedded systems. In contrast to a full discrete Fourier transform, the computational effort is significantly reduced, as only a single frequency bin is evaluated. Such digital signal processing approaches are widely used in communication systems and embedded implementations [5, 8].

A detection threshold is applied to the resulting magnitude of the frequency component to distinguish between logical '1' (carrier present) and '0' (carrier absent). To improve robustness against noise and interference, the decision is based on accumulated samples over a defined observation window rather than instantaneous values.

Communication is organized into frames consisting of a start bit, eight data bits, and a stop bit. Synchronization is achieved by detecting the start bit using a shorter sampling window, enabling rapid detection of transmission onset. After synchronization, the receiver switches to fixed-time sampling aligned with the known bit duration, ensuring reliable decoding of the subsequent data bits.

Adaptive thresholding is implemented to account for varying signal amplitudes due to cable length, load conditions, and environmental influences. For this purpose, the amplitude of the detected start bit is used as a reference to dynamically adjust the decision threshold for the following data bits. This approach improves detection reliability under changing channel conditions without requiring manual recalibration.

Figure 5 illustrates the flowcharts of the implemented software architecture for both system components. Subfigure (a) depicts the processing sequence within the transmitter unit, while subfigure (b) presents the corresponding algorithmic flow implemented in the receiver unit.

In addition, the continuous evaluation of the carrier component allows the receiver to operate in a passive listening mode, activating the decoding process only when a valid transmission is detected. This contributes to reduced computational load and supports

energy-efficient operation of the embedded system.

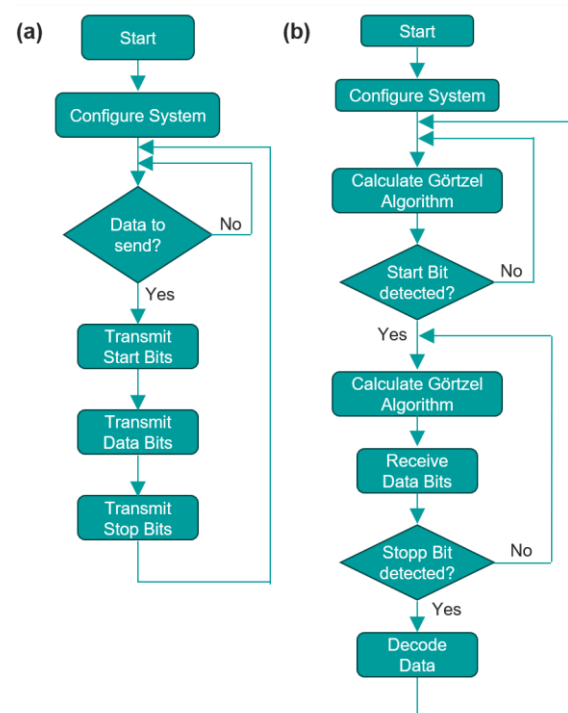


Fig. 5: Software flowcharts of the communication protocol implemented in (a) the transmitter unit and (b) the receiver unit.

Measurements and Results

A. Experimental Setup

A series of experiments were conducted to evaluate system performance under different conditions, including cable configuration, load current, generator influence, and coil integration, as well as different positions of the transmitter and receiver coils.

B. Transmission Performance

With a 200 m cable wound on a drum, reliable communication was achieved at currents up to 50 A. The increased inductance of the coiled cable improves coupling efficiency [3]. In contrast, for a 400 m unrolled cable, the maximum load current for reliable communication decreased to approximately 10 A.

The signal-to-noise ratio (SNR) was observed to decrease with increasing load current, from approximately 35 dB (no load) to 20 dB at 10 A.

C. Influence of External Disturbances

The presence of a generator significantly affected system performance. Even in idle state, the generator reduced the SNR from approximately 70 dB to 50 dB due to switching noise from internal power electronics [6].

D. Coil Interaction Effects

In addition to the inductively coupled communication system, the influence of an integrated energy harvesting module was investigated. The combined configuration consisted of a harvesting coil with approximately 1250 turns and a communication coil with 50 turns, both implemented on a shared magnetic core. As outlined previously, the communication signal is coupled via the cable shield, whereas energy harvesting is performed from the main conductor current within the cable core. The harvesting unit operates by charging an internal supercapacitor (470 mF), with a load switch enabling the supply of the electronic circuitry once a sufficient voltage level is reached.

However, the integration of both coils on a common core was found to significantly degrade the communication performance. From an electromagnetic perspective, this arrangement forms a multi-winding transformer, introducing unintended coupling between the communication and harvesting subsystems. In particular, parasitic inductive coupling and inter-winding capacitances create additional reactive loading paths, which adversely affect the high-frequency communication signal.

As a result, a portion of the injected communication signal is coupled into the harvesting coil. Although filtering is applied within the harvester circuit, the suppression of high-frequency components is incomplete. Consequently, this leads to an increased apparent impedance at the transmitter side and additional losses due to circulating currents within the harvesting branch. These effects reduce the effective signal amplitude available for reliable detection at the receiver.

Experimental results confirm this behavior, showing that the maximum permissible load current for reliable communication decreases to approximately 5 A when both coils are integrated on a single core, refer to figure 7. In contrast, a configuration employing physically separated cores for communication and energy harvesting allows operation up to approximately 10 A, as shown in figure 6.

These findings clearly demonstrate that physical and electromagnetic decoupling of the communication and energy harvesting subsystems is essential to maintain coupling efficiency and overall system performance.

E. Discussion

The results demonstrate that system performance is strongly influenced by:

- cable configuration,
- load current,
- external noise sources,

- magnetic coupling conditions.

Separating communication and harvesting coils onto different cores significantly improves performance.

Figure 6 presents the measurement results obtained for two distinct cable configurations. In configuration (a), a 200 m cable section was evaluated in conjunction with an equally long grounding conductor, forming a defined return path. In configuration (b), a total cable length of 400 m was investigated, where only the cable shields were interconnected.

Furthermore, the position of the transmitter unit was systematically varied with respect to the connection point, which represents a disturbance location introduced by a simplified junction realized through thin wire connections. Measurements were conducted with the transmitter placed both upstream and downstream of this point in order to assess the influence of discontinuities on signal propagation and coupling efficiency.

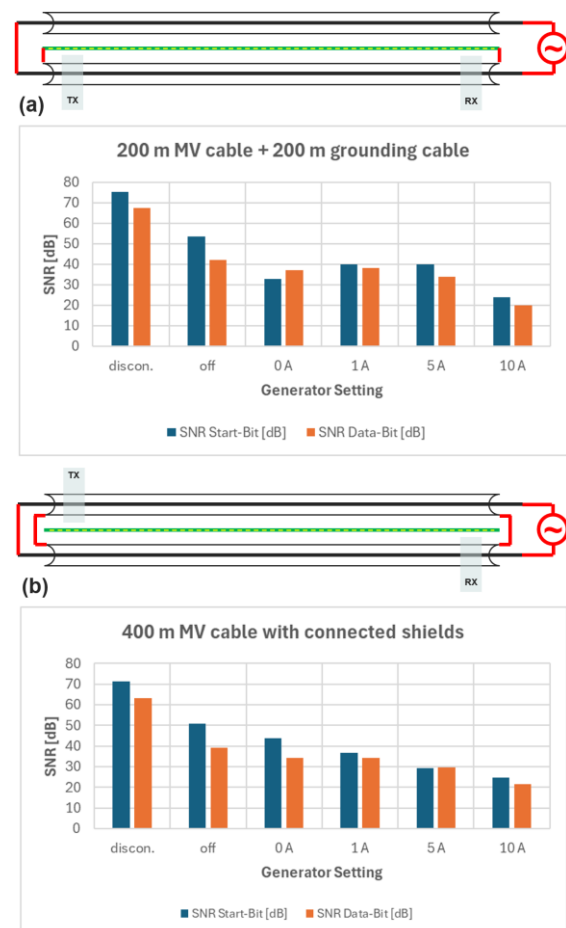


Fig. 6: Measured SNR as a function of load current for different cable configurations: (a) 200 m MV cable with an additional parallel 200 m grounding conductor, and (b) 400 m MV cable formed by two interconnected 200 m sections.

Finally, as illustrated in Fig. 7, the transmitter and receiver units are positioned in close proximity to each other, directly adjacent to the generator feeding point. In Fig. 7(a), the system operates using only split cores equipped with the communication coils, representing the baseline configuration. In contrast, Fig. 7(b) shows the results obtained when the transmitter core is replaced by the combined version integrating the energy harvesting unit.

In the latter case, communication is only established after a certain delay, corresponding to the time required for the harvester to charge its internal supercapacitor and subsequently activate the load switch supplying the electronics. Consequently, no communication results are observed when the generator is disconnected or switched off, as insufficient energy is available to power the transmitter circuitry.

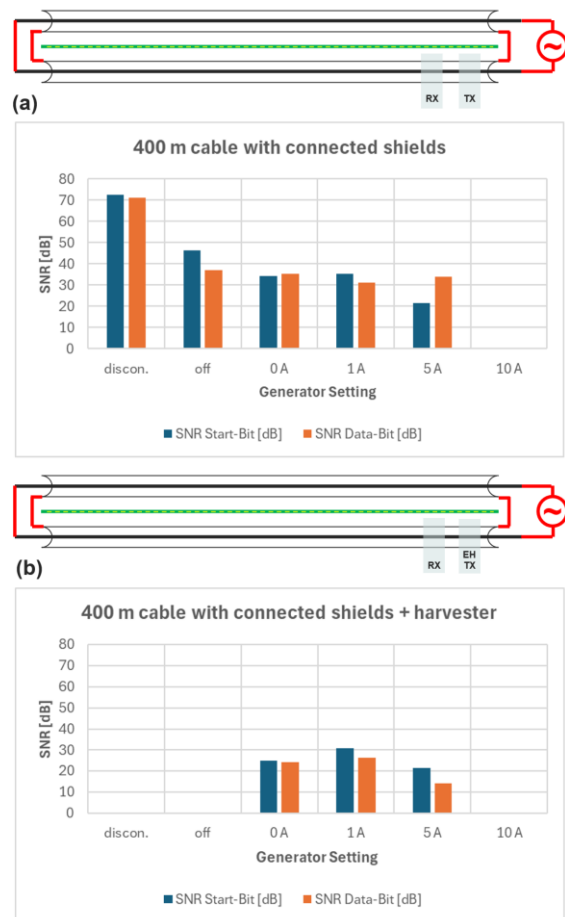


Fig. 7: Measured SNR as a function of load current for different system configurations: (a) 400 m cable with transmitter and receiver positioned in close proximity near the feeding point, and (b) 400 m cable with combined transmitter and energy harvesting coil on a shared core, evaluated against a separate receiver coil.

Conclusion and Outlook

This paper presented an inductively coupled communication system for embedded monitoring in medium-voltage cable networks. By leveraging the existing cable infrastructure as a transmission medium, the proposed approach enables wireless data transfer from buried sensor systems without additional communication lines.

The combination of resonant inductive coupling and software-based signal detection using the Goertzel algorithm results in a low-complexity and energy-efficient implementation. Experimental results demonstrate reliable communication over several hundred meters, even under realistic load conditions.

However, several limitations were identified, including sensitivity to external interference, reduced performance under load, and coupling losses in integrated coil configurations.

Future work will focus on improving system robustness and efficiency through: advanced modulation schemes (e.g., FSK or PSK), error detection and correction mechanisms, optimized coil and core designs, adaptive communication protocols for varying channel conditions.

These enhancements are expected to significantly improve transmission reliability and enable practical deployment in real-world MV grid monitoring applications.

Acknowledgement

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